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Presented to the Faculties of the University of Pennsylvania in Partial Fulfillment of the Requirements for the Degree of Master of Science in Historic Preservation 2006.
Advisor: Frank G. Matero

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Disciplines
Historic Preservation and Conservation

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PERFORMANCE ANALYSIS OF HYDRAULIC LIME GROUTS FOR MASONRY REPAIR

Victoria Isabel Pingarrón Alvarez

A THESIS

in

Historic Preservation

Presented to the Faculties of the University of Pennsylvania in
Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE IN HISTORIC PRESERVATION

2006

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cave quicquam incipias quod paeniteat postea

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CHAPTER 1 – INTRODUCTION

1.1 Use of Grout for Masonry Repair

This thesis was initiated as the third phase of a long-term laboratory and field testing program at the Architectural Conservation Laboratory at the University of Pennsylvania to evaluate critical performance properties of a grout formulation initially developed for plaster reattachment. This testing phase specifically addressed what differences, if any, the use of a new hydraulic lime binder (St. Astier NHL 3.5) would exhibit following a standardized and physical testing program.

Grouting has long been implemented as a procedure to reintegrate gross discontinuities in deteriorated masonry and soil systems. As masonry materials deteriorate, *in situ* grouting is one conservation method or mechanical repair used to reintegrate and reattach adherends or components to their substrate (e.g. crack repair). Although grouting is not a reversible or easily re-treatable application of masonry repair, it is an effective way to strengthen and repair masonry walls without invasive disassembly.

By injecting a liquid mortar into cracks and voids, under pressure or by the force of gravity, grout can enhance the structural properties lost to decay over time. Often, it can be carried out with minimal interruption to the structure and solidifies relatively quickly within a masonry cavity.

A variety of decay mechanisms can adversely affect masonry systems. Some of these decay mechanisms are structural failure from seismic activity or settlement, impact, aggressive salt intrusion, wetting / drying cycles, freezing / thawing cycles, and vegetative intrusion. Inherent incompatibilities can also create failure such as detachment

or cracking resulting from thermal movement of different masonry materials or poor construction techniques. Acidic precipitation can lead to dissolution, disaggregation, and cracking of stone and plasters. Physical, mechanical, and chemical weathering affects porosity, permeability, and the strength of a material. The ways in which deterioration mechanisms operate dictate the tests to be performed on prepared samples.

Grout components are carefully selected for their primary properties with some additives included to impart or enhance unique properties required for specific characteristics or situations. The materials used in this thesis were initially selected based on their availability and overall compatibility with small and large scale low-strength masonry systems. The irreversible nature of grouting requires that the formulations and their reactions with the substrate are well-understood.

Reactive and inert additives, such as fluid coke (high carbon content particles resulting from petroleum processing that expand after contact with water), fumed silica, and ceramic microspheres are fillers which increase viscosity, improve flow, and can actually reduce the amount of water needed in the mixture thus imparting a higher resistance to shrinkage. Acrylic emulsions are added to grout mixtures with the intention that they increase adhesion, splitting tensile strength, and bond strength however they also can lower water vapor transmission and water absorption.

Grouting is generally performed with the expectation that it will re-establish structural continuity and usually impart greater resistance to load in a masonry system. Its proper use conforms to generally upheld principles in preservation of minimal intervention, maximum effectiveness at reasonable cost, compatibility of materials, low

toxicity, and maximum retention of original fabric. It is a fairly simple procedure of repair to complete, provided that the conditions are adequate, the need is appropriate, and materials are readily available.

1.2 Performance Requirements

Performance requirements for grouts in the third phase of this research based on previous laboratory and field research were identified as follows:

1. chemically, physically, and mechanically compatible with the masonry materials to be grouted as determined by the properties displayed by each
2. address the specific problem of detachment
3. low toxicity, low cost, easy formulation and application

2.1 Previous Research

Previous research conducted at the ACL on hydraulic lime grout formulations for plaster reattachment began in 1998[1]. A second phase was focused on crack repair completed in 2001[2]. This work, described below, has provided the foundation for the research methodology in this thesis. Both previous theses have focused on grout formulations relating to earthen masonry at specific National Park Service sites; Fort Union National Monument and Casa Grande Ruins National Monument, respectively. Discussions of and comparisons to current testing results will be elaborated in the following chapters.

2.1.1 Materials

Grout formulations previously tested consisted of a dispersant (in this case water), binder, aggregate, fillers, and in some cases, acrylic admixtures in proportions that bond well and are compatible with the material to be grouted. These formulations were designed to be as low-tech as possible, as they were meant to be employed in field conditions using easily available materials provided at a relatively low cost and following simple preparation and application methods. Only an aqueous system was considered given the porous hydrophilic nature of the masonry and the general absence of salts in the field contexts.

---

[1] Bass, Angelyn. *Design and evaluation of hydraulic lime grouts for in situ reattachment of lime plaster to earthen walls*. Master's Thesis, University of Pennsylvania, 1998.
[2] Cancino Borge, Claudia N. *Assessment of grouting methods for cracks and large scale detachment repair at Casa Grande – Casa Grande Ruins National Monument*. Master's Thesis, University of Pennsylvania, 2001.

2.1.1.1 Dispersant

Deionized water has been the dispersant used in all previous ACL laboratory research. Deionized water is used to reduce the amount of possible contaminants or undesirable anions that may be found in tap water.

2.1.1.2 Binders

The binders used in previous research were: a moderately hydraulic lime manufactured by the Riverton Corporation, Riverton, Virginia; Type S Hydrated Lime manufactured by Corson's Lime Company of Plymouth Meeting, Pennsylvania; and Kaolinite from the Dry Branch Kaolin Company, of Dry Branch, Georgia. The Riverton HHL was selected because it of its overall properties as a moderately hydraulic lime (faster set than feebly hydraulic lime, slower set than eminently hydraulic lime; stronger than feebly hydraulic lime, weaker than eminently hydraulic lime) and because it was the only available hydraulic lime in the U.S. at the time.

2.1.1.3 Aggregate

The aggregate used in previous research was a fine white quartz sand, from Ace-Crete Products, Inc. of Syosset, New York. This sand conformed to ASTM C778-98 "Standard Specification for Standard Sand" with a particle range of 100 – 400 μm. It was chosen for its small grain size suitable for injection, sub-angular shape, and greater overall surface area than microspheres. In Phase 2, this sand was sieved through a #50 U.S. Standard sieve with particles < 300 μm passing in order to improve injectability

minimally through a #12 gauge stainless steel cannula with an inner diameter of 2.159 mm.

2.1.1.4 Fillers

The fillers used in previous research were Zeelan Z-Light Spheres G-3500 manufactured by Zeelan Industries, St. Paul, Minnesota later renamed 3M Scotchlite Glass Bubbles, 3M Specialty Materials, St. Paul, Minnesota. These hollow, inert ceramic spheres composed of a silica-alumina alloy with a specific gravity of 0.65 – 0.75, were used to increase viscosity and flow, reduce weight and shrinkage by reducing the amount of water needed. The particle size ranged from 10 – 350 μm which complemented the sand fraction and increased the particle size range.

2.1.1.5 Acrylic Emulsions

The acrylic emulsions (aqueous dispersions of acrylic polymers) used in previous research were El Rey Superior 200 and Rhoplex E-330, both of which were originally formulated for use with cement. Coalescent film formation gives acrylic additives their strength as water evaporates which (after cure) may soften, but does not dissolve in water. The purpose of introducing these additives was to measure their effect on bond strength, shrinkage, and frost resistance tests; however other effects were noted as well. The El Rey Stucco Company of Albuquerque, New Mexico produces and distributes Superior 200 Additive which is based on Rhoplex E-330 and contains a defoaming agent

necessary for mixing. It then contained a reported 44 ± 1% acrylic solids by weight in water.

Rhoplex-330 is produced and distributed by Rohm & Hass Company of Philadelphia, Pennsylvania and does not contain a defoaming agent. It then contained approximately 47% solids by weight in water, with a particle size ≤ 1.0 μm.

2.1.2 Formulæ

In the first phase (Bass) of the ACL grout testing program, a three-part testing and evaluation process was used to determine the best grout formulation for use in plaster to adobe reattachment after material characterization. The second phase (Cancino) refined the earlier chosen formulation by varying the amounts of sand, microspheres, and acrylic emulsion.

2.1.2.1 Phase One Formulæ

During the first phase of testing, the first set of properties used to evaluate and eliminate formulations was segregation, shrinkage, cracking, and weight. The second set of critical properties was initial set time, percent shrinkage, weight, splitting tensile strength, and water vapor transmission. The initial testing rejected all formulations with Type S lime and kaolinite as binders for plaster / adobe reattachment. The selected formulation (#19) was composed of 2 parts hydrated hydraulic lime, 1 part sand, 1 part microspheres (all parts by volume), mixed with 10% w/v acrylic emulsion.

PHASE ONE FORMULÆ: PROPORTIONS (BY WEIGHT)							
SAMPLE	**HL**	**L**	**C**	**S**	**MS**	**ACRYLIC IN H_2O**	**SUCCESS**
0	1.0	-	-	1.0	-	-	I
1	1.0	-	-	-	1.0	-	II
2	2.0	-	-	-	1.0	-	I
3	2.0	-	-	1.0	1.0	-	II
4	4.0	-	-	1.0	1.0	-	II
5	4.0	-	-	1.0	3.0	-	I
6	4.0	-	-	3.0	1.0	-	I
7	2.5	-	-	3.7	1.0	20% RH	II
8	-	1.0	-	-	1.0	-	I
9	-	1.0	-	1.0	-	-	I
10	-	2.0	-	1.0	1.0	-	I
11	-	4.0	-	1.0	1.0	-	I
12	-	4.0	-	1.0	3.0	-	I
13	-	4.0	-	3.0	1.0	-	I
14	-	-	1.0	-	1.0	-	I
15	-	-	2.0	1.0	1.0	-	I
16	3.2	-	0.8	2.0	2.0	-	I
17	3.2	-	0.9	1.0	3.0	-	I
18	3.2	-	0.8	-	4.0	-	I
19	2.0	-	-	1.0	1.0	10% ER	III
20	1.0	-	-	-	1.0	10% ER	II
HL – Riverton HHL L – Type S Lime C – Kaolinite MS – Microspheres S – Sand Acrylic – El Rey (ER) or Rhoplex (RH)							
Success in this table is determined by the part of the testing cycle that each sample completed (I, II, III) with III being the most successful formulation I – 0, 2, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18 II – 1, 3, 4, 7, 20 III – 19							

Table 2.1

2.1.2.2 Phase Two Formulæ

Phase 2 research only used a moderately hydraulic Riverton HHL as the binder in varied proportions. The amount of sand was also varied to test its influence on a variety

of physical properties of the grout in the presence or absence of the acrylic emulsion. During the second phase of testing, the following properties were used to determine the best formulation: flow, compressive and tensile strength, adhesion in shear, water vapor transmission, and porosity. The formulation composed of (all parts by volume) 2 parts hydrated hydraulic lime, 1 part sand, 1 part microspheres mixed with 10% w/v acrylic emulsion (A) was chosen as the best candidate for crack and detachment repair of the caliche masonry.

PHASE TWO FORMULÆ: PROPORTIONS (BY VOLUME)				
SAMPLE	HHL	S	MS	ACRYLIC IN H_2O
A	2.0	1	1	10% ER
B	3.0	2	1	10% ER
C	2.0	1	1	-
D	3.0	2	1	-
HHL – Riverton HHL MS – Microspheres S – Sand Acrylic – El Rey (ER)				

Table 2.2

2.1.3 Sample Preparation

Samples were prepared following general specifications of ASTM C192 "Standard Practice for Making and Curing Concrete Specimens in the Laboratory", except that the samples were not moist cured due to the possible adverse effect on acrylic film formation. All fine components including lime, hydraulic lime, and clay were sieved through a #140 U.S. Standard sieve with particles < 106 μm passing to reduce clumping, then dry mixed with the sand and microspheres. In the first phase, enough water was

added to the mixture to allow the grout to pass through a 12 gauge stainless steel cannula. Approximately 1 part water to 2 parts dry grout mixture was used in Phase 2 and then tested to pass through a 16 gauge stainless steel cannula with an inner diameter of 1.194 mm.

2.1.3.1 Mixing

The grout was mixed in a Hamilton Beach Commercial Model 936 Drink Mixer for one minute at each setting (10,000 - 17,000 rpm). This mixer was equipped with butterfly and solid agitators attached to the single stationary spindle that worked in tandem. An ordinary kitchen blender with much lower revolutions per minute was also used. The lower speed mixer resulted in visual bleeding, segregation of the mixture, and reduced thixotropy. Foaming was noted in the formulations containing acrylic emulsions even with defoaming agents present. Multiple batches of grout were prepared due to the small capacity of the mixing container, approximately 625 mL.

2.1.3.2 Molding, De-molding, & Cure

The grout was poured into the various pre-lubricated molds with the excess then scraped off. During Phase 1, the samples were housed in a damp cloth tent for 2 days immediately after pouring, and left in open air for the remainder of the 28 day cure. During Phase 2, the samples and caliche assemblies were de-molded and placed in a chamber of high humidity after being dried in air for seven days.

2.2 Current Research

The aim of current research into hydraulic lime grouts for masonry repair at the ACL seeks to establish material data for a new binder (St. Astier NHL 3.5) due to the discontinuation of the Riverton Hydrated Hydraulic Lime, varying volumes of acrylic emulsion, and amount of water used. Modifications in Phase 3 have been made to the testing program to accommodate new methods, equipment, and standardized tests with helpful results. The main variables of interest in this phase of testing is the performance of St. Astier NHL 3.5, followed by the effects of the acrylic emulsion, and then amount of water used.

2.2.1 Materials

All materials were purchased and prepared during the last months of 2004. All materials were stored at ambient temperature and relative humidity in the Architectural Conservation Laboratory prior to testing.

2.2.1.1 Dispersant

Deionized water, obtained from the filtration system installed at the Architectural Conservation Laboratory, School of Design, University of Pennsylvania. Tap water flows through two universal filter cartridges and then through two research filter cartridges before being released into the containers used to store deionized water. This filtration process removes ionized materials down to a level of ≤ 4 ppb, thus providing fewer possible variables in the experiment and is equivalent to a triple distillation process. It is

assumed potable water free of pollutants, salts, and colloidal matter would be used in actual field work.

2.2.1.2 Binder

Natural Hydraulic Lime (NHL) 3.5 (moderately hydraulic) manufactured by St. Astier in France, distributed in the U.S. by TransMineral, and purchased from Pennsylvania Lime Works in Milford Square, Pennsylvania during November 2004. This binder complies with EN 459 because: it is produced from an argillaceous limestone with some siliceous content; it is produced in the traditional manner by being burnt and then slaked; it is reduced to powder form with or without grinding; and does not include any additional components. The hydraulicity of the binder is "based almost totally on the combination of calcium oxide and reactive silica."[3]

Trace amounts of other minerals can be found in St. Astier NHL, such as tricalcium aluminate and sulfates that can contribute to sulfate attack and their effect will be observed in the salt crystallization resistance test. St. Astier NHL was chosen as the binder for testing in this thesis due to the closing of the Riverton lime kilns in February 2004 and the increased commercial availability of St. Astier's product line in the United States.

St. Astier NHL 3.5 was chosen over the other available varieties (2 & 5) as it was found to be the most similar in strength and set time to Riverton Hydrated Hydraulic Lime.

[3] St. Astier. NHL 3.5. Product Literature, n.d.

MINERALOGICAL ANALYSIS OF ST. ASTIER NHL 3.5	
CHEMICAL COMPOUND	PERCENT
H_2O (moisture content)	8
$CaCO_3$	75
SiO_2 (soluble)	11 (reactive / combinable)
SiO_2 (insoluble)	2 (Inert / uncombinable)
$MgCO_3$	1
The soluble silica, available to be combined with the CaO produced in the burning of $CaCO_3$ determines the hydraulicity of the finished products.	

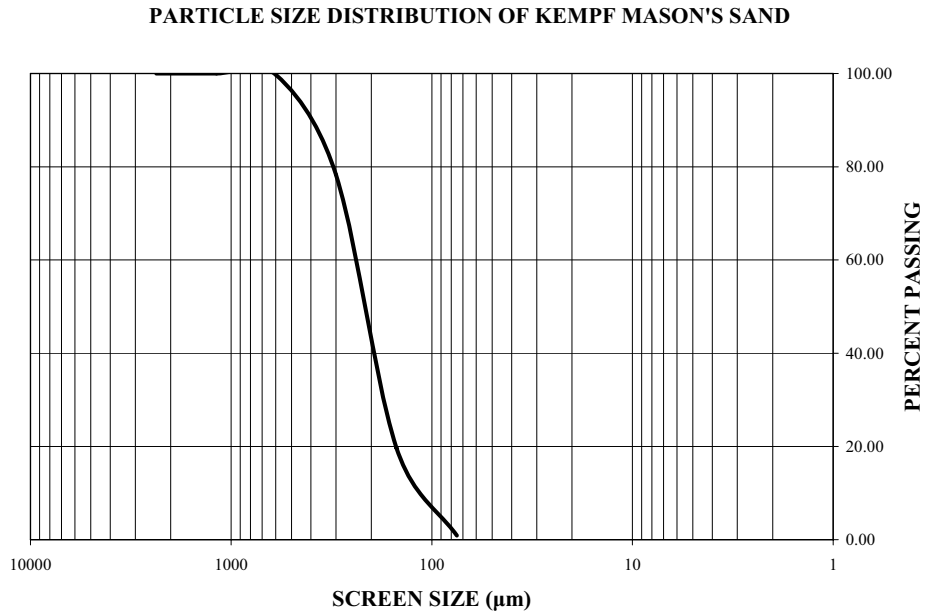
Table 2.3

2.2.1.3 Aggregate

George Kempf Mason's Sand (also known as sugar sand, fine silica banding sand, or quartz sand) was purchased at George Kempf Building Material Supply in Philadelphia, Pennsylvania during November 2004. Its small size and generally sub-angular shape impart a larger surface area for binder interface. This sand was air dried, then sieved through a #50 U.S. Standard sieve with particles < 300 μm passing (approximately 78% of bulk) and finally dried in laboratory ovens until constant weight before use. This aggregate conforms to ASTM C778-00 Standard Specification for Standard Sand.

In order to determine particle size, a sample of sand from the bulk supply was sieved following ASTM C136-01 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. The following particle size distribution (Graph 2.1) shows a well sorted, sharp, fine sand perfect for this application. The Munsell colors of the bulk sand

sample range from 10 YR 7/2 (light gray), 10 YR 8/1 (white), to 10 YR 8/2 (very pale brown).



Graph 2.1

2.2.1.4 Filler

3M Z-Light Ceramic Microspheres, G-3500 grade are hollow but thick-walled, inert ceramic spheres that have a low specific gravity, density, and weight. They fill the spaces between sand grains and binder acting as "miniature ball bearings"[4] to increase flow and viscosity. They allow the mixture to remain workable for a longer period of

[4] Bass, Angelyn. *Design and evaluation of hydraulic lime grouts for in situ reattachment of lime plaster to earthen walls*. Master's Thesis, University of Pennsylvania, 1998. 41.

time while grouting by reducing segregation and settling. Their high surface to volume ratio allows for a greater interface with the hydraulic lime binder.

The G-3500 grade of ceramic microspheres has a compressive strength of 60,000 psi. Due to their extremely small size (10 – 350 μm), a particulate mask should always be worn when working with them, as long term exposure could cause respiratory difficulty. These microspheres are of recent but undetermined date.

2.2.1.5 Acrylic Emulsion

El Rey Superior Additive 200 is an aqueous dispersion of acrylic polymers with a reported 38 ± 1% acrylic solids by weight in water, a specific gravity of 1.045, with the color and consistency of whole milk. It was purchased from the manufacturer, El Rey Stucco Company Inc., Albuquerque, New Mexico during December 2004. It is marketed for use with Portland cement mortars to lower water absorption, improve workability, reduce shrinkage, and increase freeze/thaw resistance, and improve tensile, compressive, and flexural strength.

In order to reduce foaming, it is recommended by the manufacturer to always mix below speeds of 2500 rpm despite the presence of defoaming agents. Ten liter batches of 5% and 10% acrylic emulsion in deionized water were prepared in February 2005 to ensure standardization of solution used in this testing.

2.2.2 Formulæ

All grout samples are formulated with an optimal binder to sand to filler ratio of 2:1:1 by volume as determined by previous research. ASTM C270 "Standard Specification for Mortar for Unit Masonry" was used to determine bulk density relative to batch weight.

PHASE THREE FORMULÆ				
PROPORTIONS (BY VOLUME)				
SAMPLE	NHL	S	MS	ACRYLIC IN H_2O
A	2.0	1.0	1.0	-
B	2.0	1.0	1.0	5% ER
C	2.0	1.0	1.0	10% ER
PROPORTIONS (BY WEIGHT IN GRAMS)				
SAMPLE	NHL	S	MS	
A	960	525	960	
B	960	525	960	
C	960	525	960	
NHL – St. Astier NHL S – Sand MS – Microspheres Acrylic – El Rey (ER)				

Table 2.4

2.2.3 Sample Preparation

Grout samples were prepared adhering to general specifications in ASTM C192 "Standard Practice for Making and Curing Concrete Specimens in the Laboratory" with some modifications allowed for the liquid nature of grout as opposed to mortar. The wood cube molds (Philippine mahogany, also known as Luan), disks (polyvinyl chloride pipe), and cylinders (polyvinyl chloride pipe) were prepared during December 2004 -

January 2005. All proper safety precautions were observed for proper hand, eye, and respiratory protection while fabricating the molds and mixing the components. Safety goggles, nitrile gloves, and single-use particulate masks were worn.

PHASE THREE MOLD AND SAMPLE SCHEDULE					
TEST	STANDARD	SHAPE	SIZE	AMOUNT	TOTAL
SETTING TIME	ASTM C191	truncated cone	60mm dia. top 70mm dia. base 40mm deep	3	9
DRYING SHRINKAGE	---	glazed saucer	3.25” dia. top 2.5” dia. base 1” deep	3	9
WATER VAPOR TRANSMISSION	ASTM E 96	cylinder	1½” dia x ½”	3	9
SPLITTING TENSILE STRENGTH	ASTM C192	cylinder	4” x 2id	3	9
CAPILLARY WATER ABSORPTION	NORMAL 11/85	cube	2”	3	9
WATER ABSORPTION	NORMAL 7/81	cube	2”	same as capillary rise	---
DRYING INDEX	NORMAL 29/88	cube	2”	same as water absorption	---
COMPRESSIVE STRENGTH	ASTM C109	cube	2”	3	9
SALT RESISTANCE	RILEM V.1b	cube	2”	3	9
FROST RESISTANCE	RILEM V.3	cube	2”	same as drying index	9

Table 2.5

2.2.3.1 Mixing

Successful mixing is arguably the most important part of any grouting procedure, in which times and speeds can vary based on the materials included in the grout being mixed. The aggregate was first mixed dry with microspheres and NHL in plastic buckets

to ensure even distribution of the particles. The mix was then transferred to a seamless stainless steel pail with tapered sides. This 11.8 liter pail can hold more than enough grout to fill an entire set of molds and complete all workability tests. Water was added to the dry grout mixture with a ratio of 1:2 in order to test what would more accurately mimic field use according to previous approximate ratios.

A cordless DeWalt drill was used as it has a maximum speed of 1750 rpm, below the recommended 2500 rpm to reduce foaming in formulations containing the acrylic admixture. A 48 cm long vertical stainless steel paint mixer was inserted into the drill's chuck. The mixing attachment has an agitator similar to the solid and butterfly agitators on the Hamilton Beach Commercial Model 936 Drink Mixer. One benefit is that the mixer can move around the entire vortex drum or steel pail to ensure that the grout is evenly mixed and distributed. When adding acrylic emulsions care must be taken to pour slowly in order to ensure that foaming does not occur as a result of the mixing.

The grout was mixed for 1 minute on the drill's low setting (600 rpm). The pail's sides were scraped down and the setting was adjusted to high (1750 rpm). The grout was mixed at this speed for another 2 minutes. A true centrifuge was not formed as the mixer was continually moved around the vortex drum, but it is presumed that the high speed is enough to fully incorporate all particles, redistributing them within 3 minutes. This mixing system is described by Houlsby as being adequate, but one that produces lower quality grout. As the aggregate in these formulations is so fine rather than the much larger aggregate (up to ¾") used in engineering grouting, it does not seem to compromise the grout mixing.

A second set of samples was poured for formulation A after it was evident that water was bleeding out through the wood molds quickly enough to have a significantly visible drop in the center of each sample. Thickening was evident with the more thixotropic B and C formulations that contained acrylic modifiers.

Figure 2.1 – Mixing Grout Formulation A

2.2.3.2 Molding, De-molding, & Cure

The wood molds had been assembled and brushed with mineral oil. The plastic molds, including the Vicat mold were coated with petroleum jelly as a release agent and placed on acrylic plates. A thin bead of plumber's putty was run around the base of the plastic molds in order to ensure that the grout did not escape through the bottom of the mold. The glazed clay saucers used for visual shrinkage determination were not lubricated. Each mold was filled with enough grout until they overflowed. Grout

formulations B and C required constant stirring by hand as they thickened noticeably when not in motion (i.e. thixotropy). Glass rods were moved back and forth above the spout while being poured to ensure that the samples remained easily workable. These glass rods were also used to puddle the samples in order to reduce air bubbles that may have been trapped while the grout was poured into the mold. After approximately 6 hours, the tops of the molds were scraped off with a wide metal putty knife.

The molds were placed on stainless steel trays in the upper shelves of a baker's rack where they remained for 7 days at room temperature and humidity (18° – 24°C, 30 – 50%). The samples were then sealed in a moist cabinet created by using a clear plastic baker's rack cover. The trays above and below the sets of samples were filled with deionized water. A dial hygrometer was placed on the middle rack to monitor relative humidity and temperature in the chamber during cure. Humidity within the cabinet remained between 80-90% and temperature varied from 18° – 24°C and was monitored daily.

After 21 days (a total of 28 days in cure) the trays of deionized water were removed and the sides of the cabinet left open to allow the samples to adsorb CO_2. The samples were then de-molded and returned to the cabinet, this time on wire racks which allowed for greater air flow around the samples for the remainder of cure. Any samples with grout that had overflowed remaining on the surface of the molds were delicately scraped flat with a plaster rasp. The disks and cylinders were removed with great care, as the samples remained fragile and could still easily break, especially at their edges. As the

acrylic plates had been coated with petroleum jelly, the samples were slid off to the side instead of lifted to prevent fracturing.

This curing procedure is a variation of the German standard DIN 18-555.3 recommended in "Lime Mortar: Some Considerations on Testing Standardization"[5] Curing conditions varied slightly for samples used in setting time and shrinkage tests, as they were left in open air.

Figure 2.2 – Curing Chamber containing samples

[5] Charola, A. Elena 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, edited by L.B. Sickels-Taves, 142-151. West Conshohocken, PA: American Society for Testing and Materials, 1999.

3.1 Introduction

Testing for compatibility and durability began 75 days after cure, as described in Section 2.2.3.2. Workability tests were carried out immediately after mixing. An Ohaus Adventurer Precision top-loading electronic balance accurate to 0.01 g and an Ohaus Dec-O-Gram triple beam balance accurate to 0.1 g and determinable to 0.01 g were used in weight determinations. The dial hygrometers used were accurate to ± 2.5% RH at 50% RH and ± 1.5°C at 20°C. Three samples of each formulation were tested except where noted. When the term water is mentioned it is always deionized unless otherwise noted. When a sample is said to have been dried to constant weight it means that the percentage of weight change between consecutive weighings at 24 hours was ≤ 0.1% of the sample's initial weight unless otherwise noted. Also, the oven temperature was fixed at 60 ± 5°C unless otherwise specified in order to avoid degradation of the samples containing acrylic admixtures.

The testing room temperature fluctuated between 23° - 35°C and relative humidity fluctuated between 50% - 95%. This was because the entire ventilation system servicing the Architectural Conservation Laboratory was placed offline during the bulk of the testing program. Unfortunately, this situation was out of the ACL's control and any deviations from standardized testing room temperatures and humidity are a result of this situation.

3.2 Standards

Various standardized testing methods, American and international, were consulted throughout this thesis research. ASTM, RILEM, EN, NORMAL, and DIN standards were wholly employed, modified slightly, or referenced for each of the following tests as noted. The most recent available version of each standardized testing procedures was used. SI units were used wherever possible for general consistency.

LIST OF STANDARDS EMPLOYED IN PHASE THREE TEST PROGRAM		
TEST	**STANDARD**	**ORIGIN**
Particle Size Distribution	ASTM C136	USA
Fluidity	ASTM C939	USA
Setting Time	ASTM C191	USA
Capillary Water Absorption	NORMAL 11/85	ITALY
Water Absorption Capacity	NORMAL 7/81	ITALY
Drying Index	NORMAL 29/88	ITALY
Water Vapor Transmission	ASTM E96	USA
Splitting Tensile Strength	ASTM C496	USA
Compressive Strength	ASTM C109	USA
Frost Resistance	RILEM V.3	INT NPA
Salt Crystallization Resistance	RILEM V.1b	INT NPA
FOR A COMPLETE LIST OF REFERENCED STANDARDS SEE APPENDIX A		

Table 3.1

3.3 Testing

3.3.1 Material Composition

3.3.1.1 Particle Size Distribution ASTM C 136-01 STANDARD TEST METHOD FOR SIEVE ANALYSIS OF FINE AND COARSE AGGREGATES

To determine the grade of aggregate used in this research, a bulk sample of sand is reduced to no less than 300g and dried until constant weight at 110 ± 5°C. A U.S. Standard sieve stack was placed on a mechanical sieve shaker for 15 minutes. After agitation, each sieve was removed and the material retained was transferred onto a pre-weighed plastic weighing boat, weighed, and recorded. Wet sieving was not deemed necessary, as the amount of material passing through the #200 sieve was not appreciable.

3.3.1.2 Scanning Electron Microscopy VISUAL DETERMINATION

Scanning electron microscopy is used to observe materials on a submicroscopic scale. In this procedure, a highly charged beam of electrons is emitted from a filament towards an anode or through a barrier within a high electron field (field scatter). This electron beam within a vacuum is then focused by condenser lenses before passing through an objective lens. It then scans vertically and horizontally over a small section of a sample. The sample then emits electrons which produce the image seen on the microscopes screen with the aid of a photomultiplier. The steeper areas or edges of a sample produce a higher quality images that flat surfaces subjected to SEM.

Backscatter images are created by using high energy electrons emitted by the sample and can provide data on the material composition of the sample. They create a

topographical image, but work best if there is more contrast in the chemical composition of the sample. Resolution depends on the size of the electron beam and the amount of material that is exposed to the electron beam.

X-rays that are emitted by the sample may be detected and quantified if the SEM is equipped with an EDS (or Energy Dispersive Spectrometer). This method can help distinguish various phases of chemical compounds.

Small samples of freshly broken grout from the splitting tensile strength cylinders were saved for this test. A small fragment of grout from each formulation was carefully sectioned using a Buehler Isomet low-speed saw. The sample was then rinsed in acetone to remove any traces of Stoddard solvent – the petroleum based lubricant used with the Isomet saw. The sample pieces were then dried in air in a container with anhydrous calcium sulfate ($CaSO_4$) desiccant and then mounted to an aluminum stub using conductive silver paint for SEM analysis. The stub was then coated with powder composed of gold and palladium under vacuum at the Laboratory for the Research on the Structure of Matter at the University of Pennsylvania by Dr. Eva M. Campo.

3.3.2 Workability

3.3.2.1 Fluidity ASTM C 939-97 STANDARD TEST METHOD FOR FLOW OF GROUT FOR PREPLACED-AGGREGATE CONCRETE – FLOW CONE METHOD

This testing procedure measures the time of efflux of a known quantity of grout through a standard diameter outlet and is intended for use with neat and fine-aggregate grouts with aggregate passing through a #8 U.S. Standard sieve. Other fluid grouts may

be tested for viscosity in this manner as well. The longest time of efflux allowed by the standard is 35 seconds. This test is also performed in order to maintain a quantifiable rate of flow for the grout formulations and to gain knowledge regarding the effect of acrylic emulsion on the grouts' fluidity.

The flow cone has a 0.75 inch diameter stainless steel discharge tube and a high-density funnel shaped polyethylene body. A receiving container, in this case a 2500 mL graduated beaker, was placed below the discharge orifice in order to contain the grout which was immediately used to fill molds for later testing. The flow cone was then mounted on a ring stand and calibrated. Calibration consists of leveling the cone at its top and adjusting the point gauge to indicate the level of 1725 ± 5 mL of water and then draining it with a time no longer than 8.0 ± .2 s. Within one minute of mixing, the discharge outlet is sealed with a finger or stopper and filled with deionized water to flush the cone. Within 1 minute of the efflux of water, the orifice is sealed and a representative sample of the grout, no less than 1725 ± 5 mL is introduced into the flow cone until contact with the previously adjusted and leveled point gauge.

The stopwatch is started at the same time the finger or stopper is removed from the orifice. The watch is then stopped at the first break of continuous grout flow while looking into the cone from above and noting that light is visible through the orifice. At least two samples per formulation with efflux times within 1.8 seconds of each other are required. The results are then averaged as the flow value.

Figure 3.1 - Performing Flow Cone Test

3.3.2.2 Time of Setting ASTM C 191-99: STANDARD TEST METHOD FOR TIME OF SETTING OF HYDRAULIC CEMENT BY VICAT NEEDLE (MODIFIED)

This test provides accurate measurements of the final set time of grout and allows for comparison between formulations. The sample molding was modified due to the liquid nature of grout and the testing procedure has been modified due to the significantly longer set time of grouts compared to mortar. According to previous research, initial set

time for grout has been determined as a maximum depth of 25 mm. Once the depth of penetration reaches 0 mm, the test is concluded. ICCROM has defined 48 hours as a reasonable set time for hydraulic grouts used for *in situ* mosaic repair[6] but that determination is debatable for use in larger scale reattachment and void-filling where it may take longer for water to evaporate and for grouts and mortars to fully set as well as vertical and overhead reattachment.

The Vicat molds are truncated cones with a top diameter of 60 mm, a bottom diameter of 70 mm, and a height of 40 mm. The mold rests on sheet of acrylic that has been coated with petroleum jelly. The bottom of the mold is then sealed onto its support with a bead of plumber's putty. Instead of rolling the mortar into a ball after mixing, the grout is simply poured into the mold, the interior of which has been coated with petroleum jelly. Any excess grout is removed with a single stroke of a wide metal putty knife.

The samples are placed in a controlled climate chamber with high relative humidity when they are not being measured for depth penetration. They are then placed under the penetrometer and measured until final set time is reached. The penetrometer is operated by lowering the tip of the 1 mm diameter stainless steel needle until it rests on the sample, adjusting the depth indicator to zero, and tightening the set screw. The needle is lowered by quickly loosening the set screw, releasing it and allowing it to fall and

[6] Ferragni, Daniela; Forti, Massimo; Malliet, Joseph; Teutonico, Jeanne Marie; and Torraca, Giorgio. "In situ consolidation of wall and floor mosaics by means of injection grouting techniques." *Conservation in situ: Proceedings of the 2nd conference of the international committee for the conservation of mosaics*. Aquileia, Italy, 3-7 October 1983 (1985) pp. 83-102.

settle for 30 seconds. Penetration readings cannot be closer than 0.25 inch from any previous penetration or closer than ⅜ inch from the rim of the mold.

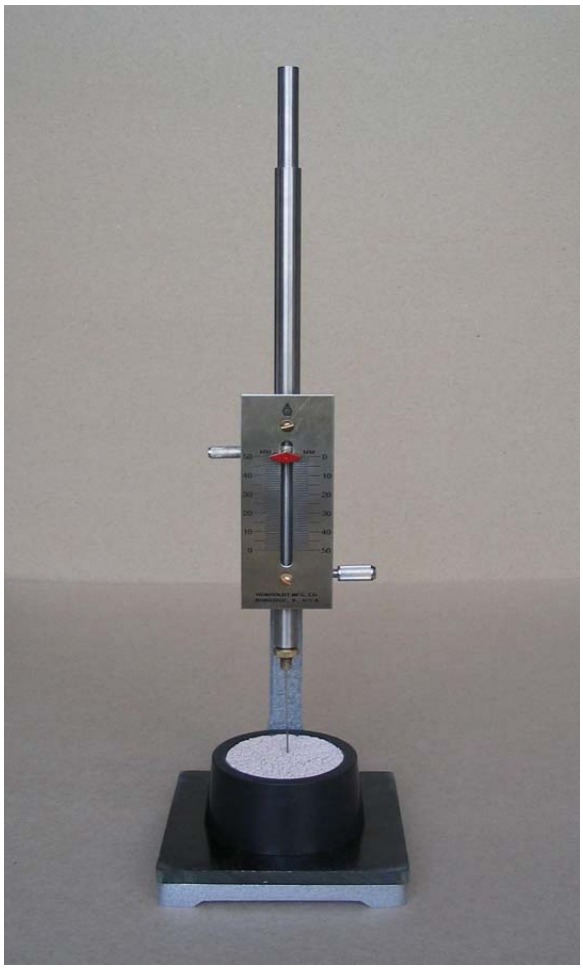


Figure 3.2 – Vicat Apparatus with Grout Sample

3.3.2.3 Drying Shrinkage VISUAL DETERMINATION

Measurement of drying shrinkage was recorded visually. The grout was poured into three pre-weighed glazed clay saucers per formulation and left to cure for the

remainder of testing. Excess grout was scraped off the tops after it began to stiffen (approximately 10 hours) and then weighed. The weight of the saucer and sample is then measured after curing and any shrinkage is observed and recorded. This is done because the standard shrinkage tests are not meant to be performed on grout which has a much longer set time than mortar and also because it can shrink anisotropically.

3.3.3 Compatibility

3.3.3.1 Capillary Water Absorption NORMAL 11/85: CAPILLARY WATER ABSORPTION AND CAPILLARY ABSORPTION COEFFICIENT

The capillary water absorption test simulates rising damp; it also can be used to record water movement and its relation to the grout's porosity and permeability, especially when there is an added component purported to increase water-repellency (e.g. acrylic emulsion). The samples are dried until constant weight and then placed on glass rods in a plastic container which is then filled with deionized water until 1cm of the base of the samples is immersed. One piece of 24 cm diameter Whatman № 4 filter paper was added placed on top of the glass rods to create an area of constant contact and transfer between the sample and deionized water.

The samples were weighed every five minutes for the first hour of the test, then every 15 minutes for the second hour, then hourly until the eighth hour. The samples were then weighed daily at 24 hour intervals. The samples were patted dry on a damp cloth, weighed in air on the electronic balance, and quickly returned to the sample container. This is repeated until the change in weight is ≤1% of the water absorbed.

The capillary water absorption (amount of water absorbed by the sample per unit surface at a time) is calculated using the following equation:

$$M_i = (m_i - m_0) / S$$

Where m_i = weight of the sample at time t_i (g)

m_0 = weight of the dry sample (g)

S = surface of the sample in contact with the porous support (cm^2) given with a 5% precision.

This is then plotted in a graph as a function of the square root of time (in seconds).

The capillary water absorption coefficient (AC) is the tangent of the linear segment of the capillary water absorption curve and can be calculated as the ratio between the ordinate (M) and the abscissa ($\sqrt{t}$) using the following equation:

$$AC = M^*/\sqrt{t} \ (g/cm^2 . s^{1/2})$$

Where M* = asymptotical value of the amount of water absorbed by the sample per unit surface (g/cm^2)

t* = abscissa at the intersection point of the line extrapolated from the asymptote and the tangent of the straight segment of the curve ($s^{1/2}$)

3.3.3.2 Water Absorption Capacity NORMAL 7/81: WATER ABSORPTION BY TOTAL IMMERSION

Water absorption by total immersion measures the quantity of water absorbed by the grout samples immersed in deionized water at room temperature and is expressed by a percentage of the samples' dry weight. Imbibition capacity is the maximum amount of water absorbed as determined by calculations performed after drying the samples according to NORMAL 29/88 (Measurement of Drying Index, section 3.9.2). Apparent porosity measures the fraction of a solid's total volume that is occupied by pore space and is determined by hydrostatic weighing.

The samples were dried to constant weight at 60°C and placed on glass rods in a plastic container which is then filled with deionized water until they were submerged by at least 2cm. The samples are then blotted with a moist paper towel and weighed in air on the balance. The intervals consisted of: every 5 minutes for the first hour; every 15 minutes for the second hour; hourly until the eighth hour; then daily until they were asymptote – the amount of water absorbed in 2 successive weighings was not more than 1% of the sample's total mass.

The amount of water absorbed can be calculated using the following equation:

$$\Delta M/M\% = M_i\text{-}M_0 \,/\, M_0 \times 100$$

Where M_i = weight of the sample imbibed with water at time ti (g)

M_0 = weight of the dry sample (g)

3.3.3.3 Drying Index NORMAL 28/88 MEASUREMENT OF THE DRYING INDEX

The experimental procedure measures the loss of water in a material due to evaporation over time. It is carried out on the same samples used in NORMAL 7/81 Water Absorption Capacity test immediately after hydrostatic weighing is performed. The samples are lightly patted dry, weighed, and placed in the dessicator with constant temperature. They must rest on a non-corrodible tray in the dessicator with openings of 1 x 1cm. The relative humidity in the chamber varied between 50% and 60%. The room temperature varied from 28°C to 22°C throughout the testing cycle, above the specified temperature of 20±1°C. The samples were then removed from the dessicator and continuously weighed at the same intervals as in the water absorption capacity test until they complied with the following formula:

$$1.0 \geq [(M_0 - M_{i-1}) / (M_0 - M_i)] \geq 0.90$$

Where m_0 = weight (g) of the sample at time t_0 (h)

m_{i-1} = weight (g) of the sample at time t_{i-1} (h)

m_i = weight (g) of the sample at time t_i (h)

The samples were then dried in an oven until constant weight.

3.3.3.4 Water Vapor Transmission ASTM E96-00: STANDARD TEST METHODS FOR WATER VAPOR TRANSMISSION OF MATERIALS (WET METHOD)

Water vapor transmission and permeance is the amount of water vapor that flows through two parallel surfaces of a material with a known thickness in a unit of time. This is due to a difference in water pressure on the opposite sides of the parallel surfaces; one being air in a controlled climate chamber and the other being a source of water below the sample. Water vapor may move through pore space and voids of the grout and the materials to be grouted. The data acquired in this testing procedure allows for the selection of the best material matched to the substrate in order to avoid moisture entrapment and subsequent decay.

The size of the samples used (1.5 inch diameter x 0.5 inch thick) satisfactorily complied with the specifications set forth in the standard. They were then placed in the laboratory oven and dried to constant weight. Each disk was wrapped with electrical tape to prevent water vapor transmission through the sides of the sample, and then placed on the inner rim of a 50 mL polypropylene tri-cornered beaker. This beaker had previously been filled with 30 mL of deionized water and cotton linters. The cotton was not required but added in order to ensure that condensation on the bottom face of the sample disk did not occur. Heated paraffin wax was applied using Pasteur pipettes to seal the sample to the cup, making it airtight.

These assemblies were then evenly arranged on one shelf in the dessicator and a dial hygrometer placed on the top shelf. The bottom of the dessicator was filled with mesh size eight anhydrous calcium sulfate desiccant in order to maintain 50 ± 2% relative

humidity in the drying chamber. The relative humidity in the chamber varied from 50% – 65% during the first few hours of testing. The humidity was stabilized by placing the bottom of a glass Petri dish on the top shelf to absorb extra rising water vapor and replaced as needed. The assembly was weighed every 15 minutes for the first hour of testing and every 24 hours following from the initial start time until the ten day test cycle was completed.

Figure 3.3 – Water Vapor Transmission Test Chamber

The water vapor transmission of the samples is calculated using the following formula:

$$WVT = G/tA = (G/t)/A$$

where: G = weight change (from straight line), g,

t = time, h,

G/t = slope of the straight line, g/h,

A = test area (sample area), m2, and

WVT = water vapor transmission, g/h·m2.

Permeance was calculated as follows:

$$Permeance = WVT/S\ (R1 - R2)$$

where: S = saturation vapor pressure at test temperature, mm Hg (1.333 x 102 Pa)

R1 = relative humidity at the source expressed as a fraction (in the dish for water method)

R2 = relative humidity at vapor sink expressed as a fraction (in the chamber for water method).

Average permeability (metric perm-cm) was calculated as follows:

$$Average\ permeability = permeance \times thickness.$$

3.3.4 Durability

3.3.4.1 Splitting Tensile Strength ASTM C496-96: STANDARD TEST METHOD FOR SPLITTING TENSILE STRENGTH OF CYLINDRICAL CONCRETE SPECIMENS

Although this is intended for use with much larger concrete specimens, cylinders 2" in diameter and 4" in length (a diameter equal to half the sample's length) were tested according to specifications. The splitting tensile strength of a cylindrical specimen can be determined by applying a diametral compressive force along the length of the sample at a constant rate. This force induces tensile stress on the plane receiving the force and high compression in the areas of the sample that surround the loaded plane. As the areas receiving the load are in a state of triaxial compression, they fail in the greatest longitudinal strength that they can bear without falling apart (which is significantly higher than uniaxial compressive strength). This test was performed at the Laboratory for the Research on the Structure of Matter at the University of Pennsylvania under the supervision of Dr. Alex Radin.

Splitting tensile stress is easier to determine than direct tensile stress and can be used to evaluate shear stresses imposed on a material. Perpendicular diametral lines were drawn on the samples ends. The diameter of each sample was then measured against those lines to the nearest 0.01" and averaged. The sample is loaded into the static Instron testing machine (model 4206) on its side, wedged between thin bearing strips of plywood (⅛" thick x ⅞" wide x 4½" long), the support plate below, and the load cell above.

The stress is applied at a constant rate (100-200 psi/minute) until fracture is evident; this is when the maximum load is also recorded. Then, calculations for indirect

tensile strength are performed. The following calculation is then used to determine the splitting tensile strength of a sample.

$$T = 2P/\pi ld$$

Where T = splitting tensile strength (psi)

P = maximum applied load indicated by the testing machine (lbf)

l = length (in)

d = diameter (in)

3.3.4.2 Compressive Strength ASTM C109-99: STANDARD TEST METHOD FOR COMPRESSIVE STRENGTH OF HYDRAULIC CEMENT MORTARS (USING 2-IN. OR [50MM] CUBE SPECIMENS)

This test measures the strength of samples in compression and is intended for hydraulic cement mortars. As the samples are compacted, they decrease in volume. Force is applied to the samples from above and failure occurs in a plane as a stress response. If the samples do not have the flattest surface possible, the results may be distorted. The sample is placed between the bearing block and the load cell, adjusting the height as closely as possible without touching the sample. The load rate is then applied in lbs / s or N / s until the sample yields and fails. Mathematical determination of indirect compressive strength is calculated using the following equation:

$$fm = P/A$$

Where fm = compressive strength (psi)

P = total maximum load (lbf)

A = area of loaded surface (in^2)

Figure 3.4: Instron Testing Machine

3.3.4.3 Frost Resistance RILEM V.3 FROST RESISTANCE

This test measures a material's performance in freezing and thawing cycles and indirectly measures durability. The samples used for this test are two inch cubes instead of the slender prisms described in the standard. The samples were dried until they reached constant mass and immersed in deionized water, placed on trays that resemble plant nursery potting trays with a grid of holes on the bottom. These holes allowed for water to completely surround the samples, provided good drainage, and easy transport between the freezing cabinet (maintained at -15 ± 2°C) and immersion container. Samples were immersed for 8 hours in the tray following 8 hours of freezing (without touching each other) in the tray. This allowed for 1.5 cycles per day of testing and deviated from the standards' prescribed 6 hour freezing and immersion cycles. After an initial six hour immersion cycle, the samples were weighed with a hydrostatic balance and in air on an electronic balance following every fourth cycle (in the middle of thawing) and then photographed to observe any deterioration.

Deionized water with a temperature of 20° - 30°C was used even though the standard specified the use of tap water at 5 ± 2°C since there were no facilities to maintain water at this temperature and because the deionized water was colder than tap water. This procedure also deviated from the standard with the times chosen for easier transfer and due to the time remaining for testing relative to the time required for this test. In this manner, frost resistance was determined visually and by measurement of the apparent volume.

Figure 3.5: Samples in Freezing Chamber

3.3.4.4 Salt Crystallization Resistance RILEM V.1B: CRYSTALLIZATION TEST BY TOTAL IMMERSION (FOR TREATED STONE)

This test attempts to simulate salt crystallization in a material under normal environmental conditions and to record the destructive effect of 10% sodium sulfate re-crystallization on the samples tested. As with the frost resistance test, it indirectly measures durability. As salts re-crystallize, they expand within a material. As two of the three sample formulations tested contained acrylic emulsions, which may be considered a treatment, this variation of the test was chosen. This testing procedure mimics extreme weathering cycles that the grout formulation may not be subjected to. Nevertheless, it establishes a comparative index of durability across samples based on their specific variables. Sample size is not specified by the standard and so two inch cubes were employed in this test.

The samples were first dried until they reached constant mass and were then photographed before immersion. They were placed on 5mm glass beads inside an 800 mL polypropylene beaker. A large volume of 10% w/v Na_2SO_4 was prepared with deionized water and poured into the beakers until the samples were submerged by 2cm of solution. The samples were immersed in this solution for two hours, removed and patted dry, and then dried in the oven for 20 hours. After drying, they were placed in the dessicator and left to cool for 2 hours. This 24 hour test cycle of immersion, drying, and cooling was repeated 15 times. The samples were photographed and weighed after every second cycle and after the fifteenth (final) cycle. The timing of the cycles deviates from the standard slightly which calls for 2 hours of immersion, 19 hours of drying, and 3 hours of cooling. The timing used for cycling was altered for ease of measurement.

At the end of the salt immersion cycling, the surviving samples are placed in a container filled with tap water. This tap water was replenished daily for a week. The samples were then dried until they reached constant weight, weighed and photographed at the end of this procedure.

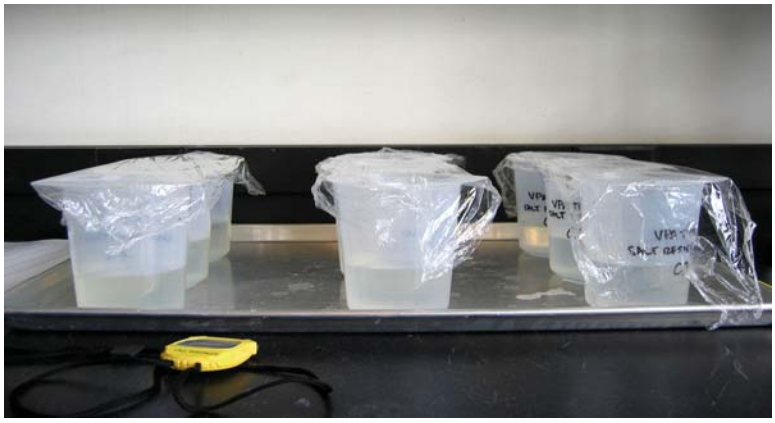


Figure 3.6 – Salt Crystallization Test

The results of the entire testing program are reported in this chapter. For full data regarding the results if not fully presented in this chapter, consult the appropriate appendices at the end of the text. A sample formulation reference table is provided below in Table 4.1.

PHASE THREE FORMULÆ – PROPORTIONS (BY VOLUME)				
SAMPLE	NHL	S	MS	ACRYLIC IN H_2O
A	2.0	1.0	1.0	0% ER
B	2.0	1.0	1.0	5% ER
C	2.0	1.0	1.0	10% ER
NHL – St. Astier NHL S – Sand MS – Microspheres Acrylic – El Rey (ER)				

Table 4.1

4.1 Material Composition

4.1.1 Scanning Electron Microscopy

The samples were observed in the Laboratory for the Research on the Structure of Matter at the University of Pennsylvania with assistance from Dr. Eva M. Campo using the FEI Strata DB235 FIB: Dual Beam Focused Ion Beam microscope. These scanning electron photo micrographs illustrate the interface between the calcite crystals from the lime and the sand aggregate, microsphere fillers, and most importantly the acrylic emulsion. The bar containing text at the bottom of Figure 4.1 displays some important reference information such as: the level of magnification (x 1000), the kind of probe used (scanning electron), the tilt of the sample (none), the strength of the electron beam (5.0 kilo-electron volts), and a reference bar for measurement.

This test was undertaken on three separate occasions with the images presented in this thesis as the best visible results. The following image is from sample formulation B, containing 5% acrylic in deionized water. Figure 4.1 shows the surface of ceramic microsphere coated with hydraulic lime and particles of sand. Long strings of acrylic are arranged around the surface of the sphere.

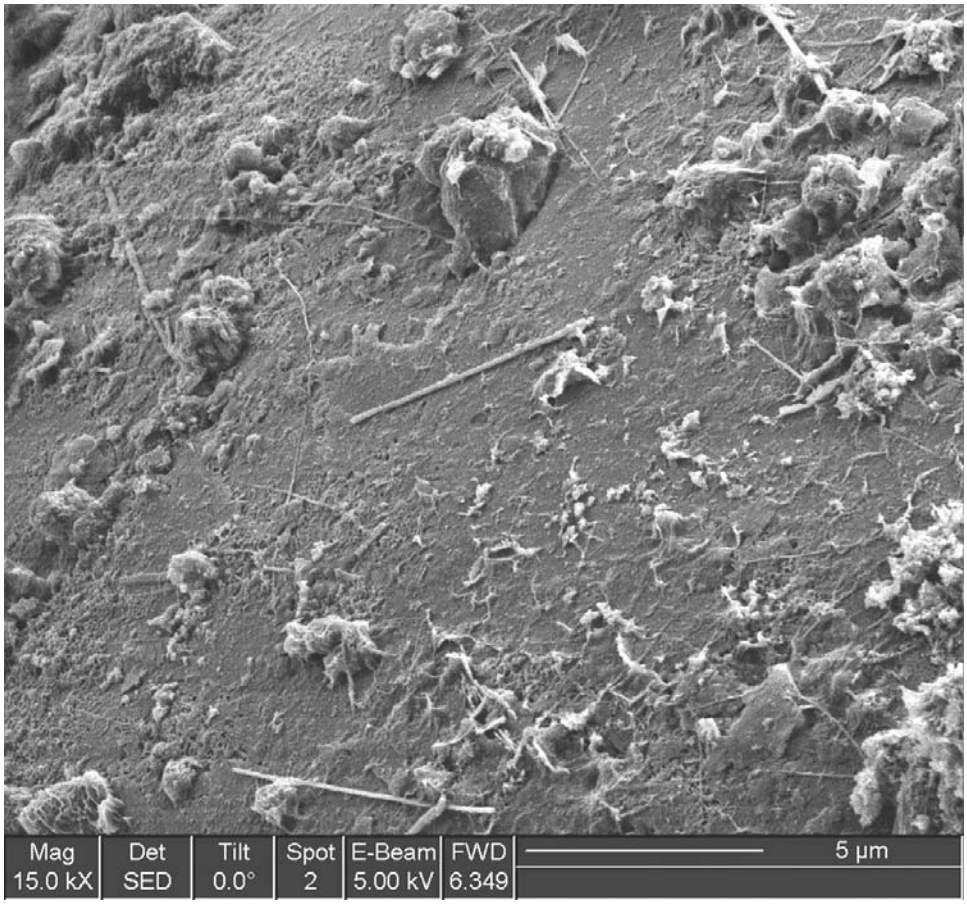


Figure 4.1 – Photomicrograph of Sample B (5% acrylic emulsion)

4.2 Workability

4.2.1 Fluidity

The permissible variation between measurements of the same formulation is 1.8 seconds, and none of the samples exceeded that time limit. The thicker formulas that contain the acrylic admixture have longer flow rates, but not significantly so than the sample formulation without acrylic, and not more than 8 seconds, as prescribed in the standard. As required by the standard, less than one minute elapsed between mixing and pouring into the flow cone for each sample. The ambient temperature in the laboratory was 21°C with a relative humidity of 31%.

MARSH FLOW CONE VALUES		
SAMPLE	TIME OF EFFLUX (S)	AVERAGE TIME OF EFFLUX (S)
A1	5.37	5.47
A2	5.56	
B1	8.56	8.41
B2	8.25	
C1	7.50	7.38
C2	7.25	

Table 4.2

4.2.2 Time of Setting

All grout formulations reached final set at approximately the same time, after 72 hours. It does not appear that the inclusion of acrylic emulsion affects set time. All data and setting time graphs are presented in Appendix E.

4.2.3 Drying Shrinkage

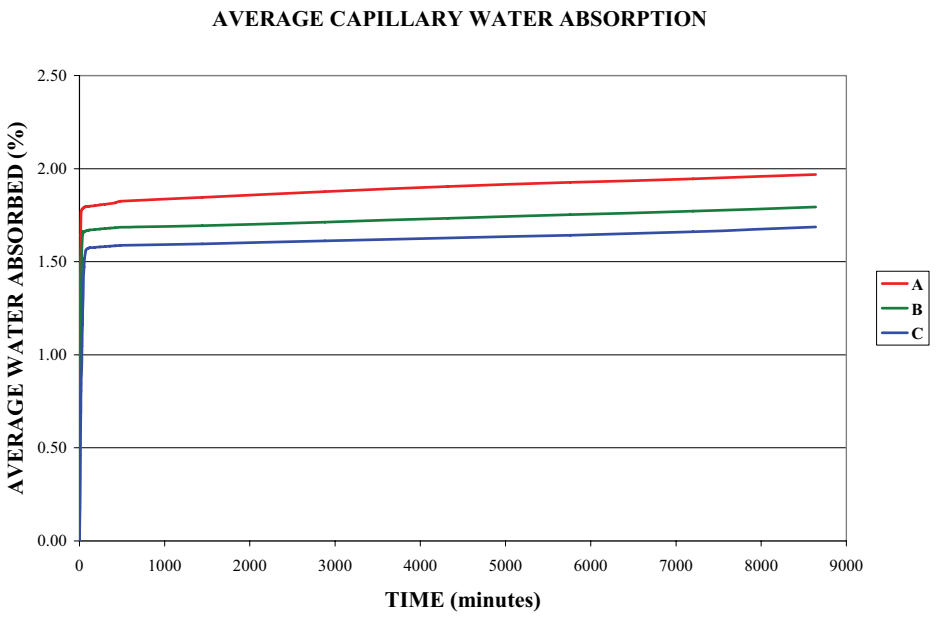
There was no visible shrinkage in these samples after the 75 day curing period and again after 1 year. However, some shrinkage was noted in the cylindrical samples (2" x 4") used for the testing of splitting tensile strength, where cracks were visible across the diameter and through the length of the sample. The most likely reason for this is that the molds were sealed with electrical tape and plumber's putty on all sides except for the top. The remedy for this cracking during cure can be found in Chapter Six.

4.3 Compatibility

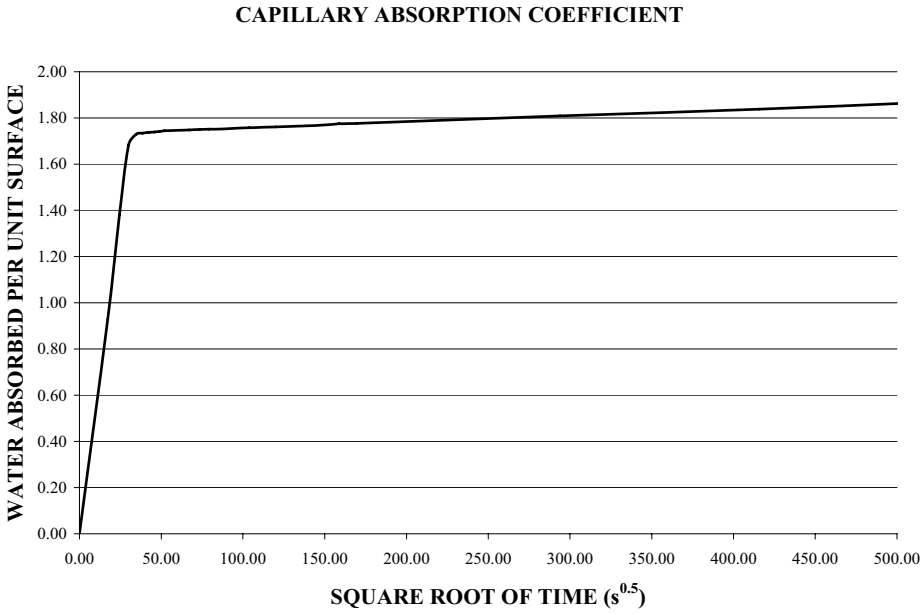
4.3.1 Capillary Water Absorption

Sample formulation A has the highest rate of capillary water absorption according to the test data. Formulation C (10% acrylic) has the lowest rate of capillary absorption. It appears that a higher percentage of acrylic directly decreases the grout's capillary water absorption.

The capillary water coefficient is the slope of the initial straight part of the capillary absorption curve and is presented in Graph 4.2.



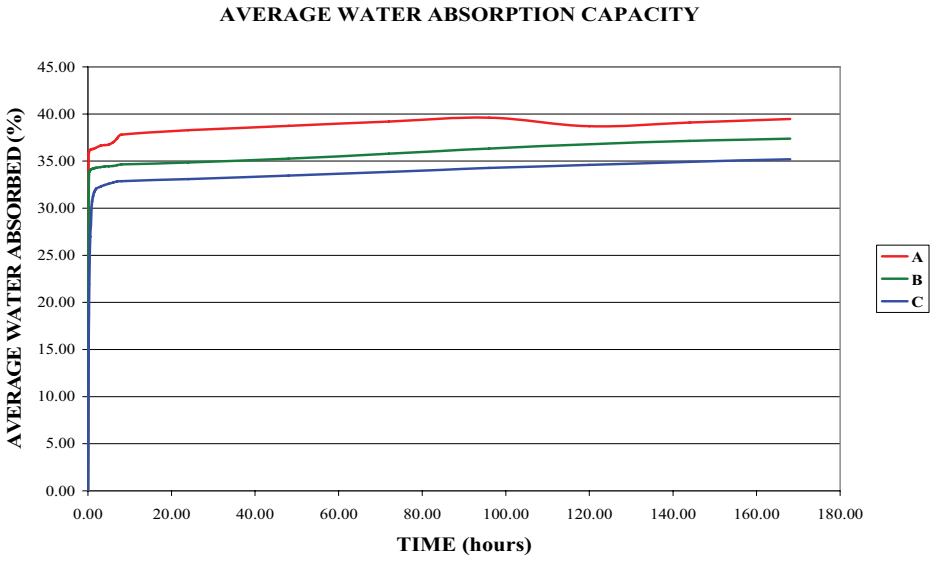
Graph 4.1



Graph 4.2

4.3.2 Water Absorption Capacity

All three grout formulations reached a relatively steady rate of water absorption, as dictated by the standard. The amount of water in two successive weighings was less than or equal to 1% of the sample's dry weight. As seen in Graph 4.3, the grout formulations containing no acrylic emulsion absorbed more water but at a similar rate to the other two formulations. Formulation C with the highest amount of acrylic emulsion absorbed the least amount of water. The addition of El Rey Superior Additive 200 appears to have decreased water absorption by approximately 5% for every 5% of acrylic emulsion in deionized water used in sample preparation.



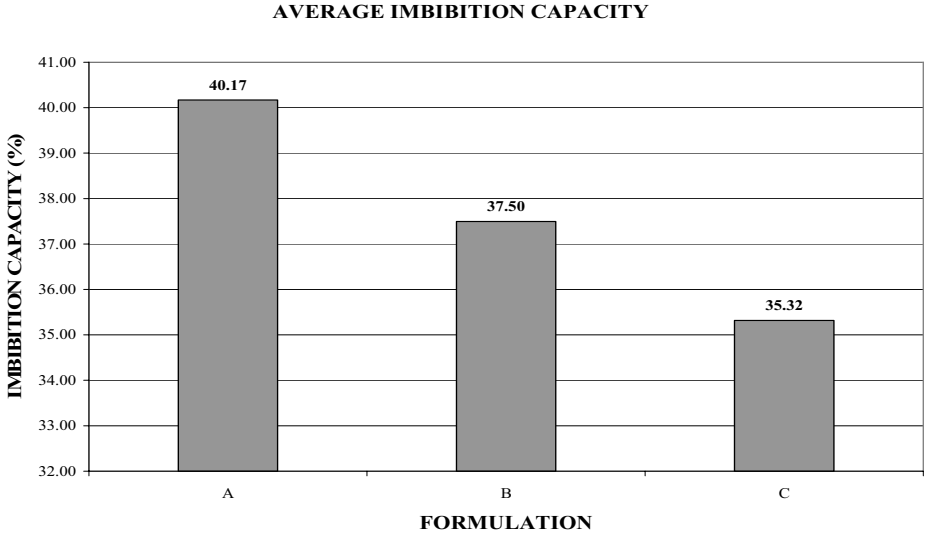
Graph 4.3

The data for the samples' imbibition capacity is presented in Table 4.3. Graph 4.4 shows the average imbibition capacity of the grout formulations. As imbibition capacity is directly related to apparent porosity, it appears that the sample set with the highest

imbibition capacity (Group A) also has the highest apparent porosity. This suggests that the inclusion of acrylic emulsion has a direct effect on the porosity of the grout. The data for each sample and corresponding graphs are located in Appendix G.

IMBIBITION CAPACITY CALCULATIONS				
SAMPLE	FINAL WEIGHT OF WATER ABSORPTION	FINAL DRY WEIGHT	IMBIBITION CAPACITY (%)	AVERAGE IMBIBITION CAPACITY (%)
A1	168.92	120.98	39.63	40.17
A2	172.95	123.36	40.20	
A3	172.71	122.77	40.68	
B1	165.33	120.49	37.21	37.50
B2	163.17	118.45	37.75	
B3	162.23	117.97	37.52	
C1	161.72	119.47	35.36	35.32
C2	160.65	118.45	35.63	
C3	160.45	118.88	34.97	

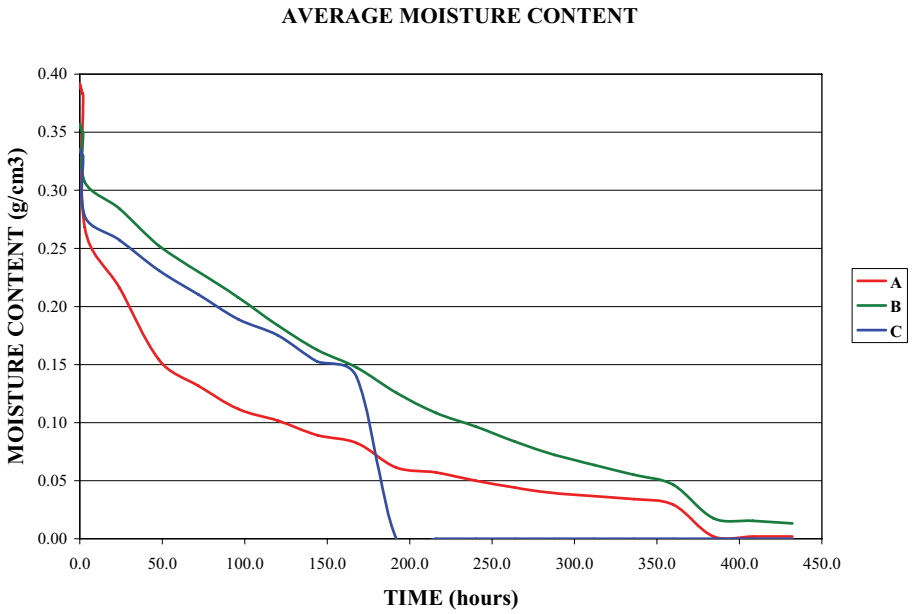
Table 4.3



Graph 4.4

4.3.3 Drying Index

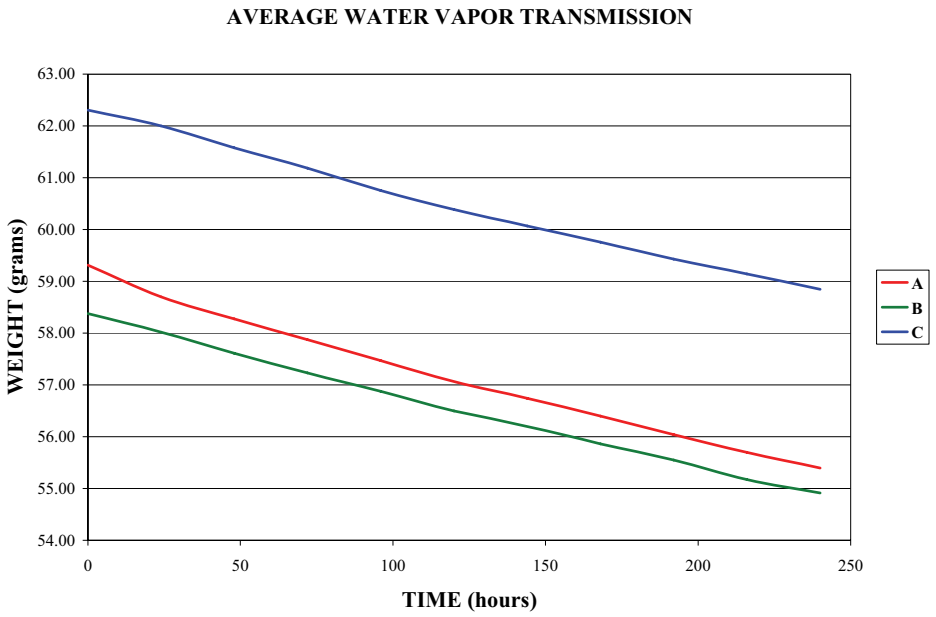
The rate of drying for all grout formulations varied more than in previous compatibility testing undertaken for this phase of testing. While the drying indices for the formulations containing none to 5% acrylic emulsion (A and B) remained relatively steady, the curve for sample set C containing 10% acrylic emulsion drops off sharply after approximately 150 hours (also the same time it entered the dessicator chamber). Formulation B (5% acrylic) had the most steady rate of drying over time. The asymptotical state in all samples was reached after 7 days of drying. Due to the sharp drop off of the graph, testing on set C should be repeated to test for any other possible variations. The average moisture content as a function of time is shown in Graph 4.5 and all other data pertaining to this test is located in Appendix H.



Graph 4.5

4.3.4 Water Vapor Transmission

As seen below in Graph 4.6, the rate of water vapor transmission was that of a fixed decline over the test period with at least six points measured for each sample, as required by the standard. All samples lost weight at almost the same rate throughout the testing procedure. All data for this test is available in Appendix I.



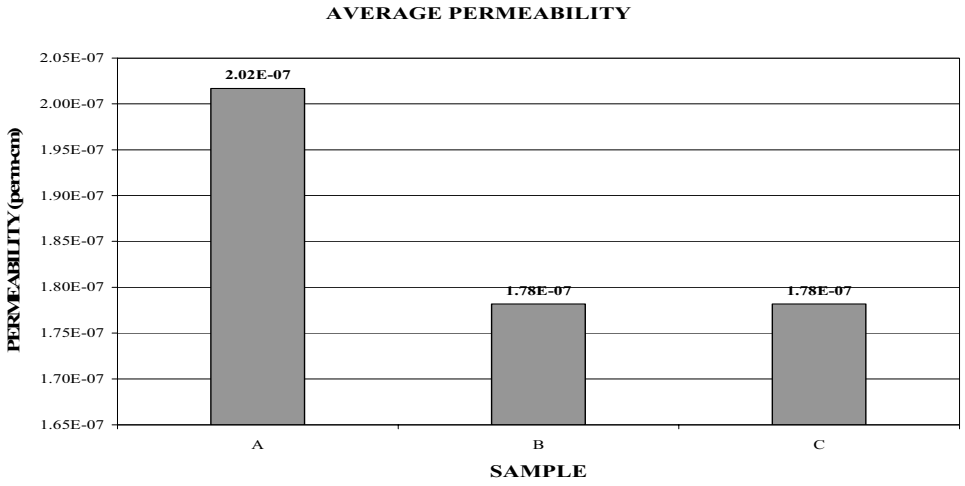
Graph 4.6

The test area of the samples was 0.013 m^2 with a thickness of 1.3 cm. The saturation vapor pressure at 31°C was 33.72 Hg (4495 Pa). The relative humidity of the chamber was 50% and the relative humidity of the dish was 100%. The following table presents the data about the samples' water vapor transmission, permeance, and permeability as well as the averages within the sample groups.

WATER VAPOR TRANSMISSION, PERMEANCE, & PERMEABILITY CALCULATIONS						
SAMPLE	WVT ($G/H \cdot M^2$)	AVERAGE WVT	PERMEANCE ($G/PA \cdot S \cdot M^2$)	AVERAGE PERMEANCE	PERMEABILITY (PERM·CM)	AVERAGE PERMEABILITY
A1	1.18	1.26	1.46E-07	1.55E-07	1.90E-07	2.02E-07
A2	1.19		1.47E-07		1.91E-07	
A3	1.40		1.73E-07		2.25E-07	
B1	1.11	1.11	1.37E-07	1.37E-07	1.78E-07	1.78E-07
B2	1.13		1.39E-07		1.81E-07	
B3	1.09		1.35E-07		1.76E-07	
C1	1.08	1.11	1.33E-07	1.37E-07	1.74E-07	1.78E-07
C2	1.08		1.33E-07		1.74E-07	
C3	1.17		1.44E-07		1.87E-07	

Table 4.4

Table 4.4 indicates that both of the formulations containing acrylic emulsion had slightly lower rates of water vapor transmission than the single formulation without acrylic emulsion. Formulation A, as seen in Graph 4.7, also had the highest average permeance at 1.55 E-07 with both B and C having equally slightly lower permeance at 1.37 E-07. The same can be said about the average permeability of formulations B and C, due to the addition of acrylic emulsion.



Graph 4.7

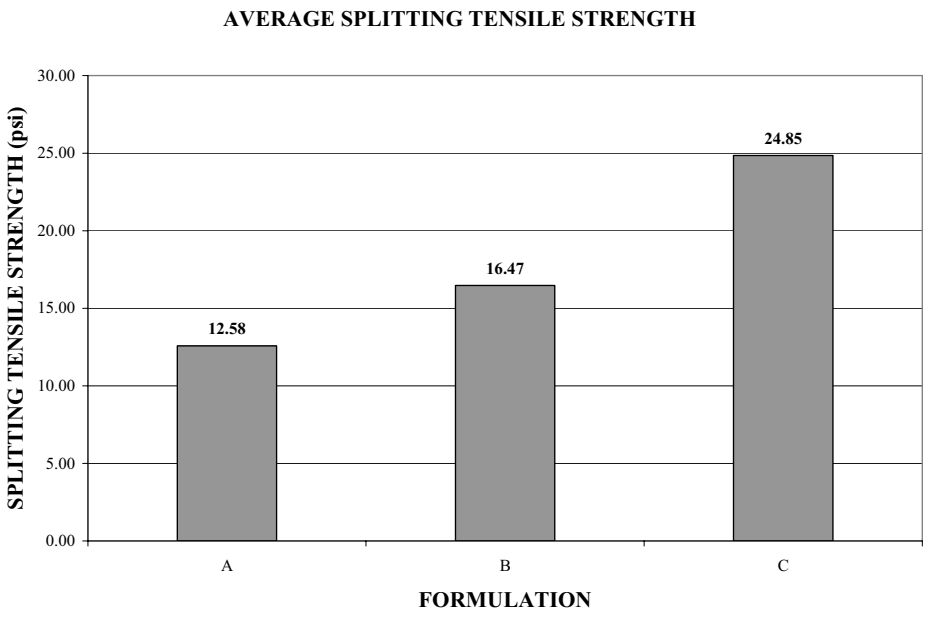
4.4 Durability

4.4.1 Splitting Tensile Strength

The inclusion of acrylic emulsion seems to have a direct and beneficial effect on the splitting tensile strength of the sample cubes. The average splitting tensile strength of the grout formulations is available in Graph 4.8 which shows that formulation C containing 10% acrylic displays almost twice the strength of formulation A containing no acrylic and moderately higher strength than formulation B with 5% acrylic. Graphs for all samples can be found in Appendix J.

SPLITTING TENSILE STRENGTH CALCULATIONS					
SAMPLE	MAXIMUM LOAD (LBF)	LENGTH (IN)	DIAMETER (IN)	SPLITTING TENSILE STRENGTH (PSI)	AVERAGE (PSI)
A1	203	3.978	2.043	15.91	12.58
A2	144	4.023	2.048	11.10	
A3	137	4.006	2.024	10.73	
B1	266	4.018	2.044	20.60	16.47
B2	102	3.990	2.026	8.06	
B3	265	4.012	2.029	20.74	
C1	218	3.995	2.043	16.97	24.85
C2	245	3.991	2.023	19.35	
C3	487	3.994	2.030	38.24	

Table 4.5



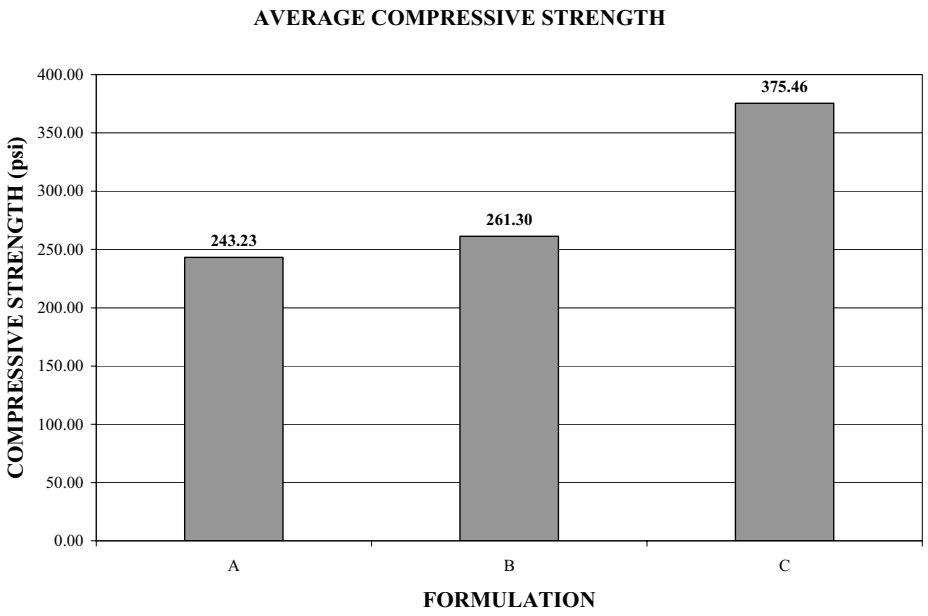
Graph 4.8

4.4.2 Compressive Strength

The addition of acrylic emulsion also increases the compressive strength of the grout formulations B and C. Grout formulation C had a compressive strength more than 100 pounds per square inch higher than formulation A as seen in the following data table and graph. The addition of acrylic emulsion increases the unmodified formulation (A) by 7.43% for B and by 54.37% for formulation C. The remainder of the data on the compressive strength of Phase 3 grout formulations is located in Appendix K.

COMPRESSIVE STRENGTH CALCULATIONS						
SAMPLE	MAXIMUM LOAD (LBF)	LENGTH (IN)	WIDTH (IN)	AREA (IN^2)	COMPRESSIVE STRENGTH (PSI)	AVERAGE (PSI)
A1	996	1.993	1.996	3.98	250.38	243.23
A2	1015	2.009	1.892	3.80	267.03	
A3	870	2.027	2.022	4.10	212.27	
B1	1031	1.983	2.008	3.98	258.92	261.30
B2	1190	2.009	1.929	3.88	307.07	
B3	866	1.983	2.004	3.97	217.92	
C1	1440	1.995	1.975	3.94	365.47	375.46
C2	1492	1.954	1.981	3.87	385.44	
C3	1469	1.973	1.983	3.91	375.47	

Table 4.6



Graph 4.9

4.4.3 Frost Resistance

All samples save for A2, survived all 15 freeze / thaw cycles. Sample A2 broke cleanly during the 15th (last) cycle and so was included in test data. The bulk volume represents the amount of material retained throughout the test. Samples that perform best and have the highest resistance to the test correspondingly have the highest amount of bulk volume retained.

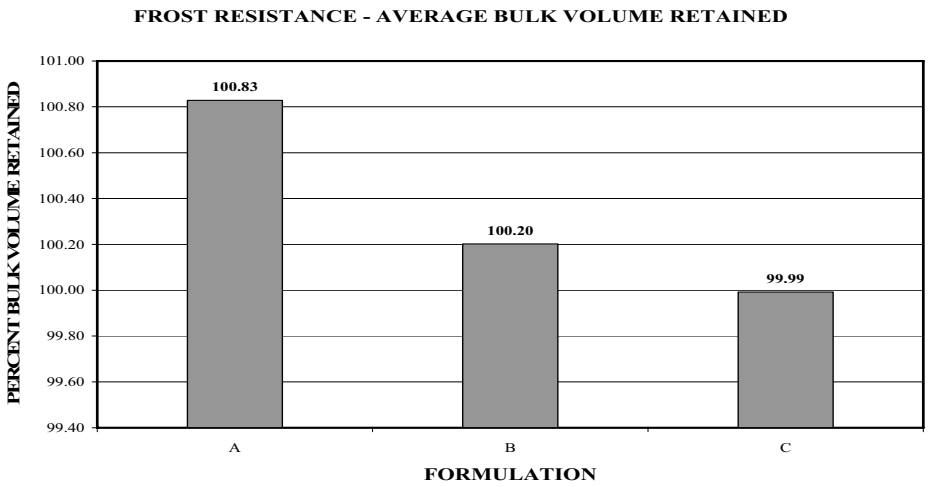
According to the data, grout formulation A was the most durable, followed by formulation B (5% acrylic), and lastly by formulation C (10% acrylic). It does not appear that the addition of acrylic emulsion had any major effect on the grout formulation. Nevertheless, a trend is discernible from previous research that the addition of acrylic reduces frost resistance. The variations between the initial and final measurements of all three formulations were closer than in all other, with only a 1% span in the average bulk volume retained.

Despite the minor disaggregation and breakage of samples (A2), it is noted that the final bulk volume calculated for sample groups A and B was slightly higher than 100%, and that the final bulk volume for group C was extremely close to 100%. This is most likely due to the limited accuracy of the hydrostatic balance used in the measurements required for this test. The full set of bulk volume calculations and photographs of the samples at the beginning and end of the testing are located in Appendix L.

FROST RESISTANCE – BULK VOLUME CALCULATIONS				
SAMPLE	INITIAL BULK VOLUME	FINAL BULK VOLUME	BULK VOLUME RETAINED (%)	AVERAGE BULK VOLUME RETAINED
A1	125.30	125.70	100.32	100.83
A2	124.05	126.22	101.75	
A3	124.40	124.92	100.42	
B1	125.10	125.28	100.14	100.20
B2	121.23	121.72	100.40	
B3	121.54	121.61	100.06	
C1	123.15	123.19	100.03	99.99
C2	122.69	122.65	99.97	
C3	121.81	121.78	99.98	

Table 4.7

As seen in the photographs in Appendix L, any breakage and material loss is recorded. Sample group A exhibited almost no deterioration, except for a 2 cracks that equally divided the sample into almost 4 equal parts. This defect appears to stem from this sample's curing which was exacerbated during the harsh freeze / thaw cycling. Sample groups B and C, containing acrylic, exhibited only very minor erosion at their edges.



Graph 4.10

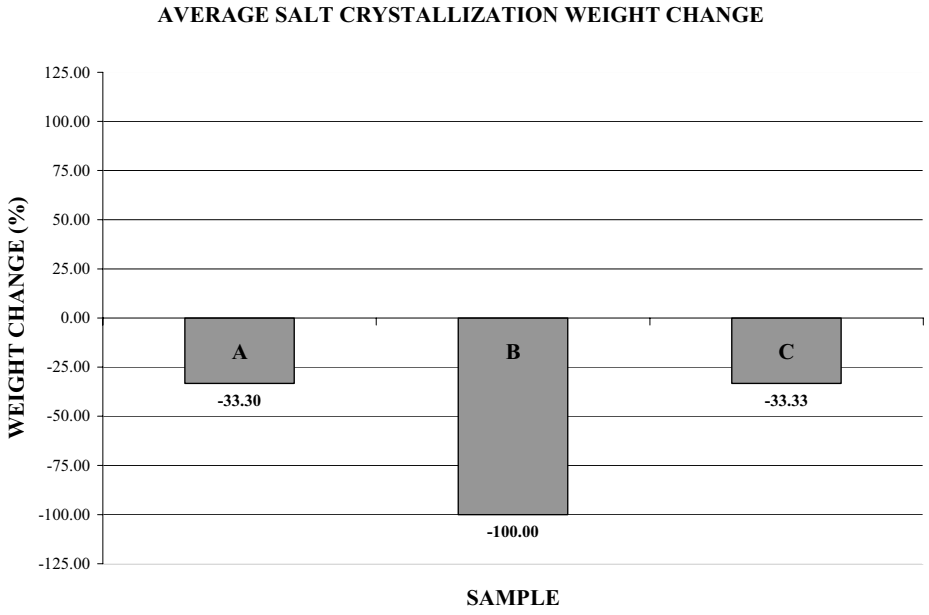
4.4.5 Salt Crystallization Resistance

The salt crystallization resistance test left few samples intact. Of sample group A only samples A1 and A3 remained with visible cracks and significant erosion after 15 cycles of testing. A2 cracked in half after the 14th cycle. Sample group B was entirely destroyed with B1 and B3 remaining intact until the 12th cycle and B2 disintegrating after the 12th cycle. Sample C3 disintegrated after the 10th cycle and sample C2 cracked in half after the 12th cycle. The remaining cube, sample C1, exhibited significant deterioration but survived the week long soaking after salt / drying cycling was complete. The faces of this formulation in particular began to shear off after the 8th cycle.

The addition of El Rey Superior 200 acrylic emulsion did not seem to increase the salt crystallization resistance of the grout formulations presented in this thesis, but this is unclear since the samples that contained no acrylic did not necessarily fare well in this experiment. All samples exhibited weight gain from the migration of salts into their cores during the first 10 cycles, after which disaggregation was evident. I believe that this interior re-crystallization continued even as the samples were exhibiting loss at their periphery. The percent weight change calculations are presented in Table 4.8, and the average weight change for each sample set is illustrated in Graph 4.12. The full set of data is found in Appendix M.

SALT CRYSTALLIZATION WEIGHT CHANGE CALCULATIONS				
SAMPLE	INITIAL WEIGHT (G)	FINAL WEIGHT (G)	WEIGHT CHANGE (%)	AVERAGE WEIGHT CHANGE
A1	120.32	129.33	7.49	-33.30
A2	119.72	0.00	-100.00	
A3	118.62	109.84	-7.40	
B1	120.73	0.00	-100.00	-100.00
B2	116.43	0.00	-100.00	
B3	120.38	0.00	-100.00	
C1	120.21	94.78	-100.00	-33.33
C2	120.19	0.00	-100.00	
C3	120.17	0.00	-100.00	

Table 4.8



Graph 4.11

The following discussion of the tested properties of the Phase Three research grout formulations will describe their behaviors related to the successful formulations of the two previous phases of grout research. Specifically it will describe the performance of the St. Astier natural hydraulic lime relative to the previously used Riverton hydrated hydraulic lime whenever data is available to compare these properties. Table 5.1 identifies a list of ideal properties (from Chapter 1) for a grout formulation for masonry repair ranked by descending order of importance.

5.1 Material Composition

The scanning electron photomicrographs confirmed the presence of acrylic dispersions in the grout matrix seen in previous theses by Hartzler and Bass. Based on their recommendations, the photomicrographs were taken at a very high level of magnification in order to observe the sand, lime, microspheres, and acrylic. The bubbles noted in previous research were not present due to the mixing process used in Phase Three grout testing and described in Chapter 2. Only one sample that was destroyed during the splitting tensile strength test in Phase 3 exhibited any evidence of bubbles. This is significant as the introduction of voids from high speed mixing was found to significantly reduce strength of the grout measured in splitting tensile strength and compressive strength testing.

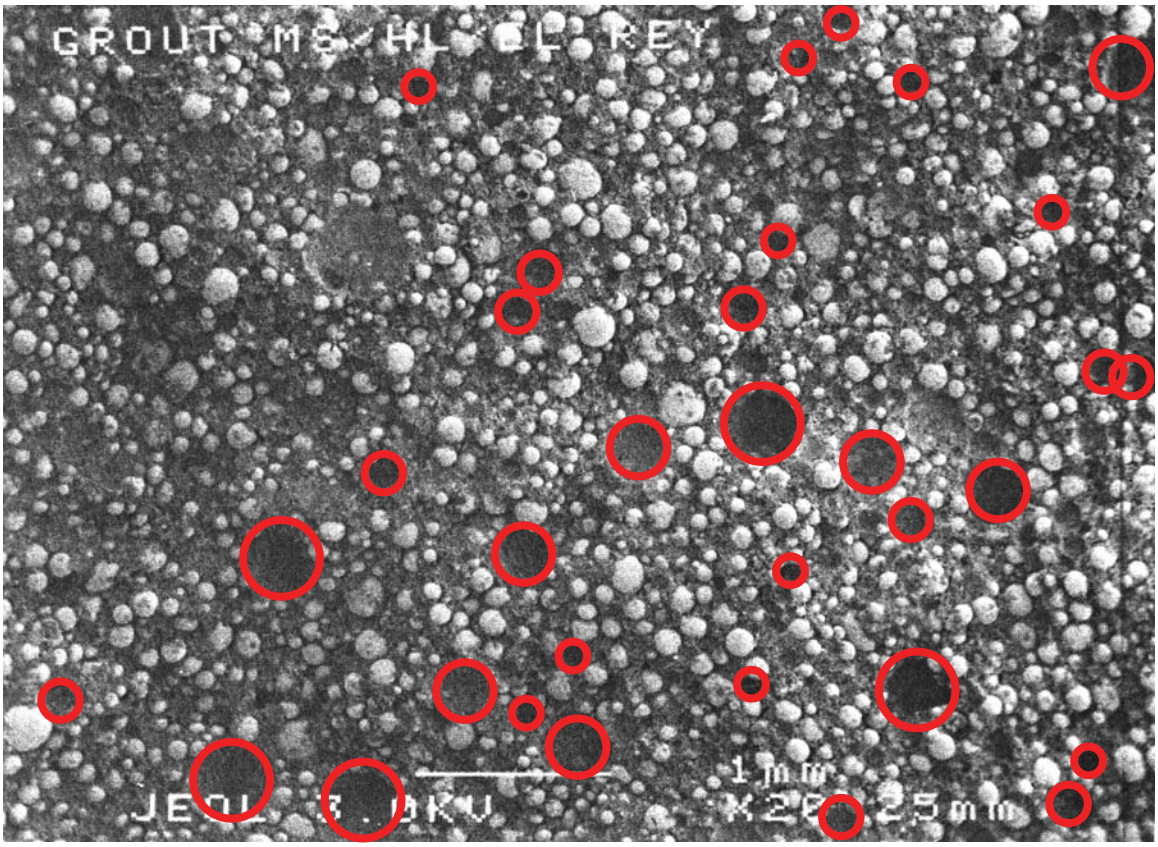


Figure 5.1 - Photomicrograph of Phase 1 Grout Formula #20 with voids highlighted. (3000X)

By increasing the amount of trapped air, the bubbles reduce the homogeneity of the mixture. Ignoul, Gemert, and Van Rickstal's "Application of mineral grouts for structural consolidation of historical monuments" stresses homogeneity of grout in order to provide a solid and functional treatment. Testing for various workable properties of grouts and for homogeneity of the treatment once cured are covered, as well as an overview of composition and procedure.

5.2 Workability

According to work performed by Bass and Cancino, a grout with a low viscosity and high rate of flow was desirable and the rate of flow in the first two phases of testing was noticeably increased by the addition of acrylic emulsion. All grout formulations presented in this thesis conform to this specification and also to ASTM C 939-97 Standard Test Method for Flow of Grout for Preplaced-Aggregate Concrete – Flow Cone Method and cannot be compared to the first two phases of testing in this regard as the same testing procedure was not followed. The addition of acrylic in the third phase of research actually slowed the flow of the grout, but the greatest difference was measured at slightly more than three seconds, which is almost negligible. Also, as the same amount of water was used in all formulations, this can most likely be attributed to the use of acrylic.

In this phase of testing, the time of final set was reached at 72 hours regardless of acrylic content, a slightly longer time than recommended by several ICCROM articles, but still adequate considering that the only way for water to evaporate was through the top of the Vicat mold, as they were sealed to plastic plates. Of course in field testing the set time would vary greatly due to humidity, temperature, adherend porosity, and condition of the area to be grouted.

Due to the extensive research by Bass regarding the shrinkage of various grouts, extremely low shrinkage was determined to be one of the most important properties of a grout. All of the grout formulations tested in this thesis exhibited little to no measurable shrinkage in over a year of cure and can be classified as having low shrinkage. The only

hairline cracking visible in these samples was determined to be from excess water in the mixture and can be easily corrected in later exercises, remembering that a standard 2 parts dry to 1 part water per volume was used in Phase 3 when mixing. Aside from environmental conditions during set and water / solids ratio, this can be attributed to the excellent particle size distribution curve determined in earlier phases.

5.3 Compatibility

Similar to Phase 2 research into the capillary water absorption of grout, it has been found that these formulations also easily absorb water and that this uptake is slightly reduced by the addition of acrylic. The rate of water absorption by total immersion was steady and positively affected by the addition of Superior Additive 200. In Phase 2 of testing, it was noted that the most successful formula (A) exhibited high water absorption and porosity, but it was determined that the high rates stemmed from the increased porosity from foaming during mixing. In this phase of testing, formulation C had the fastest drying rate; however the rate of drying was not measured in previous phases of testing so there is no data available for comparison.

In this phase of testing both grouts containing acrylic (B and C) had lower water vapor transmission rates than the un-amended samples, as seen in Table 4.4. They also had correspondingly low permeance values and the acrylic emulsion lowered these values as expected. The formulation in Phase Two of testing selected as most successful (A) also had a high concentration of bubbles resulting from the mixing procedure.

5.4 Durability

In the first phase of research, the splitting tensile strength recorded for the chosen formulation (#19) was 31.32 psi. The second phase concluded that the amount of microspheres in a formulation had a detrimental effect on the samples' splitting tensile strength with the chosen formulation (A) having a comparably very high splitting tensile strength of 122.71 psi. In Phase 3 of this grout research, the addition of acrylic emulsion directly increased the splitting tensile strength, but the highest average psi reached was relatively low, at 24.85 psi (formulation C). This overall lowering of the splitting tensile strength in Phases 1 and 2 testing can be attributed to the introduction of voids from foaming of the acrylic during mixing. Nevertheless, the Phase 3 test results indicate that while the splitting tensile strengths of these grouts are all relatively low, it appears that the introduction of 5 – 10% acrylic emulsion in water increases strength by 30.94% for sample group B and 50.93% for sample group C respectively.

As in the first phase of grout testing (Bass), linear and perimeter cracking due to compressive strain before sample failure was evident in this experiment, indicating that the grouts tested in this thesis are able to withstand some level of deformation before total failure.

The compressive strength of the samples containing levels of acrylic emulsion performed better than the one without it. Formulation C had the highest compressive strength of 375.46 psi. Phase 2 (Cancino) testing determined that the inclusion of microspheres did not affect the compressive strength of the samples with formulation A (chosen as the most successful) having a compressive strength of 110.40 psi which was

lower than all other formulations tested. Linear and perimeter cracking before failure was also evident in these samples.

The test for resistance to frost was undertaken in an attempt to replicate natural weathering systems in the laboratory. All samples survived 15 cycles of freeze thaw testing according to RILEM V.3 Frost Resistance except for A2. All samples from Phase Two (Cancino) testing survived 12 testing cycles. As amount of bulk volume retained for all samples in Phase Three testing varied so slightly, it can be said that there was little to no effect of the acrylic on this tested property, but perhaps an extended testing cycle would yield different results.

The test for resistance to salt crystallization was not performed as part of the experimental program in Phases 1 and 2. As such, there is no data for comparison. However, since none of the formulations fared well in this test, it appears that these grouts behave similarly to other moderately hydraulic lime-based mortars and do not display high resistance to salt crystallization.

5.5 Summary

In this study, a laboratory testing program was undertaken to test and refine an existing low-weight moderately hydraulic lime grout formulation using a newly available binder with and without an acrylic emulsion additive. Three slightly different formulations were prepared for an extensive testing program that appraised particle size, material composition, flow, set time, shrinkage, capillary rise, water absorption, drying rate, water vapor transmission, splitting tensile strength, compressive strength, frost

resistance, and salt crystallization resistance. Of the three formulas tested, a mixture composed of 2 parts natural hydraulic lime, 1 part sand (< 300 μm), 1 part ceramic microspheres (10 – 350 μm); (by volume) mixed with 10% acrylic emulsion (by volume, in water) was identified as exhibiting optimal properties as identified for most masonry systems. This evaluation has determined that this formulation features the desired properties of low shrinkage, high flow, low viscosity, minimal segregation with high homogeneity, reasonable set time, adequate water absorption and vapor transmission, compatible splitting tensile and compressive strengths lower than the material to be grouted (plaster and low strength masonry systems), and high resistance to frost.

6.1 Materials & Formulæ

A variety of material substitutions should be explored in any future testing involving the grout formulas outlined in this thesis. Other hydrated hydraulic limes available in Europe or with St. Astier NHL 2 and 5 which were not tested as part of this research should be tested according to acknowledged test standards to establish grout specifications with these binders. Another possible binder is dispersed lime as covered in the Rochus and Maryniak-Piaszczynski article, "Dispersed hydrated lime for the preservation and conservation of stone monuments", found in the Proceedings of the 9th International Congress on Deterioration and Conservation of Stone which advocates the use of dispersed lime as the binder for stone repair.

Any aggregate included in further testing could be sieved through smaller openings in order to create a finer mixture. Other active and inert fillers used could include fly ash, marble dust, or brick dust depending on the proposed substrate, if applicable. The percentage of acrylic emulsion in water could be increased to 15% and 20% in order to test for any other statistical variations that they would provide. Different types of acrylic emulsion could be used as well as testing against other commercially available grouts. Further research into the processes of calcium silicate hydration and the carbonation of the lime in the formulation would be beneficial to see what effect they might have on the workability, compatibility, and durability of the grout.

6.2 Sample Preparation

During the preparation of the grout samples used in this thesis, a great many suggestions and ideas on how to improve this procedure came to light, most importantly being the use of a corded drill for mixing. This supplies full power during the course of mixing that a cordless drill cannot for the required minimum time of 4 minutes of mixing for approximately 5 liters necessary to fully incorporate the grout mixture.

In order to prevent cracking of the samples due to rapid water loss immediately after molding, all molds should be placed on sheets of drywall to absorb the water bleeding through the molds which also retains moisture in contact with the samples. Vicat molds should be prepared in this manner as well, to see what the effect of a porous substrate would be on the set time results. All plastic molds should be secured to the drywall with a bead of plumber's putty to prevent slippage. In addition to this, the molds could be placed in water after the 7^{th} day of cure with another set remaining in the curing chamber as described in this thesis to test for how the variation on curing conditions affects the samples.

The grout should also be poured generously over the tops of all of the molds due to this early rapid loss of water. This allows the tops of the cube molds to be leveled off easily before they even begin to set but after the water seeps out – thus preventing shrinkage and internal cracking of the samples. Another variable for sample preparation could be using petroleum jelly to coat the interior of the wooden cube molds which may prevent the rapid escape of water.

After the grout cures, but before the samples are removed from the molds, a large flat plaster rasp may be used to level the samples. This is particularly useful for cylindrical samples in PVC molds. All of these ideas may and should be implemented in order to provide reliable data on the best preparation, curing, and testing conditions for grout sample formulations. Also, samples could be tested at longer time intervals such as 28 days, 90 days, 6 months, 12 months, up to 36 months.

6.3 Testing

In regards to further SEM-EDS analysis, the samples need to be coated much more than they were in this testing in order to improve image quality and reduce charging from the electron beam. The coating (using gold/palladium) should resemble a slightly shiny metallic finish.

The testing program could be improved by refining some testing procedures, such as the use of electrical tape to seal samples for ASTM E96-00: STANDARD TEST METHODS FOR WATER VAPOR TRANSMISSION OF MATERIALS (WET METHOD). The use of the recommended amount of tape (at least 3 turns around the disk) created an interface between the sample's dry and sandy surface and the stickiness of the tape that was not ideal when sealed in a 50% RH chamber. Because of this, many of the samples flipped diagonally to their original position after having been sealed in place. The test was restarted with less tape used to wrap the disks and more paraffin wax used to seal them in place. Also, both glazed and unglazed clay saucers should be used to determine visual shrinkage, as unglazed saucers provide a more accurate representation of field conditions.

CHAPTER 6 – RECOMMENDATIONS FOR FUTURE RESEARCH

The testing program could be expanded by adding various tests dependent on a particular substrate to be grouted such as bond strength in shear, as well as tests for seismic resistance and accelerated weathering.

Arguably, the most important test that should be performed on grout formulations is EN 1771: DETERMINATION OF INJECTABILITY USING THE SAND COLUMN TEST. This procedure provides highly important visual and mathematical data relating to the ability of a grout formulation to flow through porous materials such as sand, crushed limestone, crushed brick. Unfortunately, due to time and practicality constraints, this test was not able to be performed to test these formulations but should definitely be present in any future grout testing at the University of Pennsylvania Architectural Conservation Laboratory.

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APPENDIX A – REFERENCED STANDARDS

EMPLOYED, MODIFIED, AND REFERENCED STANDARDS USED IN EXPERIMENTAL PROGRAM	
TITLE	**DESIGNATION**
Standard Practice for Making and Curing Concrete Specimens in the Field	ASTM C 31
Standard Specification for Concrete Aggregates	ASTM C 33
Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile	ASTM C 67
Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50mm] Cube Specimens)	ASTM C 109
Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates	ASTM C 136
Standard Specification for Hydraulic Hydrated Lime for Structural Purposes	ASTM C 141
Standard Specification for Aggregate for Masonry Mortar	ASTM C 144
Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle	ASTM C 191
Standard Practice for Making and Curing Concrete Specimens in the Laboratory	ASTM C 192
Standard Specification for Hydrated Lime for Masonry Purposes	ASTM C 207
Standard Test Methods for Joint Treatment Materials for Gypsum Board Construction	ASTM C 474
Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens	ASTM C 496
Standard Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes	ASTM C 511
Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying	ASTM C 566
Standard Test Method for Flexural Strength and Modulus of Elasticity of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes	ASTM C 580
Practice for Reducing Field Samples of Aggregate to Testing Size	ASTM C 702
Standard Specification for Standard Sand	ASTM C 778
Standard Test Methods for Apparent Density of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes	ASTM C 905
Standard Specification for Grout Fluidifier for Preplaced-Aggregate Concrete	ASTM C 937
Standard Practice for Proportioning Grout Mixtures for Preplaced-Aggregate Concrete	ASTM C 938
Standard Test Method for Flow of Grout for Preplaced-Aggregate Concrete - Flow Cone Method	ASTM C 939

APPENDIX A – REFERENCED STANDARDS

EMPLOYED, MODIFIED, AND REFERENCED STANDARDS USED IN EXPERIMENTAL PROGRAM	
TITLE	**DESIGNATION**
Standard Test Method for Dry and Wet Bulk Density, Water Absorption, and Apparent Porosity of Thin-Section Glass-Fiber Reinforced Concrete	ASTM C 948
Standard Test Method for Measuring the Drying Shrinkage of Masonry Mortar	ASTM C 1148
Standard Practice for Sampling Aggregates	ASTM D 75
Standard Practice for Specifying Color by the Munsell System	ASTM D 1535
Standard Test Method for Viscosity of Chemical Grouts by Brookfield Viscometer (Laboratory Method)	ASTM D 4016
Standard Test Methods for Water Vapor Transmission of Materials	ASTM E 96
Capillary Water Absorption and Capillary Absorption Coefficient	NORMAL 11/85
Water Absorption by Total Immersion and Imbibition Capacity	NORMAL 7/81
Measurement of the Drying Index	NORMAL 29/88
Water Vapor Permeability	NORMAL 21/85
Porosity Accessible to Water	RILEM I.1
Bulk and Real Densities	RILEM I.2
Water Absorption Coefficient (Capillarity)	RILEM II.6
Linear Strain Due to Water Absorption	RILEM II.7
Ultimate Tensile Strength	RILEM III.4
Crystallization Test by Total Immersion (for Treated Stone)	RILEM V.1b
Frost Resistance	RILEM V.3
Testing of Mortars Containing Mineral Binders	DIN 18-555.3
Building Lime	EN 459
Determination of Injectability Using the Sand Column Test	EN 1771

APPENDIX B – TEST MATRIX

TEST MATRIX FOR PERFORMANCE EVALUATION OF HYDRAULIC LIME GROUTS FOR MASONRY REPAIR					
PROPERTY	**TEST**	**STANDARD (S)**	**PREPARATION / EQUIPMENT**	**PERIOD**	**TOTAL**
Material Composition	*Particle Size Distribution*	*ASTM C136*	300g of aggregate from bulk sample / U.S. Standard sieve stack / brass brush / mechanical sieve shaker / balance / weighing boats / Nikon SMZ-1 microscope / Munsell soil charts	2 days	300g
Material Composition	*Scanning Electron Microscopy*	*Observe physical characteristics*	Adhere sample to aluminum stub with carbon tape and/or putty / pre-coat sample with carbon paint / vacuum container / powder carbon coating at LRSM / scanning electron microscope	1 day	3 – 1/form
Fluidity	*Flow of Grout*	*ASTM C939* ASTM C937	3500±10mL per formulation poured into flow cone / graduated beakers / buckets / timer / deionized water / grout mixer / stopper	1 day	6 – 2/form
Setting Time	*Time of Setting by Vicat Needle*	*ASTM C191**	Vicat apparatus with 1mm needle / Vicat mold / acrylic plates / plumber's putty / timer	4 days	9 – 3/form
Shrinkage	*Measurement of Drying Shrinkage*	*ASTM C1148** ASTM C474*	250mL per formulation poured into glazed clay saucers for visual shrinkage determination / balance	90 days	9 – 3/form
Capillary Rise	*Capillary Water Absorption*	*NORMAL 11/85*	Immersion tank / glass rods / deionized water / paper towel / balance / oven / timer / dessicator / Whatman #4 filter paper	2 days dry 1 week test	9 – 3/form
Water Absorption Capacity	*Water Absorption by Total Immersion*	*NORMAL 7/81*	Immersion tank / glass rods / deionized water / paper towel / balance / oven / timer / dessicator	2 days dry 1 week test	9 – 3/form
Drying Behavior of Cured Grout	*Measurement of Drying Index*	*NORMAL 29/88*	paper towel / balance / non-corrodible tray / dessicator / dial hygrometer / desiccant / oven	2 days dry 1 week test	9 – 3/form
Water Vapor Transmission	*Water Vapor Transmission*	*ASTM E96* NORMAL 21/85 RILEM II.2	Wrap samples with electrical tape / plastic beakers / deionized water / paraffin wax / hot plate / Pasteur pipettes / oven / dessicator / hygrometer / desiccant / balance	2 days dry 10 days test	9 – 3/form

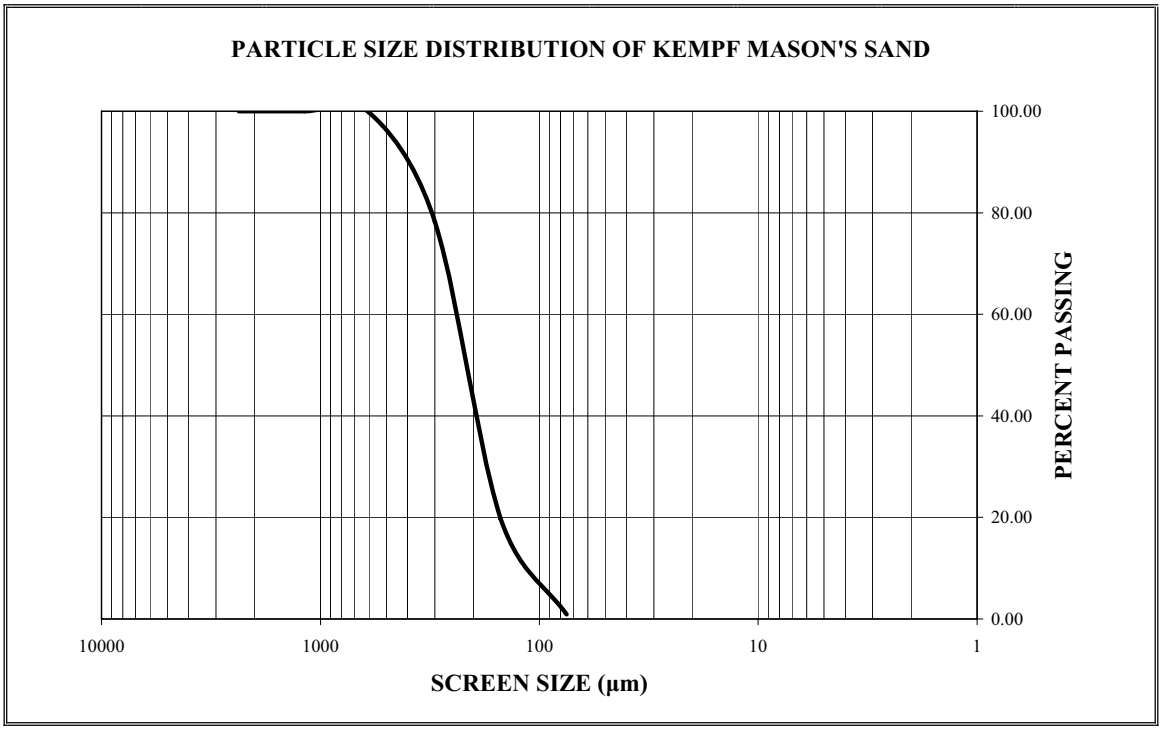
APPENDIX B – TEST MATRIX

TEST MATRIX FOR PERFORMANCE EVALUATION OF HYDRAULIC LIME GROUTS FOR MASONRY REPAIR					
PROPERTY	**TEST**	**STANDARD (S)**	**PREPARATION / EQUIPMENT**	**PERIOD**	**TOTAL**
Splitting Tensile Strength	*Splitting Tensile Strength*	*ASTM C496* RILEM III-4	Place cylinders on wood support strips on lead cell of Instron Testing Machine / apply steady force until failure	1 day	9 – 3/form
Compressive Strength	*Compressive Strength*	*ASTM C109* ASTM C942 RILEM III.5	Place samples on load cell of Instron Testing Machine / apply steady force until failure	1 day	9 – 3/form
Frost Resistance	*Freeze / Thaw Cycling*	*RILEM V.3*	Immerse and freeze samples for 15 cycles in deionized water / plastic tubs / hydrostatic balance /wire hook / beaker / freezer / dial hygrometer / balance / camera	2 days dry 3 weeks test	9 – 3/form
Salt Crystallization Resistance	*Crystallization Test by Total Immersion*	*RILEM V.1b*	Immerse and dry samples in 10% sodium sulfate solution for 15 cycles / camera / deionized water / glass beads / beakers / plastic tubs filled with tap water / oven	2 days dry 3 weeks test	9 – 3/form
ITEMS IN ITALICS WERE THE MAIN STANDARD USED IN THE PERFORMANCE OF EACH TEST AN ASTERISK (*) INDICATES THAT THE LISTED STANDARD WAS USED AS A GUIDE					

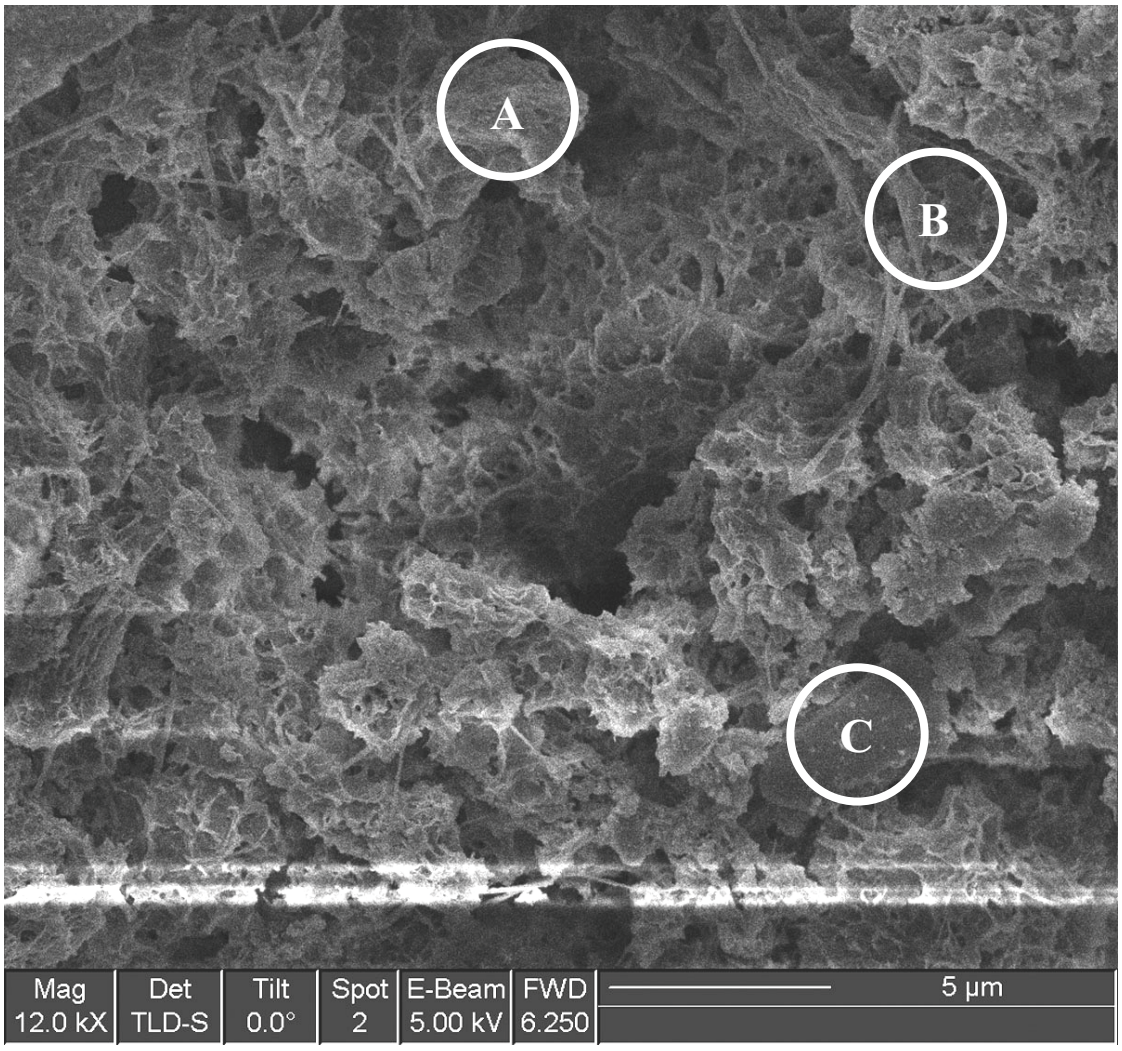
APPENDIX C – PARTICLE SIZE DISTRIBUTION

GEORGE KEMPF MASON'S SAND – PARTICLE SIZE DISTRIBUTION						
SIEVE NUMBER	PARTICLE SHAPE	MUNSELL COLOR	SPHERICITY	ROUNDNESS	SORTING	MAGNIFICATION
8	---	---	---	---	---	---
16	coarse	10 YR 7/2	low	angular	well	10 x
30	coarse	10 YR 7/2	low	angular	well	10 x
50	medium	10 YR 8/2	low	sub-angular	well	10 x
100	fine	10 YR 8/1	medium	sub-angular	well	10 x
200	fine	10 YR 8/1	high	sub-rounded	well	10 x
PAN	very fine	10 YR 8/1	high	sub-rounded	well	10 x

ASTM SIEVE NUMBER	SCREEN SIZE (MM)	MASS OF CONTAINER (G)	MASS OF SAMPLE & CONTAINER (G)	MASS RETAINED (G)	PERCENT MASS RETAINED	PERCENT ON OR ABOVE	PERCENT PASSING
8	2360	4.80	4.80	0.00	0.00	0.00	100.00
16	1180	4.85	4.91	0.06	0.02	0.02	99.98
30	600	4.86	5.78	0.92	0.23	0.25	99.75
50	300	4.92	90.23	85.31	21.47	21.72	78.28
100	150	4.90	237.63	232.73	58.58	80.29	19.71
200	75	4.92	79.60	74.68	18.80	99.09	0.91
PAN	0	4.95	6.66	1.71	0.43	99.52	0.48



APPENDIX D – SEM PHOTOMICROGRAPHS

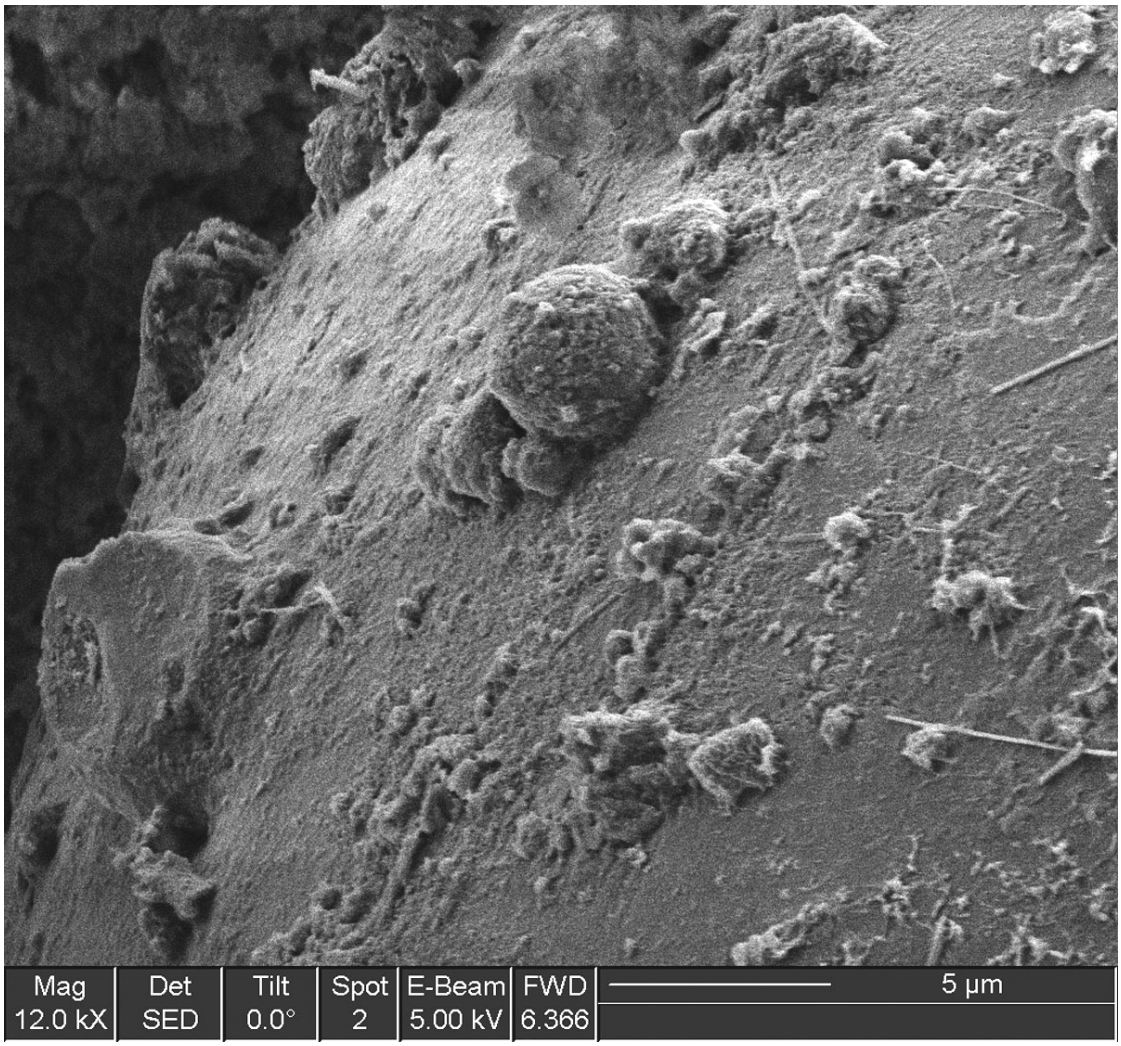


UNIVERSITY OF PENNSYLVANIA – LABORATORY FOR THE RESEARCH ON THE STRUCTURE OF MATTER
DR. EVA M. CAMPO WITH VICTORIA PINGARRON ALVAREZ
FEI STRATA DB235 FIB: DUAL BEAM FOCUSED ION BEAM MICROSCOPE

Grout formulation B composed of 2 NHL / 1 S / 1 MS / 5% ER

Hydraulic lime (a) and acrylic (b) can be seen coating the particles of sand (c). The white band on the bottom of the image is characteristic of the electron beam charging while the image was being captured.

APPENDIX D – SEM PHOTOMICROGRAPHS



UNIVERSITY OF PENNSYLVANIA – LABORATORY FOR THE RESEARCH ON THE STRUCTURE OF MATTER
DR. EVA M. CAMPO WITH VICTORIA PINGARRON ALVAREZ
FEI STRATA DB235 FIB: DUAL BEAM FOCUSED ION BEAM MICROSCOPE

Grout formulation B composed of 2 NHL / 1 S / 1 MS / 5% ER

Here, a close up view of the surface of a ceramic microsphere shows small (clay- or colloid-sized) particles of the sand attached to it. Also visible are "stringers" from the acrylic emulsion.

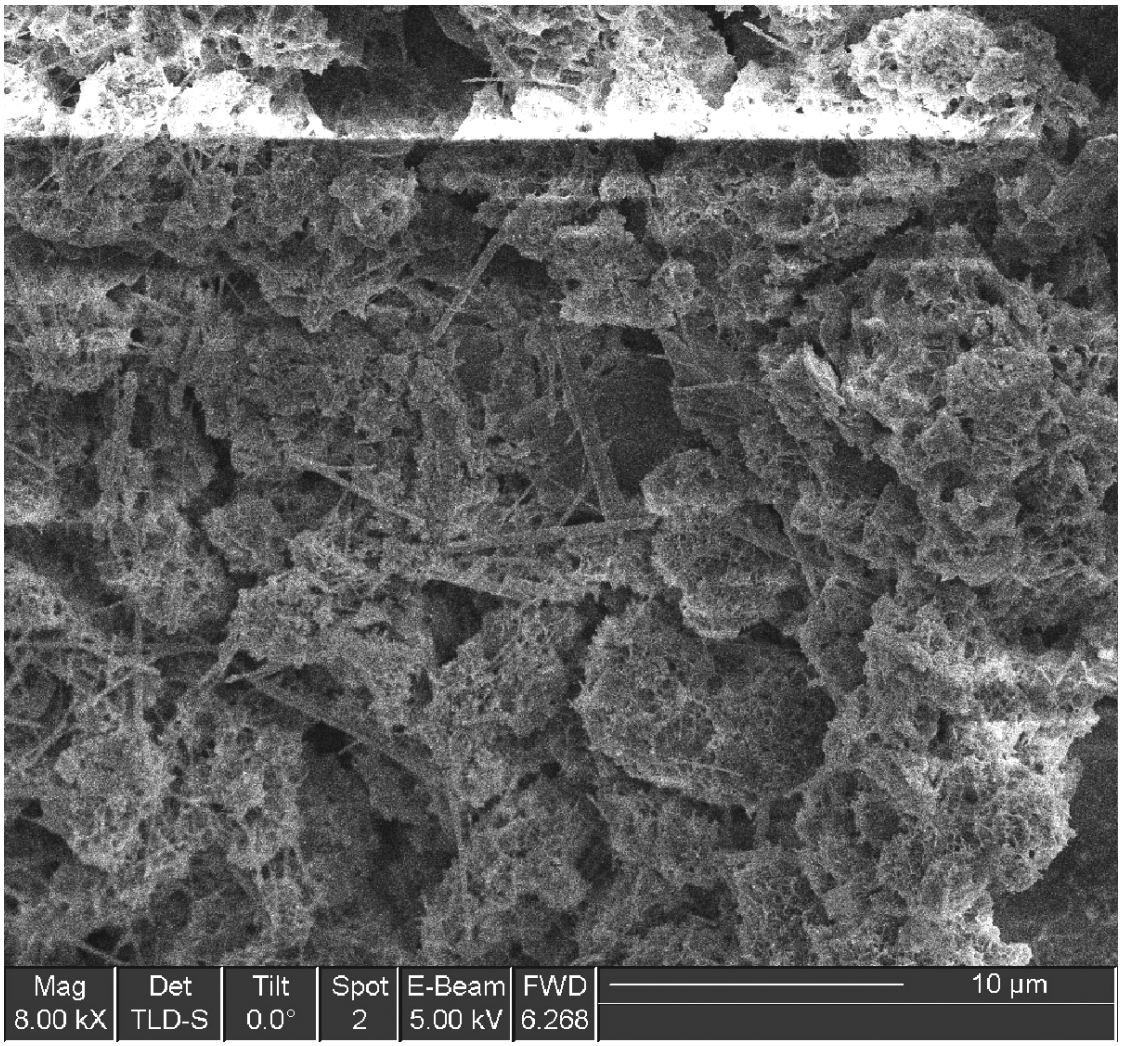
APPENDIX D – SEM PHOTOMICROGRAPHS

UNIVERSITY OF PENNSYLVANIA – LABORATORY FOR THE RESEARCH ON THE STRUCTURE OF MATTER
DR. EVA M. CAMPO WITH VICTORIA PINGARRON ALVAREZ
FEI STRATA DB235 FIB: DUAL BEAM FOCUSED ION BEAM MICROSCOPE

Grout formulation B composed of 2 NHL / 1 S / 1 MS / 5% ER

This photomicrograph shows an extreme close-up of an acrylic “stringer”.

APPENDIX D – SEM PHOTOMICROGRAPHS



UNIVERSITY OF PENNSYLVANIA – LABORATORY FOR THE RESEARCH ON THE STRUCTURE OF MATTER
DR. EVA M. CAMPO WITH VICTORIA PINGARRON ALVAREZ
FEI STRATA DB235 FIB: DUAL BEAM FOCUSED ION BEAM MICROSCOPE

Grout formulation B composed of 2 NHL / 1 S / 1 MS / 5% ER

This image shows the acrylic strands coating sand, microspheres, and lime. The needle-like projections appear random.

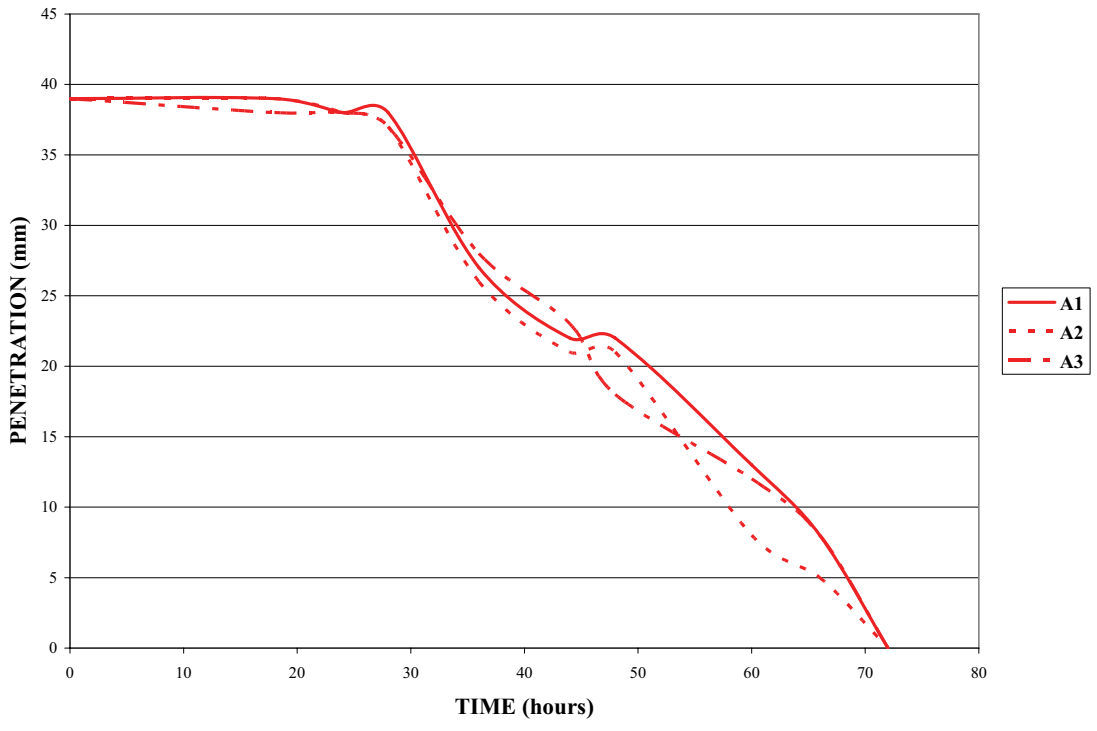
APPENDIX E – SETTING TIME DATA

SAMPLE KEY	
A	2 NHL / 1 S / 1 MS / 0% ER
B	2 NHL / 1 S / 1 MS / 5% ER
C	2 NHL / 1 S / 1 MS / 10% ER

PENETRATION MEASUREMENTS (MM) – FORMULATION A

TIME (HOURS)	SAMPLE		
	A1	A2	A3
0	39	39	39
18	39	39	38
24	38	38	38
28	38	37	37
36	27	26	28
44	22	21	23
48	22	21	18
60	13	8	12
66	8	5	8
72	0	0	0

TIME OF SETTING– FORMULATION A



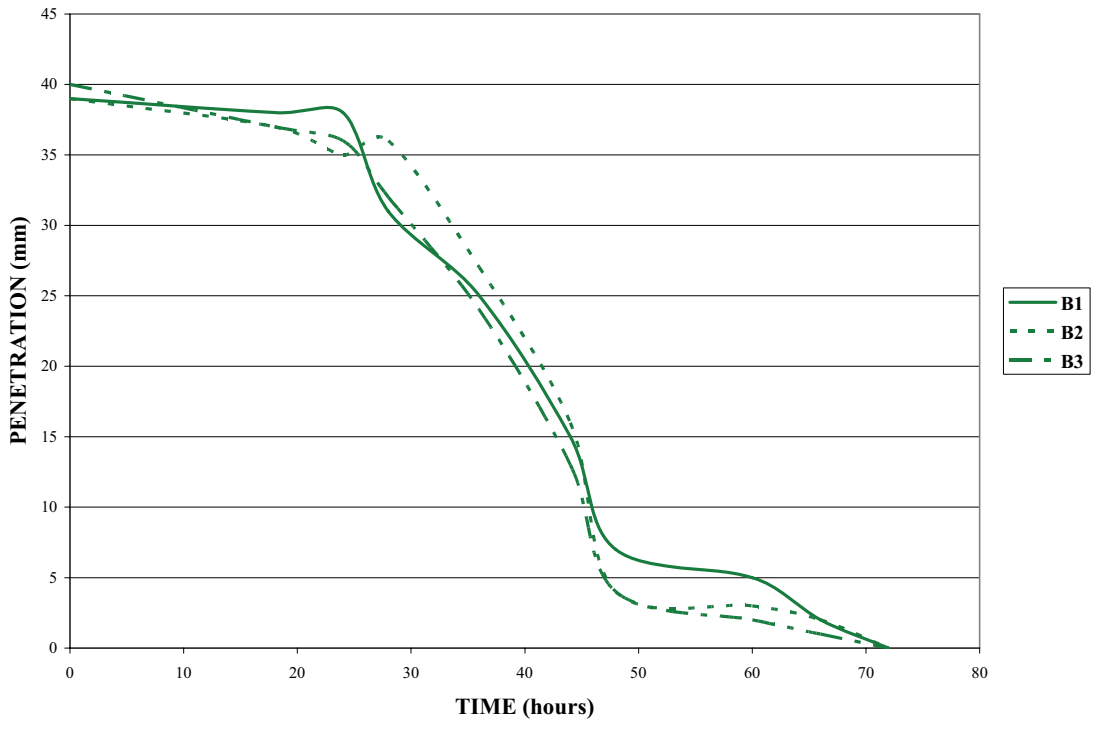
APPENDIX E – SETTING TIME DATA

SAMPLE KEY	
A	2 NHL / 1 S / 1 MS / 0% ER
B	2 NHL / 1 S / 1 MS / 5% ER
C	2 NHL / 1 S / 1 MS / 10% ER

PENETRATION MEASUREMENTS (MM) – FORMULATION B

TIME (HOURS)	SAMPLE		
	B1	B2	B3
0	39	39	40
18	38	37	37
24	38	35	36
28	31	36	32
36	25	27	24
44	15	16	13
48	7	4	4
60	5	3	2
66	2	2	1
72	0	0	0

TIME OF SETTING– FORMULATION B



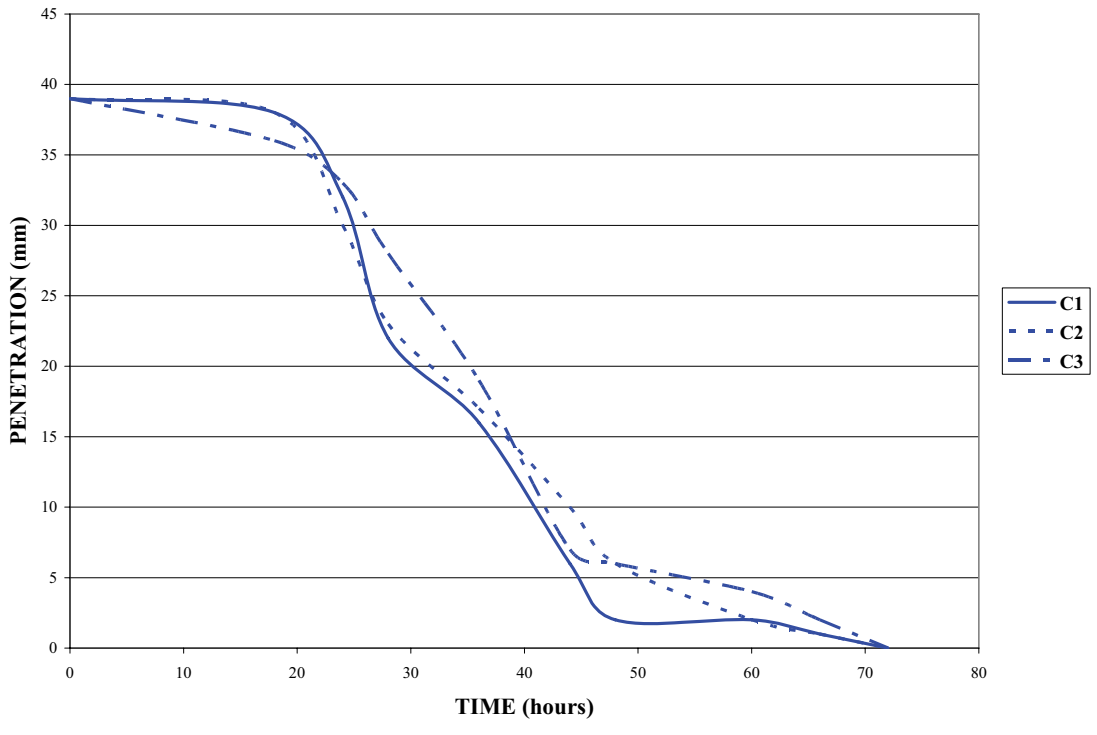
APPENDIX E – SETTING TIME DATA

SAMPLE KEY	
A	2 NHL / 1 S / 1 MS / 0% ER
B	2 NHL / 1 S / 1 MS / 5% ER
C	2 NHL / 1 S / 1 MS / 10% ER

PENETRATION MEASUREMENTS (MM) – FORMULATION C

TIME (HOURS)	SAMPLE		
	C1	C2	C3
0	39	39	39
18	38	38	36
24	32	30	33
28	22	23	28
36	16	17	19
44	6	10	7
48	2	6	6
60	2	2	4
66	1	1	2
72	0	0	0

TIME OF SETTING– FORMULATION C



APPENDIX F – CAPILLARY WATER ABSORPTION DATA

CAPILLARY WATER ABSORPTION MEASUREMENTS FOR SAMPLE A1						
CUMULATIVE TIME (S)	SQUARE ROOT TIME ($S^{0.5}$)	DRY WEIGHT, M_O (G)	WEIGHT OF SAMPLE, M_I (G)	SURFACE AREA (CM^2)	WATER ABSORBED/ UNIT SURFACE, M_I (G/CM^2)	AVERAGE M_I
0	0.00	120.93	120.93	25	0.00	0.00
300	17.32	120.93	144.18	25	0.93	0.47
600	24.49	120.93	155.45	25	1.38	1.16
900	30.00	120.93	162.98	25	1.68	1.53
1200	34.64	120.93	164.15	25	1.73	1.71
1500	38.73	120.93	164.29	25	1.73	1.73
1800	42.43	120.93	164.38	25	1.74	1.74
2100	45.83	120.93	164.41	25	1.74	1.74
2400	48.99	120.93	164.47	25	1.74	1.74
2700	51.96	120.93	164.54	25	1.74	1.74
3000	54.77	120.93	164.55	25	1.74	1.74
3300	57.45	120.93	164.56	25	1.75	1.75
3600	60.00	120.93	164.59	25	1.75	1.75
4500	67.08	120.93	164.63	25	1.75	1.75
5400	73.48	120.93	164.68	25	1.75	1.75
6300	79.37	120.93	164.72	25	1.75	1.75
7200	84.85	120.93	164.73	25	1.75	1.75
10800	103.92	120.93	164.86	25	1.76	1.75
14400	120.00	120.93	164.95	25	1.76	1.76
18000	134.16	120.93	165.05	25	1.76	1.76
21600	146.97	120.93	165.12	25	1.77	1.77
25200	158.75	120.93	165.30	25	1.77	1.77
28800	169.71	120.93	165.35	25	1.78	1.78
86400	293.94	120.93	166.14	25	1.81	1.79
172800	415.69	120.93	166.88	25	1.84	1.82
259200	509.12	120.93	167.56	25	1.87	1.85
345600	587.88	120.93	168.17	25	1.89	1.88
432000	657.27	120.93	168.70	25	1.91	1.90
518400	720.00	120.93	169.29	25	1.93	1.92

APPENDIX F – CAPILLARY WATER ABSORPTION DATA

CAPILLARY WATER ABSORPTION MEASUREMENTS FOR SAMPLE A2						
CUMULATIVE TIME (S)	SQUARE ROOT TIME ($S^{0.5}$)	DRY WEIGHT, M_O (G)	WEIGHT OF SAMPLE, M_I (G)	SURFACE AREA (CM^2)	WATER ABSORBED/ UNIT SURFACE, M_I (G/CM^2)	AVERAGE M_I
0	0.00	123.33	123.33	25	0.00	0.00
300	17.32	123.33	149.57	25	1.05	0.52
600	24.49	123.33	162.07	25	1.55	1.30
900	30.00	123.33	167.90	25	1.78	1.67
1200	34.64	123.33	168.08	25	1.79	1.79
1500	38.73	123.33	168.18	25	1.79	1.79
1800	42.43	123.33	168.22	25	1.80	1.79
2100	45.83	123.33	168.26	25	1.80	1.80
2400	48.99	123.33	168.37	25	1.80	1.80
2700	51.96	123.33	168.40	25	1.80	1.80
3000	54.77	123.33	168.44	25	1.80	1.80
3300	57.45	123.33	168.50	25	1.81	1.81
3600	60.00	123.33	168.53	25	1.81	1.81
4500	67.08	123.33	168.54	25	1.81	1.81
5400	73.48	123.33	168.60	25	1.81	1.81
6300	79.37	123.33	168.57	25	1.81	1.81
7200	84.85	123.33	168.65	25	1.81	1.81
10800	103.92	123.33	168.79	25	1.82	1.82
14400	120.00	123.33	168.85	25	1.82	1.82
18000	134.16	123.33	168.96	25	1.83	1.82
21600	146.97	123.33	169.06	25	1.83	1.83
25200	158.75	123.33	169.11	25	1.83	1.83
28800	169.71	123.33	169.79	25	1.86	1.84
86400	293.94	123.33	170.64	25	1.89	1.88
172800	415.69	123.33	171.38	25	1.92	1.91
259200	509.12	123.33	171.88	25	1.94	1.93
345600	587.88	123.33	172.50	25	1.97	1.95
432000	657.27	123.33	173.05	25	1.99	1.98
518400	720.00	123.33	173.72	25	2.02	2.00

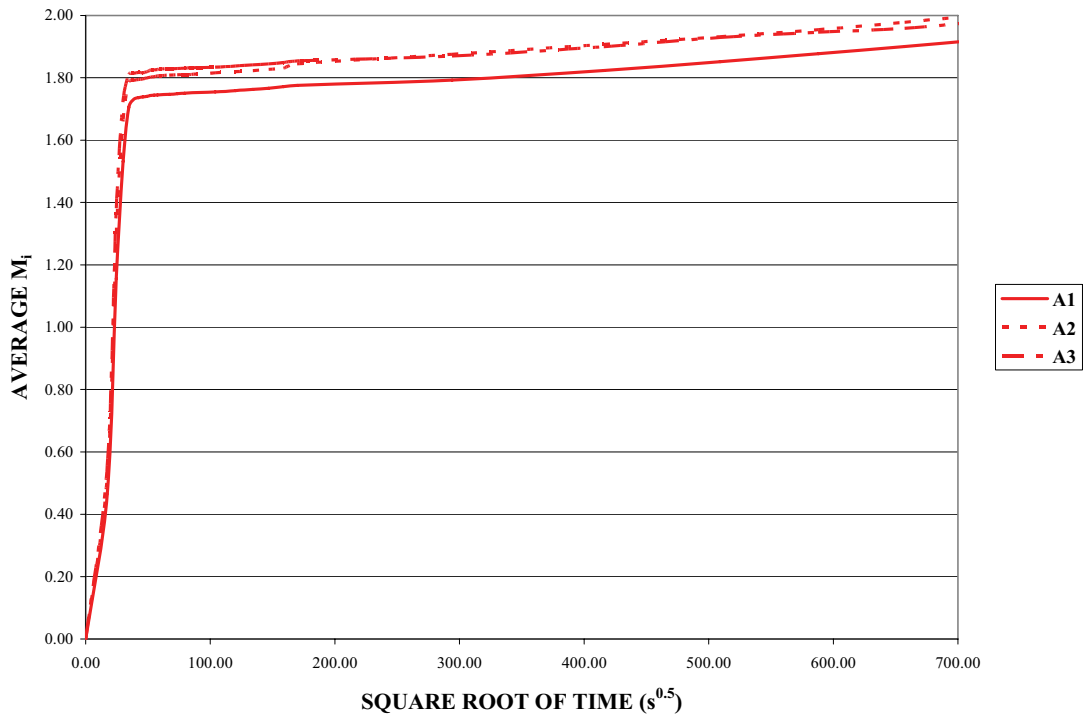
APPENDIX F – CAPILLARY WATER ABSORPTION DATA

CAPILLARY WATER ABSORPTION MEASUREMENTS FOR SAMPLE A3						
CUMULATIVE TIME (S)	SQUARE ROOT TIME ($S^{0.5}$)	DRY WEIGHT, M_O (G)	WEIGHT OF SAMPLE, M_I (G)	SURFACE AREA (CM^2)	WATER ABSORBED/ UNIT SURFACE, M_I (G/CM^2)	AVERAGE M_I
0	0.00	122.67	122.67	25	0.00	0.00
300	17.32	122.67	150.52	25	1.11	0.56
600	24.49	122.67	163.88	25	1.65	1.38
900	30.00	122.67	167.86	25	1.81	1.73
1200	34.64	122.67	168.01	25	1.81	1.81
1500	38.73	122.67	168.07	25	1.82	1.81
1800	42.43	122.67	168.13	25	1.82	1.82
2100	45.83	122.67	168.01	25	1.81	1.82
2400	48.99	122.67	168.27	25	1.82	1.82
2700	51.96	122.67	168.29	25	1.82	1.82
3000	54.77	122.67	168.31	25	1.83	1.83
3300	57.45	122.67	168.36	25	1.83	1.83
3600	60.00	122.67	168.40	25	1.83	1.83
4500	67.08	122.67	168.40	25	1.83	1.83
5400	73.48	122.67	168.42	25	1.83	1.83
6300	79.37	122.67	168.47	25	1.83	1.83
7200	84.85	122.67	168.49	25	1.83	1.83
10800	103.92	122.67	168.55	25	1.84	1.83
14400	120.00	122.67	168.67	25	1.84	1.84
18000	134.16	122.67	168.74	25	1.84	1.84
21600	146.97	122.67	168.82	25	1.85	1.84
25200	158.75	122.67	168.99	25	1.85	1.85
28800	169.71	122.67	169.05	25	1.86	1.85
86400	293.94	122.67	169.77	25	1.88	1.87
172800	415.69	122.67	170.55	25	1.92	1.90
259200	509.12	122.67	171.26	25	1.94	1.93
345600	587.88	122.67	171.39	25	1.95	1.95
432000	657.27	122.67	171.89	25	1.97	1.96
518400	720.00	122.67	172.50	25	1.99	1.98

APPENDIX F – CAPILLARY WATER ABSORPTION DATA

SAMPLE KEY	
A	2 NHL / 1 S / 1 MS / 0% ER
B	2 NHL / 1 S / 1 MS / 5% ER
C	2 NHL / 1 S / 1 MS / 10% ER

CAPILLARY WATER ABSORPTION CURVES – FORMULATION A



APPENDIX F – CAPILLARY WATER ABSORPTION DATA

CAPILLARY WATER ABSORPTION MEASUREMENTS FOR SAMPLE B1						
CUMULATIVE TIME (S)	SQUARE ROOT TIME ($S^{0.5}$)	DRY WEIGHT, M_O (G)	WEIGHT OF SAMPLE, M_I (G)	SURFACE AREA (CM^2)	WATER ABSORBED/ UNIT SURFACE, M_I (G/CM^2)	AVERAGE M_I
0	0.00	120.41	120.41	25	0.00	0.00
300	17.32	120.41	137.54	25	0.69	0.34
600	24.49	120.41	144.94	25	0.98	0.83
900	30.00	120.41	150.56	25	1.21	1.09
1200	34.64	120.41	155.25	25	1.39	1.30
1500	38.73	120.41	159.27	25	1.55	1.47
1800	42.43	120.41	161.47	25	1.64	1.60
2100	45.83	120.41	161.76	25	1.65	1.65
2400	48.99	120.41	161.85	25	1.66	1.66
2700	51.96	120.41	161.92	25	1.66	1.66
3000	54.77	120.41	161.99	25	1.66	1.66
3300	57.45	120.41	162.05	25	1.67	1.66
3600	60.00	120.41	162.12	25	1.67	1.67
4500	67.08	120.41	162.17	25	1.67	1.67
5400	73.48	120.41	162.23	25	1.67	1.67
6300	79.37	120.41	162.26	25	1.67	1.67
7200	84.85	120.41	162.30	25	1.68	1.67
10800	103.92	120.41	162.40	25	1.68	1.68
14400	120.00	120.41	162.42	25	1.68	1.68
18000	134.16	120.41	162.53	25	1.68	1.68
21600	146.97	120.41	162.56	25	1.69	1.69
25200	158.75	120.41	162.61	25	1.69	1.69
28800	169.71	120.41	162.68	25	1.69	1.69
86400	293.94	120.41	163.04	25	1.71	1.70
172800	415.69	120.41	163.62	25	1.73	1.72
259200	509.12	120.41	164.08	25	1.75	1.74
345600	587.88	120.41	164.53	25	1.76	1.76
432000	657.27	120.41	165.08	25	1.79	1.78
518400	720.00	120.41	165.69	25	1.81	1.80

APPENDIX F – CAPILLARY WATER ABSORPTION DATA

CAPILLARY WATER ABSORPTION MEASUREMENTS FOR SAMPLE B2						
CUMULATIVE TIME (S)	SQUARE ROOT TIME ($S^{0.5}$)	DRY WEIGHT, M_O (G)	WEIGHT OF SAMPLE, M_I (G)	SURFACE AREA (CM^2)	WATER ABSORBED/ UNIT SURFACE, M_I (G/CM^2)	AVERAGE M_I
0	0.00	118.36	118.36	25	0.00	0.00
300	17.32	118.36	132.98	25	0.58	0.29
600	24.49	118.36	141.28	25	0.92	0.75
900	30.00	118.36	147.28	25	1.16	1.04
1200	34.64	118.36	152.30	25	1.36	1.26
1500	38.73	118.36	156.46	25	1.52	1.44
1800	42.43	118.36	159.20	25	1.63	1.58
2100	45.83	118.36	159.71	25	1.65	1.64
2400	48.99	118.36	159.81	25	1.66	1.66
2700	51.96	118.36	159.90	25	1.66	1.66
3000	54.77	118.36	159.93	25	1.66	1.66
3300	57.45	118.36	159.99	25	1.67	1.66
3600	60.00	118.36	160.06	25	1.67	1.67
4500	67.08	118.36	160.11	25	1.67	1.67
5400	73.48	118.36	160.18	25	1.67	1.67
6300	79.37	118.36	160.21	25	1.67	1.67
7200	84.85	118.36	160.24	25	1.68	1.67
10800	103.92	118.36	160.33	25	1.68	1.68
14400	120.00	118.36	160.38	25	1.68	1.68
18000	134.16	118.36	160.47	25	1.68	1.68
21600	146.97	118.36	160.49	25	1.69	1.68
25200	158.75	118.36	160.58	25	1.69	1.69
28800	169.71	118.36	160.63	25	1.69	1.69
86400	293.94	118.36	161.01	25	1.71	1.70
172800	415.69	118.36	161.61	25	1.73	1.72
259200	509.12	118.36	162.10	25	1.75	1.74
345600	587.88	118.36	162.54	25	1.77	1.76
432000	657.27	118.36	163.09	25	1.79	1.78
518400	720.00	118.36	163.69	25	1.81	1.80

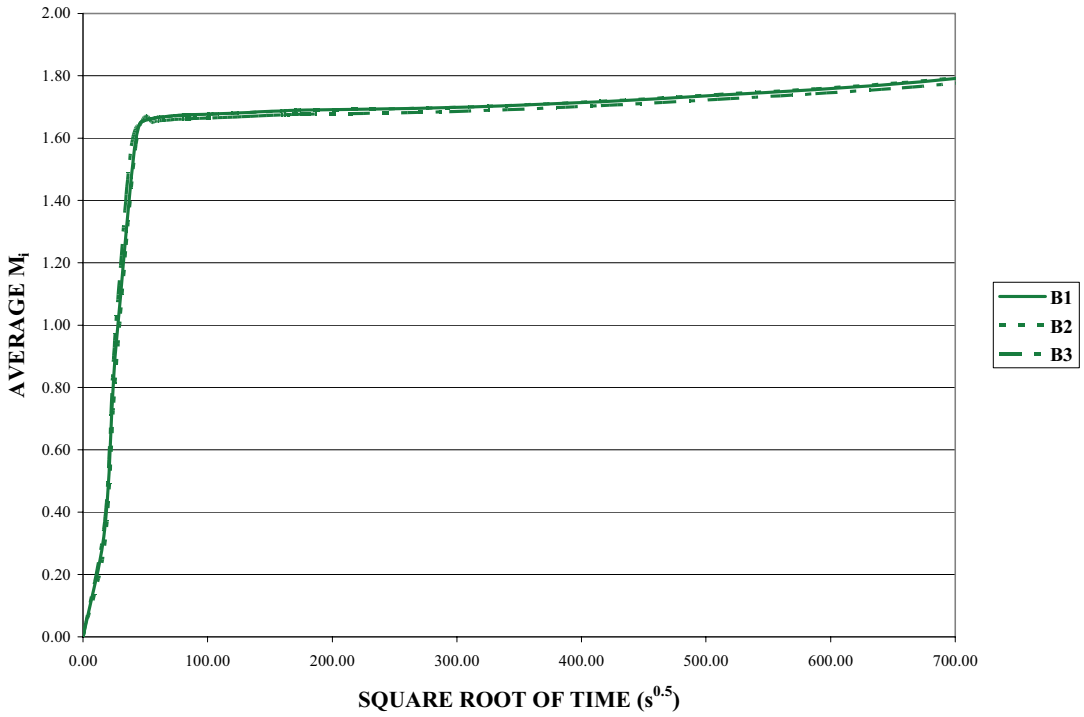
APPENDIX F – CAPILLARY WATER ABSORPTION DATA

CAPILLARY WATER ABSORPTION MEASUREMENTS FOR SAMPLE B3						
CUMULATIVE TIME (S)	SQUARE ROOT TIME ($S^{0.5}$)	DRY WEIGHT, M_O (G)	WEIGHT OF SAMPLE, M_I (G)	SURFACE AREA (CM^2)	WATER ABSORBED/ UNIT SURFACE, M_I (G/CM^2)	AVERAGE M_I
0	0.00	117.77	117.77	25	0.00	0.00
300	17.32	117.77	136.31	25	0.74	0.37
600	24.49	117.77	144.40	25	1.07	0.90
900	30.00	117.77	150.65	25	1.32	1.19
1200	34.64	117.77	155.85	25	1.52	1.42
1500	38.73	117.77	158.44	25	1.63	1.58
1800	42.43	117.77	158.78	25	1.64	1.63
2100	45.83	117.77	158.92	25	1.65	1.64
2400	48.99	117.77	159.97	25	1.69	1.67
2700	51.96	117.77	159.02	25	1.65	1.67
3000	54.77	117.77	159.07	25	1.65	1.65
3300	57.45	117.77	159.12	25	1.65	1.65
3600	60.00	117.77	159.19	25	1.66	1.66
4500	67.08	117.77	159.23	25	1.66	1.66
5400	73.48	117.77	159.29	25	1.66	1.66
6300	79.37	117.77	159.31	25	1.66	1.66
7200	84.85	117.77	159.36	25	1.66	1.66
10800	103.92	117.77	159.43	25	1.67	1.67
14400	120.00	117.77	159.47	25	1.67	1.67
18000	134.16	117.77	159.56	25	1.67	1.67
21600	146.97	117.77	159.59	25	1.67	1.67
25200	158.75	117.77	159.66	25	1.68	1.67
28800	169.71	117.77	159.70	25	1.68	1.68
86400	293.94	117.77	160.10	25	1.69	1.69
172800	415.69	117.77	160.65	25	1.72	1.70
259200	509.12	117.77	161.11	25	1.73	1.72
345600	587.88	117.77	161.55	25	1.75	1.74
432000	657.27	117.77	162.06	25	1.77	1.76
518400	720.00	117.77	162.64	25	1.79	1.78

APPENDIX F – CAPILLARY WATER ABSORPTION DATA

SAMPLE KEY	
A	2 NHL / 1 S / 1 MS / 0% ER
B	2 NHL / 1 S / 1 MS / 5% ER
C	2 NHL / 1 S / 1 MS / 10% ER

CAPILLARY WATER ABSORPTION CURVES – FORMULATION B



APPENDIX F – CAPILLARY WATER ABSORPTION DATA

CAPILLARY WATER ABSORPTION MEASUREMENTS FOR SAMPLE C1						
CUMULATIVE TIME (S)	SQUARE ROOT TIME ($S^{0.5}$)	DRY WEIGHT, M_O (G)	WEIGHT OF SAMPLE, M_I (G)	SURFACE AREA (CM^2)	WATER ABSORBED/ UNIT SURFACE, M_I (G/CM^2)	AVERAGE M_I
0	0.00	119.57	119.57	25	0.00	0.00
300	17.32	119.57	127.86	25	0.33	0.17
600	24.49	119.57	133.28	25	0.55	0.44
900	30.00	119.57	137.60	25	0.72	0.63
1200	34.64	119.57	140.96	25	0.86	0.79
1500	38.73	119.57	144.12	25	0.98	0.92
1800	42.43	119.57	146.82	25	1.09	1.04
2100	45.83	119.57	150.06	25	1.22	1.15
2400	48.99	119.57	151.80	25	1.29	1.25
2700	51.96	119.57	154.86	25	1.41	1.35
3000	54.77	119.57	156.14	25	1.46	1.44
3300	57.45	119.57	157.92	25	1.53	1.50
3600	60.00	119.57	158.73	25	1.57	1.55
4500	67.08	119.57	159.08	25	1.58	1.57
5400	73.48	119.57	159.15	25	1.58	1.58
6300	79.37	119.57	159.25	25	1.59	1.59
7200	84.85	119.57	159.29	25	1.59	1.59
10800	103.92	119.57	159.34	25	1.59	1.59
14400	120.00	119.57	159.40	25	1.59	1.59
18000	134.16	119.57	159.45	25	1.60	1.59
21600	146.97	119.57	159.49	25	1.60	1.60
25200	158.75	119.57	159.54	25	1.60	1.60
28800	169.71	119.57	159.61	25	1.60	1.60
86400	293.94	119.57	159.69	25	1.60	1.60
172800	415.69	119.57	160.70	25	1.65	1.63
259200	509.12	119.57	160.71	25	1.65	1.65
345600	587.88	119.57	161.18	25	1.66	1.66
432000	657.27	119.57	161.65	25	1.68	1.67
518400	720.00	119.57	162.43	25	1.71	1.70

APPENDIX F – CAPILLARY WATER ABSORPTION DATA

CAPILLARY WATER ABSORPTION MEASUREMENTS FOR SAMPLE C2						
CUMULATIVE TIME (S)	SQUARE ROOT TIME ($S^{0.5}$)	DRY WEIGHT, M_O (G)	WEIGHT OF SAMPLE, M_I (G)	SURFACE AREA (CM^2)	WATER ABSORBED/ UNIT SURFACE, M_I (G/CM^2)	AVERAGE M_I
0	0.00	118.51	118.51	25	0.00	0.00
300	17.32	118.51	126.94	25	0.34	0.17
600	24.49	118.51	132.57	25	0.56	0.45
900	30.00	118.51	137.29	25	0.75	0.66
1200	34.64	118.51	140.76	25	0.89	0.82
1500	38.73	118.51	143.98	25	1.02	0.95
1800	42.43	118.51	146.76	25	1.13	1.07
2100	45.83	118.51	149.99	25	1.26	1.19
2400	48.99	118.51	151.77	25	1.33	1.29
2700	51.96	118.51	154.82	25	1.45	1.39
3000	54.77	118.51	155.92	25	1.50	1.47
3300	57.45	118.51	157.22	25	1.55	1.52
3600	60.00	118.51	157.53	25	1.56	1.55
4500	67.08	118.51	157.77	25	1.57	1.57
5400	73.48	118.51	157.84	25	1.57	1.57
6300	79.37	118.51	157.89	25	1.58	1.57
7200	84.85	118.51	157.92	25	1.58	1.58
10800	103.92	118.51	158.05	25	1.58	1.58
14400	120.00	118.51	158.09	25	1.58	1.58
18000	134.16	118.51	158.12	25	1.58	1.58
21600	146.97	118.51	158.13	25	1.58	1.58
25200	158.75	118.51	158.20	25	1.59	1.59
28800	169.71	118.51	158.24	25	1.59	1.59
86400	293.94	118.51	158.88	25	1.61	1.60
172800	415.69	118.51	158.98	25	1.62	1.62
259200	509.12	118.51	159.38	25	1.63	1.63
345600	587.88	118.51	159.85	25	1.65	1.64
432000	657.27	118.51	160.32	25	1.67	1.66
518400	720.00	118.51	161.11	25	1.70	1.69

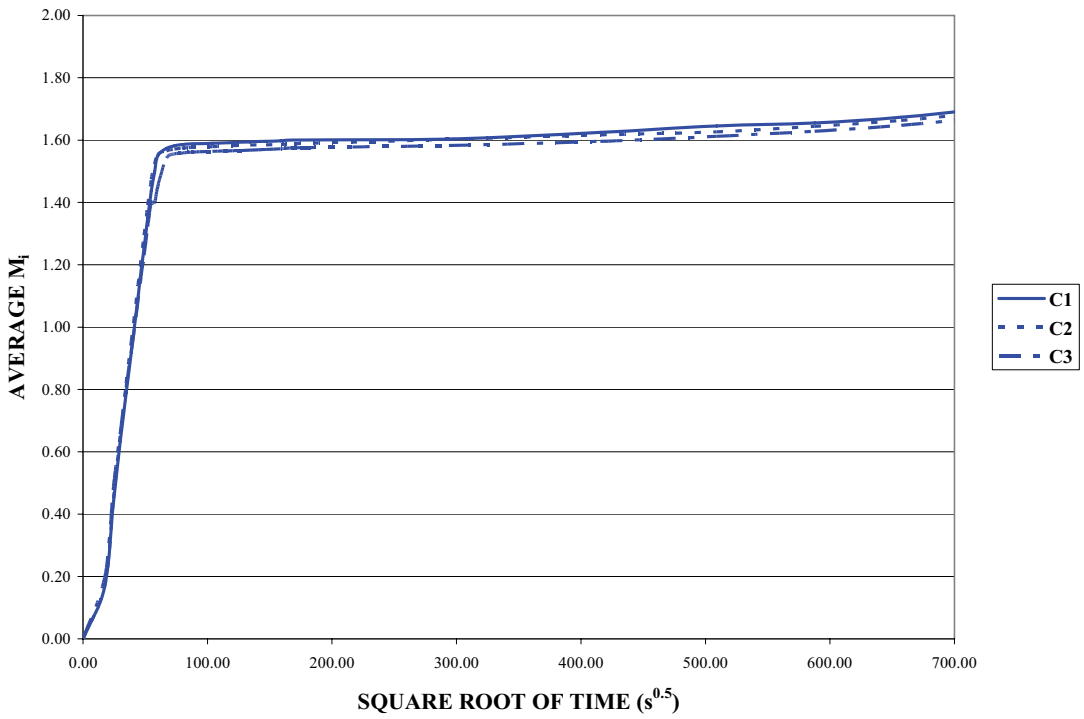
APPENDIX F – CAPILLARY WATER ABSORPTION DATA

CAPILLARY WATER ABSORPTION MEASUREMENTS FOR SAMPLE C3						
CUMULATIVE TIME (S)	SQUARE ROOT TIME ($S^{0.5}$)	DRY WEIGHT, M_O (G)	WEIGHT OF SAMPLE, M_I (G)	SURFACE AREA (CM^2)	WATER ABSORBED/ UNIT SURFACE, M_I (G/CM^2)	AVERAGE M_I
0	0.00	118.85	118.85	25	0.00	0.00
300	17.32	118.85	128.66	25	0.39	0.20
600	24.49	118.85	133.42	25	0.58	0.49
900	30.00	118.85	137.52	25	0.75	0.66
1200	34.64	118.85	140.51	25	0.87	0.81
1500	38.73	118.85	143.39	25	0.98	0.92
1800	42.43	118.85	145.89	25	1.08	1.03
2100	45.83	118.85	148.77	25	1.20	1.14
2400	48.99	118.85	150.46	25	1.26	1.23
2700	51.96	118.85	153.37	25	1.38	1.32
3000	54.77	118.85	154.43	25	1.42	1.40
3300	57.45	118.85	153.13	25	1.37	1.40
3600	60.00	118.85	157.15	25	1.53	1.45
4500	67.08	118.85	157.70	25	1.55	1.54
5400	73.48	118.85	157.78	25	1.56	1.56
6300	79.37	118.85	157.85	25	1.56	1.56
7200	84.85	118.85	157.90	25	1.56	1.56
10800	103.92	118.85	157.99	25	1.57	1.56
14400	120.00	118.85	158.01	25	1.57	1.57
18000	134.16	118.85	158.09	25	1.57	1.57
21600	146.97	118.85	158.12	25	1.57	1.57
25200	158.75	118.85	158.18	25	1.57	1.57
28800	169.71	118.85	158.29	25	1.58	1.58
86400	293.94	118.85	158.55	25	1.59	1.58
172800	415.69	118.85	158.96	25	1.60	1.60
259200	509.12	118.85	159.34	25	1.62	1.61
345600	587.88	118.85	159.80	25	1.64	1.63
432000	657.27	118.85	160.27	25	1.66	1.65
518400	720.00	118.85	161.05	25	1.69	1.67

APPENDIX F – CAPILLARY WATER ABSORPTION DATA

SAMPLE KEY	
A	2 NHL / 1 S / 1 MS / 0% ER
B	2 NHL / 1 S / 1 MS / 5% ER
C	2 NHL / 1 S / 1 MS / 10% ER

CAPILLARY WATER ABSORPTION CURVES – FORMULATION C



APPENDIX G – WATER ABSORPTION DATA

WATER ABSORPTION MEASUREMENTS FOR SAMPLE A1					
TIME (HOURS)	WEIGHT (G)	DIFFERENCE IN SUCCESSIVE WEIGHINGS (G)	CHANGE IN WEIGHT FROM INITIAL WEIGHT (G)	AMOUNT OF WATER ABSORBED (%)	AVERAGE WATER ABSORBED (%)
0.00	120.98	0.00	0.00	0.00	0.00
0.08	163.44	42.46	42.46	35.10	17.55
0.17	163.72	0.28	42.74	35.33	35.21
0.25	163.85	0.13	42.87	35.44	35.38
0.33	164.01	0.16	43.03	35.57	35.50
0.42	164.03	0.02	43.05	35.58	35.58
0.50	164.04	0.01	43.06	35.59	35.59
0.58	164.04	0.00	43.06	35.59	35.59
0.67	164.05	0.01	43.07	35.60	35.60
0.75	164.08	0.03	43.10	35.63	35.61
0.83	164.12	0.04	43.14	35.66	35.64
0.92	164.13	0.01	43.15	35.67	35.66
1.00	164.16	0.03	43.18	35.69	35.68
1.25	164.20	0.04	43.22	35.72	35.71
1.50	164.27	0.07	43.29	35.78	35.75
1.75	164.29	0.02	43.31	35.80	35.79
2.00	164.37	0.08	43.39	35.87	35.83
3.00	164.52	0.15	43.54	35.99	35.93
4.00	164.58	0.06	43.60	36.04	36.01
5.00	164.65	0.07	43.67	36.10	36.07
6.00	164.73	0.08	43.75	36.16	36.13
7.00	164.77	0.04	43.79	36.20	36.18
8.00	164.84	0.07	43.86	36.25	36.22
24.0	165.56	0.72	44.58	36.85	36.55
48.0	166.25	0.69	45.27	37.42	37.13
72.0	167.04	0.79	46.06	38.07	37.75
96.0	167.54	0.50	46.56	38.49	38.28
120.0	168.04	0.50	47.06	38.90	38.69
144.0	168.51	0.47	47.53	39.29	39.09
168.0	168.92	0.41	47.94	39.63	39.46

APPENDIX G – WATER ABSORPTION DATA

WATER ABSORPTION MEASUREMENTS FOR SAMPLE A2					
TIME (HOURS)	WEIGHT (G)	DIFFERENCE IN SUCCESSIVE WEIGHINGS (G)	CHANGE IN WEIGHT FROM INITIAL WEIGHT (G)	AMOUNT OF WATER ABSORBED (%)	AVERAGE WATER ABSORBED (%)
0.00	123.36	0.00	0.00	0.00	0.00
0.08	167.29	43.93	43.93	35.61	17.81
0.17	167.60	0.31	44.24	35.86	35.74
0.25	167.79	0.19	44.43	36.02	35.94
0.33	168.06	0.27	44.70	36.24	36.13
0.42	168.08	0.02	44.72	36.25	36.24
0.50	168.10	0.02	44.74	36.27	36.26
0.58	168.10	0.00	44.74	36.27	36.27
0.67	168.10	0.00	44.74	36.27	36.27
0.75	168.11	0.01	44.75	36.28	36.27
0.83	168.14	0.03	44.78	36.30	36.29
0.92	168.18	0.04	44.82	36.33	36.32
1.00	168.22	0.04	44.86	36.37	36.35
1.25	168.22	0.00	44.86	36.37	36.37
1.50	168.26	0.04	44.90	36.40	36.38
1.75	168.26	0.00	44.90	36.40	36.40
2.00	168.43	0.17	45.07	36.54	36.47
3.00	168.52	0.09	45.16	36.61	36.57
4.00	168.60	0.08	45.24	36.67	36.64
5.00	168.63	0.03	45.27	36.70	36.69
6.00	168.74	0.11	45.38	36.79	36.74
7.00	168.77	0.03	45.41	36.81	36.80
8.00	168.86	0.09	45.50	36.88	36.85
24.0	169.52	0.66	46.16	37.42	37.15
48.0	170.21	0.69	46.85	37.98	37.70
72.0	171.10	0.89	47.74	38.70	38.34
96.0	171.56	0.46	48.20	39.07	38.89
120.0	172.07	0.51	48.71	39.49	39.28
144.0	172.6	0.53	49.24	39.92	39.70
168.0	172.95	0.35	49.59	40.20	40.06

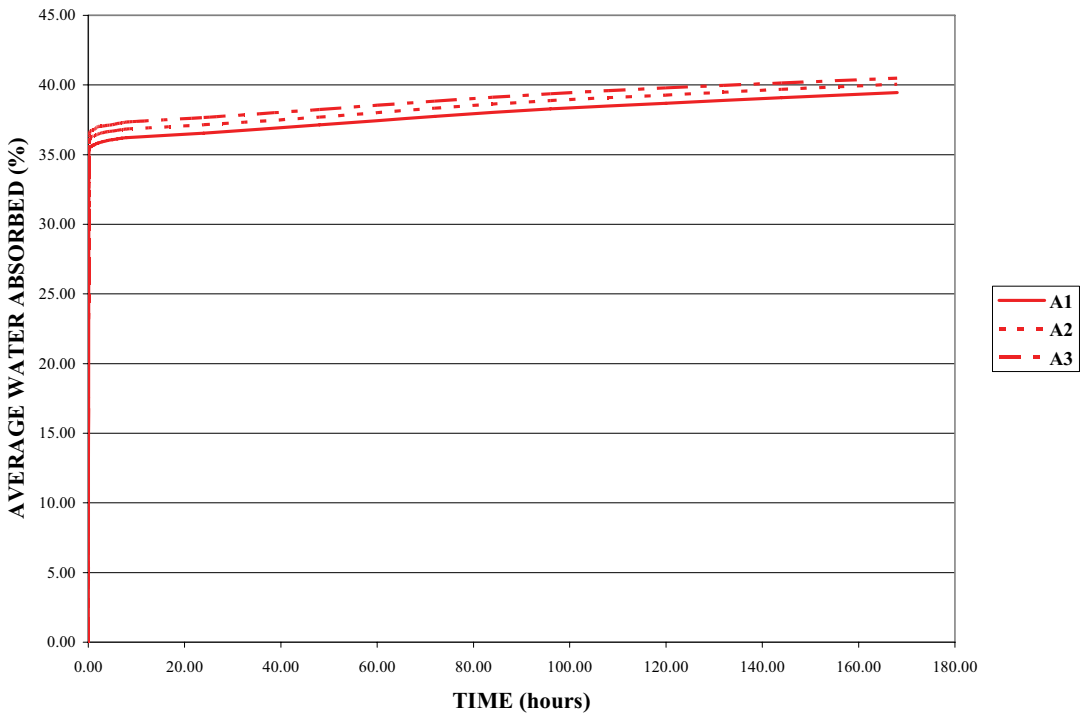
APPENDIX G – WATER ABSORPTION DATA

WATER ABSORPTION MEASUREMENTS FOR SAMPLE A3					
TIME (HOURS)	WEIGHT (G)	DIFFERENCE IN SUCCESSIVE WEIGHINGS (G)	CHANGE IN WEIGHT FROM INITIAL WEIGHT (G)	AMOUNT OF WATER ABSORBED (%)	AVERAGE WATER ABSORBED (%)
0.00	122.77	0.00	0.00	0.00	0.00
0.08	167.17	44.40	44.40	36.17	18.08
0.17	167.41	0.24	44.64	36.36	36.26
0.25	167.64	0.23	44.87	36.55	36.45
0.33	167.82	0.18	45.05	36.69	36.62
0.42	167.85	0.03	45.08	36.72	36.71
0.50	167.85	0.00	45.08	36.72	36.72
0.58	167.85	0.00	45.08	36.72	36.72
0.67	167.89	0.04	45.12	36.75	36.74
0.75	167.90	0.01	45.13	36.76	36.76
0.83	167.93	0.03	45.16	36.78	36.77
0.92	167.93	0.00	45.16	36.78	36.78
1.00	167.94	0.01	45.17	36.79	36.79
1.25	167.96	0.02	45.19	36.81	36.80
1.50	168.06	0.10	45.29	36.89	36.85
1.75	168.20	0.14	45.43	37.00	36.95
2.00	168.20	0.00	45.43	37.00	37.00
3.00	168.32	0.12	45.55	37.10	37.05
4.00	168.33	0.01	45.56	37.11	37.11
5.00	168.44	0.11	45.67	37.20	37.15
6.00	168.53	0.09	45.76	37.27	37.24
7.00	168.55	0.02	45.78	37.29	37.28
8.00	168.68	0.13	45.91	37.40	37.34
24.0	169.35	0.67	46.58	37.94	37.67
48.0	170.08	0.73	47.31	38.54	38.24
72.0	170.83	0.75	48.06	39.15	38.84
96.0	171.39	0.56	48.62	39.60	39.37
120.0	171.87	0.48	49.10	39.99	39.80
144.0	172.25	0.38	49.48	40.30	40.15
168.0	172.71	0.46	49.94	40.68	40.49

APPENDIX G – WATER ABSORPTION DATA

SAMPLE KEY	
A	2 NHL / 1 S / 1 MS / 0% ER
B	2 NHL / 1 S / 1 MS / 5% ER
C	2 NHL / 1 S / 1 MS / 10% ER

WATER ABSORPTION CURVES FOR SAMPLE GROUP A



APPENDIX G – WATER ABSORPTION DATA

WATER ABSORPTION MEASUREMENTS FOR SAMPLE B1					
TIME (HOURS)	WEIGHT (G)	DIFFERENCE IN SUCCESSIVE WEIGHINGS (G)	CHANGE IN WEIGHT FROM INITIAL WEIGHT (G)	AMOUNT OF WATER ABSORBED (%)	AVERAGE WATER ABSORBED (%)
0.00	120.49	0.00	0.00	0.00	0.00
0.08	151.20	30.71	30.71	25.49	12.74
0.17	159.13	7.93	38.64	32.07	28.78
0.25	160.34	1.21	39.85	33.07	32.57
0.33	160.61	0.27	40.12	33.30	33.19
0.42	160.75	0.14	40.26	33.41	33.36
0.50	160.94	0.19	40.45	33.57	33.49
0.58	160.98	0.04	40.49	33.60	33.59
0.67	161.01	0.03	40.52	33.63	33.62
0.75	161.11	0.10	40.62	33.71	33.67
0.83	161.12	0.01	40.63	33.72	33.72
0.92	161.16	0.04	40.67	33.75	33.74
1.00	161.20	0.04	40.71	33.79	33.77
1.25	161.22	0.02	40.73	33.80	33.80
1.50	161.23	0.01	40.74	33.81	33.81
1.75	161.33	0.10	40.84	33.89	33.85
2.00	161.41	0.08	40.92	33.96	33.93
3.00	161.50	0.09	41.01	34.04	34.00
4.00	161.58	0.08	41.09	34.10	34.07
5.00	161.59	0.01	41.10	34.11	34.11
6.00	161.72	0.13	41.23	34.22	34.16
7.00	161.73	0.01	41.24	34.23	34.22
8.00	161.81	0.08	41.32	34.29	34.26
24.0	162.33	0.52	41.84	34.72	34.51
48.0	162.87	0.54	42.38	35.17	34.95
72.0	163.63	0.76	43.14	35.80	35.49
96.0	164.13	0.50	43.64	36.22	36.01
120.0	164.74	0.61	44.25	36.73	36.47
144.0	164.98	0.24	44.49	36.92	36.82
168.0	165.33	0.35	44.84	37.21	37.07

APPENDIX G – WATER ABSORPTION DATA

WATER ABSORPTION MEASUREMENTS FOR SAMPLE B2					
TIME (HOURS)	WEIGHT (G)	DIFFERENCE IN SUCCESSIVE WEIGHINGS (G)	CHANGE IN WEIGHT FROM INITIAL WEIGHT (G)	AMOUNT OF WATER ABSORBED (%)	AVERAGE WATER ABSORBED (%)
0.00	118.45	0.00	0.00	0.00	0.00
0.08	150.71	32.26	32.26	27.24	13.62
0.17	158.72	8.01	40.27	34.00	30.62
0.25	158.89	0.17	40.44	34.14	34.07
0.33	158.96	0.07	40.51	34.20	34.17
0.42	159.03	0.07	40.58	34.26	34.23
0.50	159.09	0.06	40.64	34.31	34.28
0.58	159.09	0.00	40.64	34.31	34.31
0.67	159.10	0.01	40.65	34.32	34.31
0.75	159.17	0.07	40.72	34.38	34.35
0.83	159.17	0.00	40.72	34.38	34.38
0.92	159.20	0.03	40.75	34.40	34.39
1.00	159.22	0.02	40.77	34.42	34.41
1.25	159.30	0.08	40.85	34.49	34.45
1.50	159.30	0.00	40.85	34.49	34.49
1.75	159.35	0.05	40.90	34.53	34.51
2.00	159.35	0.00	40.90	34.53	34.53
3.00	159.46	0.11	41.01	34.62	34.58
4.00	159.48	0.02	41.03	34.64	34.63
5.00	159.48	0.00	41.03	34.64	34.64
6.00	159.56	0.08	41.11	34.71	34.67
7.00	159.63	0.07	41.18	34.77	34.74
8.00	159.79	0.16	41.34	34.90	34.83
24.0	160.17	0.38	41.72	35.22	35.06
48.0	160.60	0.43	42.15	35.58	35.40
72.0	161.42	0.82	42.97	36.28	35.93
96.0	161.94	0.52	43.49	36.72	36.50
120.0	162.43	0.49	43.98	37.13	36.92
144.0	162.74	0.31	44.29	37.39	37.26
168.0	163.17	0.43	44.72	37.75	37.57

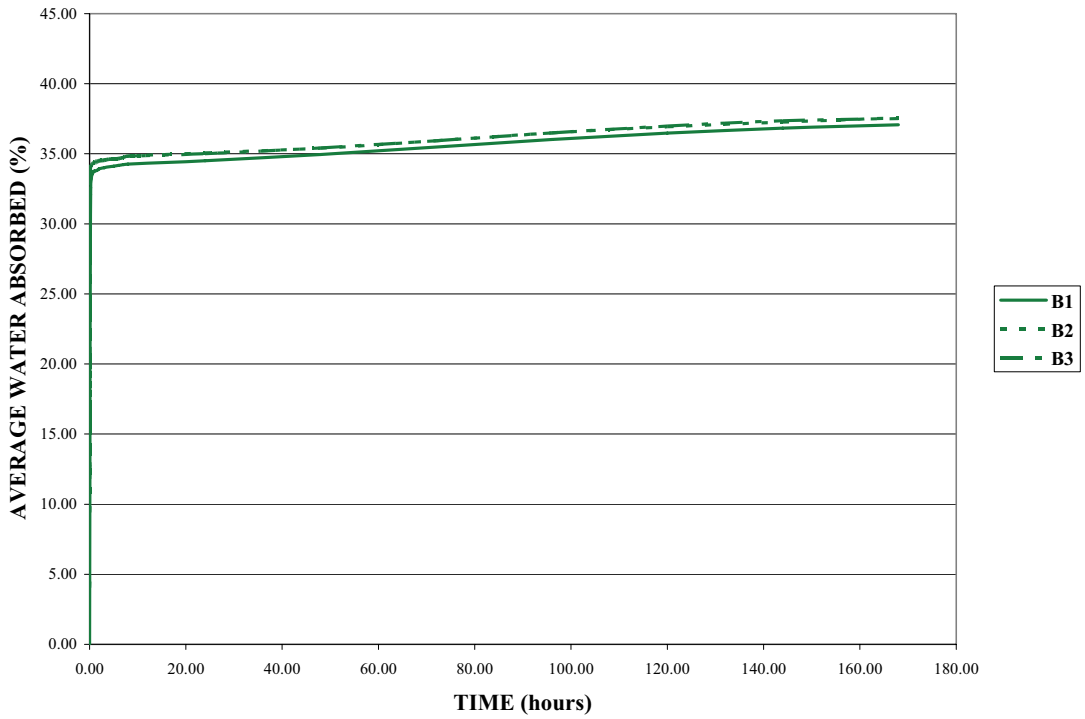
APPENDIX G – WATER ABSORPTION DATA

WATER ABSORPTION MEASUREMENTS FOR SAMPLE B3					
TIME (HOURS)	WEIGHT (G)	DIFFERENCE IN SUCCESSIVE WEIGHINGS (G)	CHANGE IN WEIGHT FROM INITIAL WEIGHT (G)	AMOUNT OF WATER ABSORBED (%)	AVERAGE WATER ABSORBED (%)
0.00	117.97	0.00	0.00	0.00	0.00
0.08	155.34	37.37	37.37	31.68	15.84
0.17	158.01	2.67	40.04	33.94	32.81
0.25	158.15	0.14	40.18	34.06	34.00
0.33	158.21	0.06	40.24	34.11	34.08
0.42	158.28	0.07	40.31	34.17	34.14
0.50	158.36	0.08	40.39	34.24	34.20
0.58	158.36	0.00	40.39	34.24	34.24
0.67	158.44	0.08	40.47	34.31	34.27
0.75	158.45	0.01	40.48	34.31	34.31
0.83	158.45	0.00	40.48	34.31	34.31
0.92	158.45	0.00	40.48	34.31	34.31
1.00	158.48	0.03	40.51	34.34	34.33
1.25	158.48	0.00	40.51	34.34	34.34
1.50	158.56	0.08	40.59	34.41	34.37
1.75	158.62	0.06	40.65	34.46	34.43
2.00	158.62	0.00	40.65	34.46	34.46
3.00	158.75	0.13	40.78	34.57	34.51
4.00	158.78	0.03	40.81	34.59	34.58
5.00	158.81	0.03	40.84	34.62	34.61
6.00	158.81	0.00	40.84	34.62	34.62
7.00	159.05	0.24	41.08	34.82	34.72
8.00	159.07	0.02	41.10	34.84	34.83
24.0	159.48	0.41	41.51	35.19	35.01
48.0	160.01	0.53	42.04	35.64	35.41
72.0	160.71	0.70	42.74	36.23	35.93
96.0	161.33	0.62	43.36	36.76	36.49
120.0	161.85	0.52	43.88	37.20	36.98
144.0	162.22	0.37	44.25	37.51	37.35
168.0	162.23	0.01	44.26	37.52	37.51

APPENDIX G – WATER ABSORPTION DATA

SAMPLE KEY	
A	2 NHL / 1 S / 1 MS / 0% ER
B	2 NHL / 1 S / 1 MS / 5% ER
C	2 NHL / 1 S / 1 MS / 10% ER

WATER ABSORPTION CURVES FOR SAMPLE GROUP B



APPENDIX G – WATER ABSORPTION DATA

WATER ABSORPTION MEASUREMENTS FOR SAMPLE C1					
TIME (HOURS)	WEIGHT (G)	DIFFERENCE IN SUCCESSIVE WEIGHINGS (G)	CHANGE IN WEIGHT FROM INITIAL WEIGHT (G)	AMOUNT OF WATER ABSORBED (%)	AVERAGE WATER ABSORBED (%)
0.00	119.47	0.00	0.00	0.00	0.00
0.08	134.54	15.07	15.07	12.61	6.31
0.17	138.96	4.42	19.49	16.31	14.46
0.25	142.96	4.00	23.49	19.66	17.99
0.33	145.10	2.14	25.63	21.45	20.56
0.42	147.19	2.09	27.72	23.20	22.33
0.50	148.63	1.44	29.16	24.41	23.81
0.58	149.89	1.26	30.42	25.46	24.94
0.67	151.38	1.49	31.91	26.71	26.09
0.75	152.65	1.27	33.18	27.77	27.24
0.83	153.61	0.96	34.14	28.58	28.17
0.92	154.04	0.43	34.57	28.94	28.76
1.00	154.77	0.73	35.30	29.55	29.24
1.25	156.16	1.39	36.69	30.71	30.13
1.50	156.58	0.42	37.11	31.06	30.89
1.75	156.91	0.33	37.44	31.34	31.20
2.00	157.26	0.35	37.79	31.63	31.48
3.00	157.74	0.48	38.27	32.03	31.83
4.00	158.01	0.27	38.54	32.26	32.15
5.00	158.23	0.22	38.76	32.44	32.35
6.00	158.32	0.09	38.85	32.52	32.48
7.00	158.51	0.19	39.04	32.68	32.60
8.00	158.55	0.04	39.08	32.71	32.69
24.0	159.21	0.66	39.74	33.26	32.99
48.0	159.69	0.48	40.22	33.67	33.46
72.0	160.35	0.66	40.88	34.22	33.94
96.0	160.71	0.36	41.24	34.52	34.37
120.0	161.07	0.36	41.60	34.82	34.67
144.0	161.42	0.35	41.95	35.11	34.97
168.0	161.72	0.30	42.25	35.36	35.24

APPENDIX G – WATER ABSORPTION DATA

WATER ABSORPTION MEASUREMENTS FOR SAMPLE C2					
TIME (HOURS)	WEIGHT (G)	DIFFERENCE IN SUCCESSIVE WEIGHINGS (G)	CHANGE IN WEIGHT FROM INITIAL WEIGHT (G)	AMOUNT OF WATER ABSORBED (%)	AVERAGE WATER ABSORBED (%)
0.00	118.45	0.00	0.00	0.00	0.00
0.08	132.24	13.79	13.79	11.64	5.82
0.17	136.67	4.43	18.22	15.38	13.51
0.25	141.35	4.68	22.90	19.33	17.36
0.33	144.65	3.30	26.20	22.12	20.73
0.42	147.24	2.59	28.79	24.31	23.21
0.50	148.80	1.56	30.35	25.62	24.96
0.58	150.41	1.61	31.96	26.98	26.30
0.67	152.19	1.78	33.74	28.48	27.73
0.75	153.56	1.37	35.11	29.64	29.06
0.83	154.71	1.15	36.26	30.61	30.13
0.92	155.01	0.30	36.56	30.87	30.74
1.00	155.73	0.72	37.28	31.47	31.17
1.25	156.52	0.79	38.07	32.14	31.81
1.50	156.85	0.33	38.40	32.42	32.28
1.75	157.11	0.26	38.66	32.64	32.53
2.00	157.31	0.20	38.86	32.81	32.72
3.00	157.46	0.15	39.01	32.93	32.87
4.00	157.63	0.17	39.18	33.08	33.01
5.00	157.74	0.11	39.29	33.17	33.12
6.00	157.96	0.22	39.51	33.36	33.26
7.00	157.98	0.02	39.53	33.37	33.36
8.00	157.99	0.01	39.54	33.38	33.38
24.0	158.40	0.41	39.95	33.73	33.55
48.0	158.66	0.26	40.21	33.95	33.84
72.0	159.18	0.52	40.73	34.39	34.17
96.0	159.58	0.40	41.13	34.72	34.55
120.0	160.05	0.47	41.60	35.12	34.92
144.0	160.36	0.31	41.91	35.38	35.25
168.0	160.65	0.29	42.20	35.63	35.50

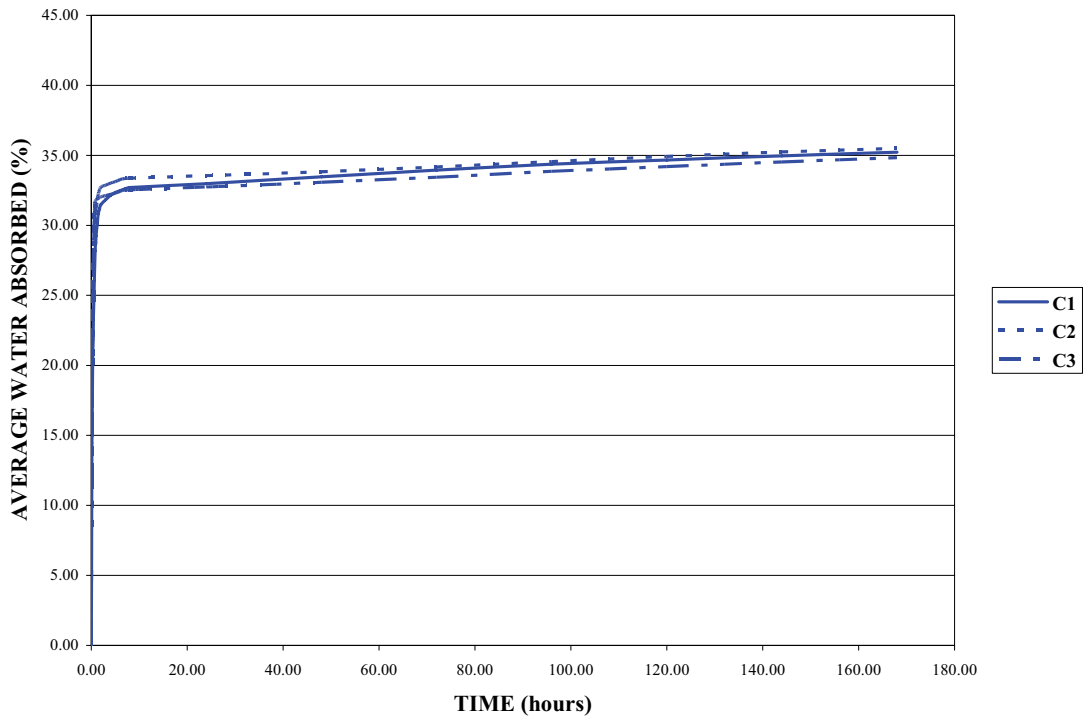
APPENDIX G – WATER ABSORPTION DATA

WATER ABSORPTION MEASUREMENTS FOR SAMPLE C3					
TIME (HOURS)	WEIGHT (G)	DIFFERENCE IN SUCCESSIVE WEIGHINGS (G)	CHANGE IN WEIGHT FROM INITIAL WEIGHT (G)	AMOUNT OF WATER ABSORBED (%)	AVERAGE WATER ABSORBED (%)
0.00	118.88	0.00	0.00	0.00	0.00
0.08	136.66	17.78	17.78	14.96	7.48
0.17	141.45	4.79	22.57	18.99	16.97
0.25	146.45	5.00	27.57	23.19	21.09
0.33	149.57	3.12	30.69	25.82	24.50
0.42	151.93	2.36	33.05	27.80	26.81
0.50	153.73	1.80	34.85	29.32	28.56
0.58	154.73	1.00	35.85	30.16	29.74
0.67	155.93	1.20	37.05	31.17	30.66
0.75	156.50	0.57	37.62	31.65	31.41
0.83	156.60	0.10	37.72	31.73	31.69
0.92	156.68	0.08	37.80	31.80	31.76
1.00	156.77	0.09	37.89	31.87	31.83
1.25	156.83	0.06	37.95	31.92	31.90
1.50	156.85	0.02	37.97	31.94	31.93
1.75	156.92	0.07	38.04	32.00	31.97
2.00	157.02	0.10	38.14	32.08	32.04
3.00	157.11	0.09	38.23	32.16	32.12
4.00	157.23	0.12	38.35	32.26	32.21
5.00	157.30	0.07	38.42	32.32	32.29
6.00	157.54	0.24	38.66	32.52	32.42
7.00	157.56	0.02	38.68	32.54	32.53
8.00	157.57	0.01	38.69	32.55	32.54
24.0	158.05	0.48	39.17	32.95	32.75
48.0	158.35	0.30	39.47	33.20	33.08
72.0	158.91	0.56	40.03	33.67	33.44
96.0	159.36	0.45	40.48	34.05	33.86
120.0	159.7	0.34	40.82	34.34	34.19
144.0	160.16	0.46	41.28	34.72	34.53
168.0	160.45	0.29	41.57	34.97	34.85

APPENDIX G – WATER ABSORPTION DATA

SAMPLE KEY	
A	2 NHL / 1 S / 1 MS / 0% ER
B	2 NHL / 1 S / 1 MS / 5% ER
C	2 NHL / 1 S / 1 MS / 10% ER

WATER ABSORPTION CURVES FOR SAMPLE GROUP C



APPENDIX H – DRYING INDEX DATA

DRYING MEASUREMENTS FOR SAMPLE A1										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, $\Delta Y/\Delta T$	MOISTURE CONTENT, Ψ (G/CM^3)
0.00	0.00	172.71	122.93	40.49	49.78	49.78	100.00	0.00	0.00	0.40
0.08	0.08	172.70	122.93	40.49	49.78	49.77	99.98	0.01	0.13	0.40
0.17	0.09	172.61	122.93	40.41	49.78	49.68	99.80	0.10	1.11	0.40
0.25	0.08	172.54	122.93	40.36	49.78	49.61	99.66	0.17	2.13	0.40
0.33	0.08	172.49	122.93	40.32	49.78	49.56	99.56	0.22	2.75	0.40
0.42	0.09	172.43	122.93	40.27	49.78	49.50	99.44	0.28	3.11	0.40
0.50	0.08	172.35	122.93	40.20	49.78	49.42	99.28	0.36	4.50	0.40
0.58	0.08	172.30	122.93	40.16	49.78	49.37	99.18	0.41	5.12	0.39
0.67	0.09	172.24	122.93	40.11	49.78	49.31	99.06	0.47	5.22	0.39
0.75	0.08	172.19	122.93	40.07	49.78	49.26	98.96	0.52	6.50	0.39
0.83	0.08	172.14	122.93	40.03	49.78	49.21	98.85	0.57	7.13	0.39
0.92	0.09	172.10	122.93	40.00	49.78	49.17	98.77	0.61	6.78	0.39
1.00	0.08	172.04	122.93	39.95	49.78	49.11	98.65	0.67	8.38	0.39
1.25	0.25	171.90	122.93	39.84	49.78	48.97	98.37	0.81	3.24	0.39
1.50	0.25	171.74	122.93	39.71	49.78	48.81	98.05	0.97	3.88	0.39
1.75	0.25	171.61	122.93	39.60	49.78	48.68	97.79	1.10	4.40	0.39
2.00	0.25	171.48	122.93	39.49	49.78	48.55	97.53	1.23	4.92	0.39
3.00	1.00	171.02	122.93	39.12	49.78	48.09	96.61	1.69	1.69	0.38
24.0	21.00	167.03	122.93	35.87	49.78	44.10	88.59	5.68	0.27	0.35
48.0	24.00	161.60	122.93	31.46	49.78	38.67	77.68	11.11	0.46	0.31
72.0	24.00	156.63	122.93	27.41	49.78	33.70	67.70	16.08	0.67	0.27
96.0	24.00	150.43	122.93	22.37	49.78	27.50	55.24	22.28	0.93	0.22

DRYING MEASUREMENTS FOR SAMPLE A1 – CONTINUED										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, $\Delta Y/\Delta T$	MOISTURE CONTENT, Ψ (G/CM^3)
120.0	24.00	143.07	122.93	16.38	49.78	20.14	40.46	29.64	1.24	0.16
144.0	24.00	139.96	122.93	13.85	49.78	17.03	34.21	32.75	1.36	0.14
168.0	24.00	137.17	122.93	11.58	49.78	14.24	28.61	35.54	1.48	0.11
192.0	24.00	135.82	122.93	10.49	49.78	12.89	25.89	36.89	1.54	0.10
216.0	24.00	134.20	122.93	9.17	49.78	11.27	22.64	38.51	1.60	0.09
240.0	24.00	133.27	122.93	8.41	49.78	10.34	20.77	39.44	1.64	0.08
264.0	24.00	131.00	122.93	6.56	49.78	8.07	16.21	41.71	1.74	0.06
288.0	24.00	130.56	122.93	6.21	49.78	7.63	15.33	42.15	1.76	0.06
312.0	24.00	129.09	122.93	5.01	49.78	6.16	12.37	43.62	1.82	0.05
336.0	24.00	128.30	122.93	4.37	49.78	5.37	10.79	44.41	1.85	0.04
360.0	24.00	127.69	122.93	3.87	49.78	4.76	9.56	45.02	1.88	0.04
384.0	24.00	127.35	122.93	3.60	49.78	4.42	8.88	45.36	1.89	0.04
408.0	24.00	127.06	122.93	3.36	49.78	4.13	8.30	45.65	1.90	0.03
432.0	24.00	126.45	122.93	2.86	49.78	3.52	7.07	46.26	1.93	0.03
456.0	24.00	123.19	122.93	0.21	49.78	0.26	0.52	49.52	2.06	0.00
480.0	24.00	123.17	122.93	0.20	49.78	0.24	0.48	49.54	2.06	0.00
504.0	24.00	123.16	122.93	0.19	49.78	0.23	0.46	49.55	2.06	0.00
528.0	24.00	123.15	122.93	0.18	49.78	0.22	0.44	49.56	2.07	0.00
552.0	24.00	123.12	122.93	0.15	49.78	0.19	0.38	49.59	2.07	0.00
576.0	24.00	123.00	122.93	0.06	49.78	0.07	0.14	49.71	2.07	0.00
600.0	24.00	122.93	122.93	0.00	49.78	0.00	0.00	49.78	2.07	0.00
SHADED MEASUREMENTS WERE TAKEN AFTER SAMPLE WAS PLACED IN THE OVEN.										

APPENDIX H – DRYING INDEX DATA

DRYING MEASUREMENTS FOR SAMPLE A2										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, $\Delta Y/\Delta T$	MOISTURE CONTENT, Ψ (G/CM^3)
0.00	0.00	172.95	123.53	40.01	49.42	49.42	100.00	0.00	0.00	0.40
0.08	0.08	172.91	123.53	39.97	49.42	49.38	99.92	0.04	0.50	0.40
0.17	0.09	172.84	123.53	39.92	49.42	49.31	99.78	0.11	1.22	0.39
0.25	0.08	172.76	123.53	39.85	49.42	49.23	99.62	0.19	2.37	0.39
0.33	0.08	172.73	123.53	39.83	49.42	49.20	99.55	0.22	2.75	0.39
0.42	0.09	172.66	123.53	39.77	49.42	49.13	99.41	0.29	3.22	0.39
0.50	0.08	172.59	123.53	39.72	49.42	49.06	99.27	0.36	4.50	0.39
0.58	0.08	172.55	123.53	39.68	49.42	49.02	99.19	0.40	5.00	0.39
0.67	0.09	172.48	123.53	39.63	49.42	48.95	99.05	0.47	5.22	0.39
0.75	0.08	172.44	123.53	39.59	49.42	48.91	98.97	0.51	6.37	0.39
0.83	0.08	172.39	123.53	39.55	49.42	48.86	98.87	0.56	7.00	0.39
0.92	0.09	172.35	123.53	39.52	49.42	48.82	98.79	0.60	6.67	0.39
1.00	0.08	172.29	123.53	39.47	49.42	48.76	98.66	0.66	8.25	0.39
1.25	0.25	172.15	123.53	39.36	49.42	48.62	98.38	0.80	3.20	0.39
1.50	0.25	172.01	123.53	39.25	49.42	48.48	98.10	0.94	3.76	0.39
1.75	0.25	171.89	123.53	39.15	49.42	48.36	97.86	1.06	4.24	0.39
2.00	0.25	171.78	123.53	39.06	49.42	48.25	97.63	1.17	4.68	0.39
3.00	1.00	171.39	123.53	38.74	49.42	47.86	96.84	1.56	1.56	0.38
24.0	21.00	167.85	123.53	35.88	49.42	44.32	89.68	5.10	0.24	0.35
48.0	24.00	163.06	123.53	32.00	49.42	39.53	79.99	9.89	0.41	0.32
72.0	24.00	158.34	123.53	28.18	49.42	34.81	70.44	14.61	0.61	0.28
96.0	24.00	152.11	123.53	23.14	49.42	28.58	57.83	20.84	0.87	0.23

DRYING MEASUREMENTS FOR SAMPLE A2 – CONTINUED										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, ΔY/ΔT	MOISTURE CONTENT, Ψ (G/CM^3)
120.0	24.00	143.88	123.53	16.47	49.42	20.35	41.18	29.07	1.21	0.16
144.0	24.00	140.86	123.53	14.03	49.42	17.33	35.07	32.09	1.34	0.14
168.0	24.00	138.38	123.53	12.02	49.42	14.85	30.05	34.57	1.44	0.12
192.0	24.00	137.00	123.53	10.90	49.42	13.47	27.26	35.95	1.50	0.11
216.0	24.00	135.41	123.53	9.62	49.42	11.88	24.04	37.54	1.56	0.10
240.0	24.00	134.53	123.53	8.90	49.42	11.00	22.26	38.42	1.60	0.09
264.0	24.00	131.00	123.53	6.05	49.42	7.47	15.12	41.95	1.75	0.06
288.0	24.00	130.74	123.53	5.84	49.42	7.21	14.59	42.21	1.76	0.06
312.0	24.00	130.40	123.53	5.56	49.42	6.87	13.90	42.55	1.77	0.05
336.0	24.00	129.59	123.53	4.91	49.42	6.06	12.26	43.36	1.81	0.05
360.0	24.00	128.90	123.53	4.35	49.42	5.37	10.87	44.05	1.84	0.04
384.0	24.00	128.51	123.53	4.03	49.42	4.98	10.08	44.44	1.85	0.04
408.0	24.00	128.14	123.53	3.73	49.42	4.61	9.33	44.81	1.87	0.04
432.0	24.00	127.46	123.53	3.18	49.42	3.93	7.95	45.49	1.90	0.03
456.0	24.00	123.75	123.53	0.18	49.42	0.22	0.45	49.20	2.05	0.00
480.0	24.00	123.75	123.53	0.18	49.42	0.22	0.45	49.20	2.05	0.00
504.0	24.00	123.74	123.53	0.17	49.42	0.21	0.42	49.21	2.05	0.00
528.0	24.00	123.72	123.53	0.15	49.42	0.19	0.38	49.23	2.05	0.00
552.0	24.00	123.71	123.53	0.15	49.42	0.18	0.36	49.24	2.05	0.00
576.0	24.00	123.60	123.53	0.06	49.42	0.07	0.14	49.35	2.06	0.00
600.0	24.00	123.53	123.53	0.00	49.42	0.00	0.00	49.42	2.06	0.00
SHADED MEASUREMENTS WERE TAKEN AFTER SAMPLE WAS PLACED IN THE OVEN.										

APPENDIX H – DRYING INDEX DATA

DRYING MEASUREMENTS FOR SAMPLE A3										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, $\Delta Y/\Delta T$	MOISTURE CONTENT, Ψ (G/CM^3)
0.00	0.00	172.71	122.93	40.49	49.78	49.78	100.00	0.00	0.00	0.40
0.08	0.08	172.70	122.93	40.49	49.78	49.77	99.98	0.01	0.13	0.40
0.17	0.09	172.61	122.93	40.41	49.78	49.68	99.80	0.10	1.11	0.40
0.25	0.08	172.54	122.93	40.36	49.78	49.61	99.66	0.17	2.13	0.40
0.33	0.08	172.49	122.93	40.32	49.78	49.56	99.56	0.22	2.75	0.40
0.42	0.09	172.43	122.93	40.27	49.78	49.50	99.44	0.28	3.11	0.40
0.50	0.08	172.35	122.93	40.20	49.78	49.42	99.28	0.36	4.50	0.40
0.58	0.08	172.30	122.93	40.16	49.78	49.37	99.18	0.41	5.12	0.39
0.67	0.09	172.24	122.93	40.11	49.78	49.31	99.06	0.47	5.22	0.39
0.75	0.08	172.19	122.93	40.07	49.78	49.26	98.96	0.52	6.50	0.39
0.83	0.08	172.14	122.93	40.03	49.78	49.21	98.85	0.57	7.13	0.39
0.92	0.09	172.10	122.93	40.00	49.78	49.17	98.77	0.61	6.78	0.39
1.00	0.08	172.04	122.93	39.95	49.78	49.11	98.65	0.67	8.38	0.39
1.25	0.25	171.90	122.93	39.84	49.78	48.97	98.37	0.81	3.24	0.39
1.50	0.25	171.74	122.93	39.71	49.78	48.81	98.05	0.97	3.88	0.39
1.75	0.25	171.61	122.93	39.60	49.78	48.68	97.79	1.10	4.40	0.39
2.00	0.25	171.48	122.93	39.49	49.78	48.55	97.53	1.23	4.92	0.39
3.00	1.00	171.02	122.93	39.12	49.78	48.09	96.61	1.69	1.69	0.38
24.0	21.00	167.03	122.93	35.87	49.78	44.10	88.59	5.68	0.27	0.35
48.0	24.00	161.60	122.93	31.46	49.78	38.67	77.68	11.11	0.46	0.31
72.0	24.00	156.63	122.93	27.41	49.78	33.70	67.70	16.08	0.67	0.27
96.0	24.00	150.43	122.93	22.37	49.78	27.50	55.24	22.28	0.93	0.22

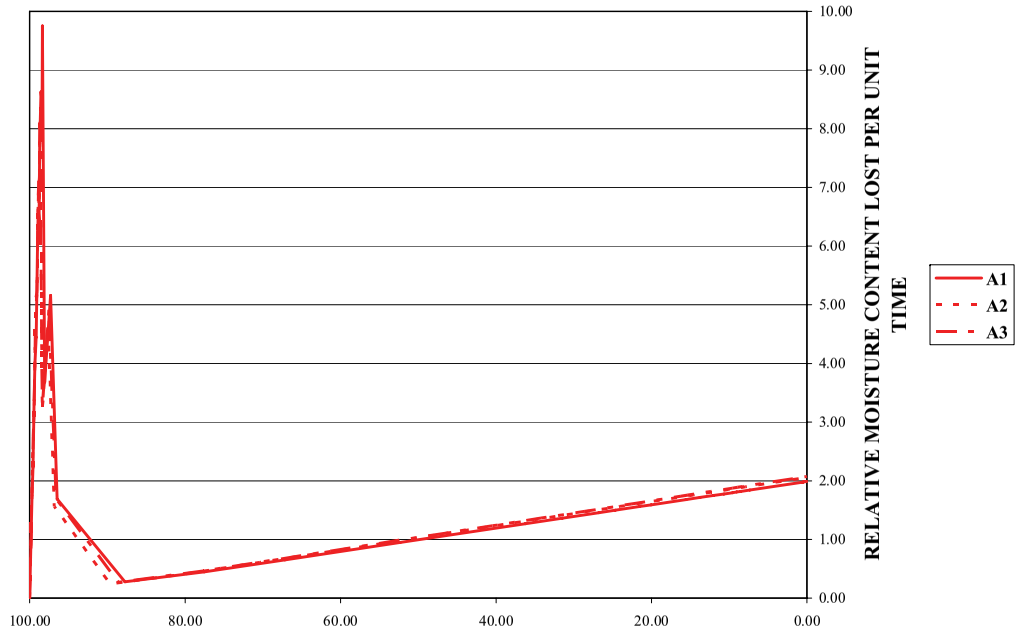
APPENDIX H – DRYING INDEX DATA

DRYING MEASUREMENTS FOR SAMPLE A3 – CONTINUED										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, $\Delta Y/\Delta T$	MOISTURE CONTENT, Ψ (G/CM^3)
120.0	24.00	143.07	122.93	16.38	49.78	20.14	40.46	29.64	1.24	0.16
144.0	24.00	139.96	122.93	13.85	49.78	17.03	34.21	32.75	1.36	0.14
168.0	24.00	137.17	122.93	11.58	49.78	14.24	28.61	35.54	1.48	0.11
192.0	24.00	135.82	122.93	10.49	49.78	12.89	25.89	36.89	1.54	0.10
216.0	24.00	134.20	122.93	9.17	49.78	11.27	22.64	38.51	1.60	0.09
240.0	24.00	133.27	122.93	8.41	49.78	10.34	20.77	39.44	1.64	0.08
264.0	24.00	131.00	122.93	6.56	49.78	8.07	16.21	41.71	1.74	0.06
288.0	24.00	130.56	122.93	6.21	49.78	7.63	15.33	42.15	1.76	0.06
312.0	24.00	129.09	122.93	5.01	49.78	6.16	12.37	43.62	1.82	0.05
336.0	24.00	128.30	122.93	4.37	49.78	5.37	10.79	44.41	1.85	0.04
360.0	24.00	127.69	122.93	3.87	49.78	4.76	9.56	45.02	1.88	0.04
384.0	24.00	127.35	122.93	3.60	49.78	4.42	8.88	45.36	1.89	0.04
408.0	24.00	127.06	122.93	3.36	49.78	4.13	8.30	45.65	1.90	0.03
432.0	24.00	126.45	122.93	2.86	49.78	3.52	7.07	46.26	1.93	0.03
456.0	24.00	123.19	122.93	0.21	49.78	0.26	0.52	49.52	2.06	0.00
480.0	24.00	123.17	122.93	0.20	49.78	0.24	0.48	49.54	2.06	0.00
504.0	24.00	123.16	122.93	0.19	49.78	0.23	0.46	49.55	2.06	0.00
528.0	24.00	123.15	122.93	0.18	49.78	0.22	0.44	49.56	2.07	0.00
552.0	24.00	123.12	122.93	0.15	49.78	0.19	0.38	49.59	2.07	0.00
576.0	24.00	123.00	122.93	0.06	49.78	0.07	0.14	49.71	2.07	0.00
600.0	24.00	122.93	122.93	0.00	49.78	0.00	0.00	49.78	2.07	0.00
SHADED MEASUREMENTS WERE TAKEN AFTER SAMPLE WAS PLACED IN THE OVEN.										

APPENDIX H – DRYING INDEX DATA

SAMPLE KEY	
A	2 NHL / 1 S / 1 MS / 0% ER
B	2 NHL / 1 S / 1 MS / 5% ER
C	2 NHL / 1 S / 1 MS / 10% ER

DRYING INDEX CURVES FOR SAMPLE GROUP A



APPENDIX H – DRYING INDEX DATA

DRYING MEASUREMENTS FOR SAMPLE B1										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, $\Delta Y/\Delta T$	MOISTURE CONTENT, Ψ (G/CM^3)
0.00	0.00	165.33	120.58	37.11	44.75	44.75	100.00	0.00	0.00	0.36
0.08	0.08	165.25	120.58	37.05	44.75	44.67	99.82	0.08	1.00	0.36
0.17	0.09	165.22	120.58	37.02	44.75	44.64	99.75	0.11	1.22	0.36
0.25	0.08	165.12	120.58	36.94	44.75	44.54	99.53	0.21	2.63	0.36
0.33	0.08	165.09	120.58	36.91	44.75	44.51	99.46	0.24	3.00	0.36
0.42	0.09	165.03	120.58	36.86	44.75	44.45	99.33	0.30	3.33	0.36
0.50	0.08	164.98	120.58	36.82	44.75	44.40	99.22	0.35	4.38	0.36
0.58	0.08	164.94	120.58	36.79	44.75	44.36	99.13	0.39	4.88	0.35
0.67	0.09	164.90	120.58	36.76	44.75	44.32	99.04	0.43	4.78	0.35
0.75	0.08	164.84	120.58	36.71	44.75	44.26	98.91	0.49	6.13	0.35
0.83	0.08	164.80	120.58	36.67	44.75	44.22	98.82	0.53	6.63	0.35
0.92	0.09	164.73	120.58	36.61	44.75	44.15	98.66	0.60	6.67	0.35
1.00	0.08	164.68	120.58	36.57	44.75	44.10	98.55	0.65	8.13	0.35
1.25	0.25	164.60	120.58	36.51	44.75	44.02	98.37	0.73	2.92	0.35
1.50	0.25	164.54	120.58	36.46	44.75	43.96	98.23	0.79	3.16	0.35
1.75	0.25	164.46	120.58	36.39	44.75	43.88	98.06	0.87	3.48	0.35
2.00	0.25	164.38	120.58	36.32	44.75	43.80	97.88	0.95	3.80	0.35
3.00	1.00	164.18	120.58	36.16	44.75	43.60	97.43	1.15	1.15	0.35
24.0	21.00	161.70	120.58	34.10	44.75	41.12	91.89	3.63	0.17	0.33
48.0	24.00	158.71	120.58	31.62	44.75	38.13	85.21	6.62	0.28	0.31
72.0	24.00	156.33	120.58	29.65	44.75	35.75	79.89	9.00	0.38	0.29
96.0	24.00	153.45	120.58	27.26	44.75	32.87	73.45	11.88	0.50	0.26

DRYING MEASUREMENTS FOR SAMPLE B1 – CONTINUED										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, ΔY/ΔT	MOISTURE CONTENT, Ψ (G/CM^3)
120.0	24.00	149.27	120.58	23.79	44.75	28.69	64.11	16.06	0.67	0.23
144.0	24.00	146.89	120.58	21.82	44.75	26.31	58.79	18.44	0.77	0.21
168.0	24.00	144.23	120.58	19.61	44.75	23.65	52.85	21.10	0.88	0.19
192.0	24.00	142.04	120.58	17.80	44.75	21.46	47.96	23.29	0.97	0.17
216.0	24.00	139.10	120.58	15.36	44.75	18.52	41.39	26.23	1.09	0.15
240.0	24.00	139.01	120.58	15.28	44.75	18.43	41.18	26.32	1.10	0.15
264.0	24.00	134.72	120.58	11.73	44.75	14.14	31.60	30.61	1.28	0.11
288.0	24.00	132.85	120.58	10.18	44.75	12.27	27.42	32.48	1.35	0.10
312.0	24.00	131.61	120.58	9.15	44.75	11.03	24.65	33.72	1.41	0.09
336.0	24.00	130.19	120.58	7.97	44.75	9.61	21.47	35.14	1.46	0.08
360.0	24.00	128.68	120.58	6.72	44.75	8.10	18.10	36.65	1.53	0.06
384.0	24.00	127.69	120.58	5.90	44.75	7.11	15.89	37.64	1.57	0.06
408.0	24.00	126.75	120.58	5.12	44.75	6.17	13.79	38.58	1.61	0.05
432.0	24.00	125.83	120.58	4.35	44.75	5.25	11.73	39.50	1.65	0.04
456.0	24.00	120.83	120.58	0.21	44.75	0.25	0.56	44.50	1.85	0.00
480.0	24.00	120.82	120.58	0.20	44.75	0.24	0.54	44.51	1.85	0.00
504.0	24.00	120.81	120.58	0.19	44.75	0.23	0.51	44.52	1.86	0.00
528.0	24.00	120.8	120.58	0.18	44.75	0.22	0.49	44.53	1.86	0.00
552.0	24.00	120.79	120.58	0.17	44.75	0.21	0.47	44.54	1.86	0.00
576.0	24.00	120.69	120.58	0.09	44.75	0.11	0.25	44.64	1.86	0.00
600.0	24.00	120.58	120.58	0.00	44.75	0.00	0.00	44.75	1.86	0.00
SHADED MEASUREMENTS WERE TAKEN AFTER SAMPLE WAS PLACED IN THE OVEN.										

APPENDIX H – DRYING INDEX DATA

DRYING MEASUREMENTS FOR SAMPLE B2										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, $\Delta Y/\Delta T$	MOISTURE CONTENT, Ψ (G/CM^3)
0.00	0.00	163.14	118.53	37.64	44.61	44.61	100.00	0.00	0.00	0.36
0.08	0.08	163.03	118.53	37.54	44.61	44.50	99.75	0.11	1.37	0.36
0.17	0.09	162.99	118.53	37.51	44.61	44.46	99.66	0.15	1.67	0.36
0.25	0.08	162.90	118.53	37.43	44.61	44.37	99.46	0.24	3.00	0.35
0.33	0.08	162.88	118.53	37.42	44.61	44.35	99.42	0.26	3.25	0.35
0.42	0.09	162.83	118.53	37.37	44.61	44.30	99.31	0.31	3.44	0.35
0.50	0.08	162.77	118.53	37.32	44.61	44.24	99.17	0.37	4.62	0.35
0.58	0.08	162.73	118.53	37.29	44.61	44.20	99.08	0.41	5.12	0.35
0.67	0.09	162.70	118.53	37.26	44.61	44.17	99.01	0.44	4.89	0.35
0.75	0.08	162.66	118.53	37.23	44.61	44.13	98.92	0.48	6.00	0.35
0.83	0.08	162.61	118.53	37.19	44.61	44.08	98.81	0.53	6.62	0.35
0.92	0.09	162.56	118.53	37.15	44.61	44.03	98.70	0.58	6.44	0.35
1.00	0.08	162.51	118.53	37.10	44.61	43.98	98.59	0.63	7.87	0.35
1.25	0.25	162.44	118.53	37.05	44.61	43.91	98.43	0.70	2.80	0.35
1.50	0.25	162.37	118.53	36.99	44.61	43.84	98.27	0.77	3.08	0.35
1.75	0.25	162.31	118.53	36.94	44.61	43.78	98.14	0.83	3.32	0.35
2.00	0.25	162.24	118.53	36.88	44.61	43.71	97.98	0.90	3.60	0.35
3.00	1.00	162.07	118.53	36.73	44.61	43.54	97.60	1.07	1.07	0.35
24.00	21.00	159.81	118.53	34.83	44.61	41.28	92.54	3.33	0.16	0.33
48.00	24.00	157.04	118.53	32.49	44.61	38.51	86.33	6.10	0.25	0.31
72.00	24.00	154.72	118.53	30.53	44.61	36.19	81.13	8.42	0.35	0.29
96.00	24.00	151.62	118.53	27.92	44.61	33.09	74.18	11.52	0.48	0.26

APPENDIX H – DRYING INDEX DATA

DRYING MEASUREMENTS FOR SAMPLE B2 – CONTINUED										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, ΔY/ΔT	MOISTURE CONTENT, Ψ (G/CM^3)
120.00	24.00	146.88	118.53	23.92	44.61	28.35	63.55	16.26	0.68	0.23
144.00	24.00	143.86	118.53	21.37	44.61	25.33	56.78	19.28	0.80	0.20
168.00	24.00	140.76	118.53	18.75	44.61	22.23	49.83	22.38	0.93	0.18
192.00	24.00	138.51	118.53	16.86	44.61	19.98	44.79	24.63	1.03	0.16
216.00	24.00	136.10	118.53	14.82	44.61	17.57	39.39	27.04	1.13	0.14
240.00	24.00	134.42	118.53	13.41	44.61	15.89	35.62	28.72	1.20	0.13
264.00	24.00	132.28	118.53	11.60	44.61	13.75	30.82	30.86	1.29	0.11
288.00	24.00	130.75	118.53	10.31	44.61	12.22	27.39	32.39	1.35	0.10
312.00	24.00	129.41	118.53	9.18	44.61	10.88	24.39	33.73	1.41	0.09
336.00	24.00	128.00	118.53	7.99	44.61	9.47	21.23	35.14	1.46	0.08
360.00	24.00	126.47	118.53	6.70	44.61	7.94	17.80	36.67	1.53	0.06
384.00	24.00	125.52	118.53	5.90	44.61	6.99	15.67	37.62	1.57	0.06
408.00	24.00	124.60	118.53	5.12	44.61	6.07	13.61	38.54	1.61	0.05
432.00	24.00	123.70	118.53	4.36	44.61	5.17	11.59	39.44	1.64	0.04
456.00	24.00	118.79	118.53	0.22	44.61	0.26	0.58	44.35	1.85	0.00
480.00	24.00	118.76	118.53	0.19	44.61	0.23	0.52	44.38	1.85	0.00
504.00	24.00	118.76	118.53	0.19	44.61	0.23	0.52	44.38	1.85	0.00
528.00	24.00	118.73	118.53	0.17	44.61	0.20	0.45	44.41	1.85	0.00
552.00	24.00	118.72	118.53	0.16	44.61	0.19	0.43	44.42	1.85	0.00
576.00	24.00	118.62	118.53	0.08	44.61	0.09	0.20	44.52	1.86	0.00
600.00	24.00	118.53	118.53	0.00	44.61	0.00	0.00	44.61	1.86	0.00
SHADED MEASUREMENTS WERE TAKEN AFTER SAMPLE WAS PLACED IN THE OVEN.										

APPENDIX H – DRYING INDEX DATA

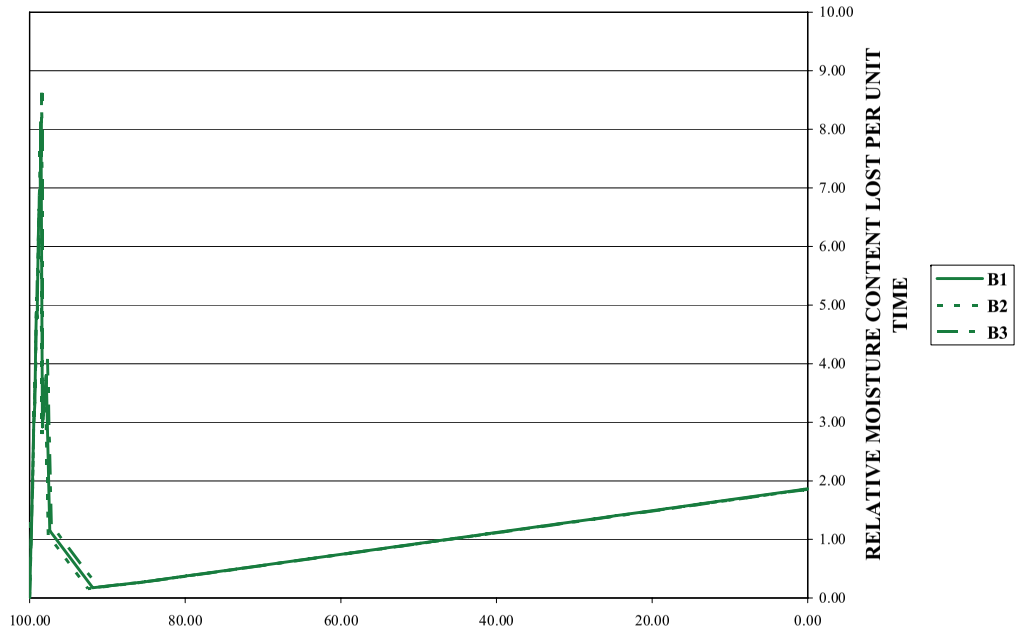
DRYING MEASUREMENTS FOR SAMPLE B3										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, $\Delta Y/\Delta T$	MOISTURE CONTENT, Ψ (G/CM^3)
0.00	0.00	162.63	118.10	37.71	44.53	44.53	100.00	0.00	0.00	0.36
0.08	0.08	162.52	118.10	37.61	44.53	44.42	99.75	0.11	1.37	0.36
0.17	0.09	162.46	118.10	37.56	44.53	44.36	99.62	0.17	1.89	0.35
0.25	0.08	162.38	118.10	37.49	44.53	44.28	99.44	0.25	3.13	0.35
0.33	0.08	162.35	118.10	37.47	44.53	44.25	99.37	0.28	3.50	0.35
0.42	0.09	162.29	118.10	37.42	44.53	44.19	99.24	0.34	3.78	0.35
0.50	0.08	162.25	118.10	37.38	44.53	44.15	99.15	0.38	4.75	0.35
0.58	0.08	162.18	118.10	37.32	44.53	44.08	98.99	0.45	5.62	0.35
0.67	0.09	162.13	118.10	37.28	44.53	44.03	98.88	0.50	5.56	0.35
0.75	0.08	162.08	118.10	37.24	44.53	43.98	98.76	0.55	6.87	0.35
0.83	0.08	162.04	118.10	37.21	44.53	43.94	98.68	0.59	7.38	0.35
0.92	0.09	162.00	118.10	37.17	44.53	43.90	98.59	0.63	7.00	0.35
1.00	0.08	161.94	118.10	37.12	44.53	43.84	98.45	0.69	8.62	0.35
1.25	0.25	161.87	118.10	37.06	44.53	43.77	98.29	0.76	3.04	0.35
1.50	0.25	161.79	118.10	36.99	44.53	43.69	98.11	0.84	3.36	0.35
1.75	0.25	161.70	118.10	36.92	44.53	43.60	97.91	0.93	3.72	0.35
2.00	0.25	161.61	118.10	36.84	44.53	43.51	97.71	1.02	4.08	0.35
3.00	1.00	161.39	118.10	36.66	44.53	43.29	97.22	1.24	1.24	0.35
24.00	21.00	158.70	118.10	34.38	44.53	40.60	91.17	3.93	0.19	0.32
48.00	24.00	155.67	118.10	31.81	44.53	37.57	84.37	6.96	0.29	0.30
72.00	24.00	152.67	118.10	29.27	44.53	34.57	77.63	9.96	0.42	0.28
96.00	24.00	150.16	118.10	27.15	44.53	32.06	72.00	12.47	0.52	0.26

DRYING MEASUREMENTS FOR SAMPLE B3 – CONTINUED										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, $\Delta Y/\Delta T$	MOISTURE CONTENT, Ψ (G/CM^3)
120.00	24.00	145.56	118.10	23.25	44.53	27.46	61.67	17.07	0.71	0.22
144.00	24.00	143.00	118.10	21.08	44.53	24.90	55.92	19.63	0.82	0.20
168.00	24.00	139.02	118.10	17.71	44.53	20.92	46.98	23.61	0.98	0.17
192.00	24.00	137.34	118.10	16.29	44.53	19.24	43.21	25.29	1.05	0.15
216.00	24.00	134.28	118.10	13.70	44.53	16.18	36.34	28.35	1.18	0.13
240.00	24.00	132.40	118.10	12.11	44.53	14.30	32.11	30.23	1.26	0.11
264.00	24.00	130.37	118.10	10.39	44.53	12.27	27.55	32.26	1.34	0.10
288.00	24.00	129.15	118.10	9.36	44.53	11.05	24.81	33.48	1.40	0.09
312.00	24.00	127.82	118.10	8.23	44.53	9.72	21.83	34.81	1.45	0.08
336.00	24.00	126.49	118.10	7.10	44.53	8.39	18.84	36.14	1.51	0.07
360.00	24.00	125.05	118.10	5.88	44.53	6.95	15.61	37.58	1.57	0.06
384.00	24.00	124.22	118.10	5.18	44.53	6.12	13.74	38.41	1.60	0.05
408.00	24.00	123.40	118.10	4.49	44.53	5.30	11.90	39.23	1.63	0.04
432.00	24.00	122.58	118.10	3.79	44.53	4.48	10.06	40.05	1.67	0.04
456.00	24.00	118.37	118.10	0.23	44.53	0.27	0.61	44.26	1.84	0.00
480.00	24.00	118.35	118.10	0.21	44.53	0.25	0.56	44.28	1.85	0.00
504.00	24.00	118.34	118.10	0.20	44.53	0.24	0.54	44.29	1.85	0.00
528.00	24.00	118.33	118.10	0.19	44.53	0.23	0.52	44.30	1.85	0.00
552.00	24.00	118.31	118.10	0.18	44.53	0.21	0.47	44.32	1.85	0.00
576.00	24.00	118.21	118.10	0.09	44.53	0.11	0.25	44.42	1.85	0.00
600.00	24.00	118.10	118.10	0.00	44.53	0.00	0.00	44.53	1.86	0.00
SHADED MEASUREMENTS WERE TAKEN AFTER SAMPLE WAS PLACED IN THE OVEN.										

APPENDIX H – DRYING INDEX DATA

SAMPLE KEY	
A	2 NHL / 1 S / 1 MS / 0% ER
B	2 NHL / 1 S / 1 MS / 5% ER
C	2 NHL / 1 S / 1 MS / 10% ER

DRYING INDEX CURVES FOR SAMPLE GROUP B



APPENDIX H – DRYING INDEX DATA

DRYING MEASUREMENTS FOR SAMPLE C1										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, ΔY/ΔT	MOISTURE CONTENT, Ψ (G/CM^3)
0.00	0.00	161.72	119.53	35.30	42.19	42.19	100.00	0.00	0.00	0.34
0.08	0.08	161.65	119.53	35.24	42.19	42.12	99.83	0.07	0.87	0.34
0.17	0.09	161.60	119.53	35.20	42.19	42.07	99.72	0.12	1.33	0.34
0.25	0.08	161.57	119.53	35.17	42.19	42.04	99.64	0.15	1.88	0.34
0.33	0.08	161.51	119.53	35.12	42.19	41.98	99.50	0.21	2.63	0.34
0.42	0.09	161.48	119.53	35.10	42.19	41.95	99.43	0.24	2.67	0.34
0.50	0.08	161.45	119.53	35.07	42.19	41.92	99.36	0.27	3.38	0.34
0.58	0.08	161.39	119.53	35.02	42.19	41.86	99.22	0.33	4.13	0.33
0.67	0.09	161.36	119.53	35.00	42.19	41.83	99.15	0.36	4.00	0.33
0.75	0.08	161.31	119.53	34.95	42.19	41.78	99.03	0.41	5.12	0.33
0.83	0.08	161.30	119.53	34.95	42.19	41.77	99.00	0.42	5.25	0.33
0.92	0.09	161.25	119.53	34.90	42.19	41.72	98.89	0.47	5.22	0.33
1.00	0.08	161.22	119.53	34.88	42.19	41.69	98.81	0.50	6.25	0.33
1.25	0.25	161.16	119.53	34.83	42.19	41.63	98.67	0.56	2.24	0.33
1.50	0.25	161.09	119.53	34.77	42.19	41.56	98.51	0.63	2.52	0.33
1.75	0.25	161.03	119.53	34.72	42.19	41.50	98.36	0.69	2.76	0.33
2.00	0.25	160.99	119.53	34.69	42.19	41.46	98.27	0.73	2.92	0.33
3.00	1.00	160.80	119.53	34.53	42.19	41.27	97.82	0.92	0.92	0.33
24.0	21.00	158.87	119.53	32.91	42.19	39.34	93.24	2.85	0.14	0.31
48.0	24.00	156.35	119.53	30.80	42.19	36.82	87.27	5.37	0.22	0.29
72.0	24.00	154.64	119.53	29.37	42.19	35.11	83.22	7.08	0.30	0.28
96.0	24.00	151.56	119.53	26.80	42.19	32.03	75.92	10.16	0.42	0.26

DRYING MEASUREMENTS FOR SAMPLE C1 – CONTINUED										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, $\Delta Y/\Delta T$	MOISTURE CONTENT, Ψ (G/CM^3)
120.0	24.00	147.81	119.53	23.66	42.19	28.28	67.03	13.91	0.58	0.23
144.0	24.00	145.48	119.53	21.71	42.19	25.95	61.51	16.24	0.68	0.21
168.0	24.00	142.76	119.53	19.43	42.19	23.23	55.06	18.96	0.79	0.19
192.0	24.00	141.02	119.53	17.98	42.19	21.49	50.94	20.70	0.86	0.17
216.0	24.00	138.36	119.53	15.75	42.19	18.83	44.63	23.36	0.97	0.15
240.0	24.00	136.67	119.53	14.34	42.19	17.14	40.63	25.05	1.04	0.14
264.0	24.00	134.54	119.53	12.56	42.19	15.01	35.58	27.18	1.13	0.12
288.0	24.00	132.75	119.53	11.06	42.19	13.22	31.33	28.97	1.21	0.11
312.0	24.00	131.34	119.53	9.88	42.19	11.81	27.99	30.38	1.27	0.09
336.0	24.00	129.89	119.53	8.67	42.19	10.36	24.56	31.83	1.33	0.08
360.0	24.00	128.48	119.53	7.49	42.19	8.95	21.21	33.24	1.39	0.07
384.0	24.00	127.58	119.53	6.73	42.19	8.05	19.08	34.14	1.42	0.06
408.0	24.00	126.69	119.53	5.99	42.19	7.16	16.97	35.03	1.46	0.06
432.0	24.00	125.67	119.53	5.14	42.19	6.14	14.55	36.05	1.50	0.05
456.0	24.00	119.72	119.53	0.16	42.19	0.19	0.45	42.00	1.75	0.00
480.0	24.00	119.72	119.53	0.16	42.19	0.19	0.45	42.00	1.75	0.00
504.0	24.00	119.70	119.53	0.14	42.19	0.17	0.40	42.02	1.75	0.00
528.0	24.00	119.69	119.53	0.13	42.19	0.16	0.38	42.03	1.75	0.00
552.0	24.00	119.69	119.53	0.13	42.19	0.16	0.38	42.03	1.75	0.00
576.0	24.00	119.60	119.53	0.06	42.19	0.07	0.17	42.12	1.76	0.00
600.0	24.00	119.53	119.53	0.00	42.19	0.00	0.00	42.19	1.76	0.00
SHADED MEASUREMENTS WERE TAKEN AFTER SAMPLE WAS PLACED IN THE OVEN.										

APPENDIX H – DRYING INDEX DATA

DRYING MEASUREMENTS FOR SAMPLE C2										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, ΔY/ΔT	MOISTURE CONTENT, Ψ (G/CM^3)
0.00	0.00	160.65	118.51	35.56	42.14	42.14	100.00	0.00	0.00	0.34
0.08	0.08	160.59	118.51	35.51	42.14	42.08	99.86	0.06	0.75	0.34
0.17	0.09	160.55	118.51	35.47	42.14	42.04	99.76	0.10	1.11	0.34
0.25	0.08	160.50	118.51	35.43	42.14	41.99	99.64	0.15	1.88	0.34
0.33	0.08	160.44	118.51	35.38	42.14	41.93	99.50	0.21	2.63	0.34
0.42	0.09	160.41	118.51	35.36	42.14	41.90	99.43	0.24	2.67	0.34
0.50	0.08	160.38	118.51	35.33	42.14	41.87	99.36	0.27	3.38	0.33
0.58	0.08	160.34	118.51	35.30	42.14	41.83	99.26	0.31	3.88	0.33
0.67	0.09	160.30	118.51	35.26	42.14	41.79	99.17	0.35	3.89	0.33
0.75	0.08	160.26	118.51	35.23	42.14	41.75	99.07	0.39	4.88	0.33
0.83	0.08	160.22	118.51	35.20	42.14	41.71	98.98	0.43	5.38	0.33
0.92	0.09	160.20	118.51	35.18	42.14	41.69	98.93	0.45	5.00	0.33
1.00	0.08	160.16	118.51	35.14	42.14	41.65	98.84	0.49	6.13	0.33
1.25	0.25	160.11	118.51	35.10	42.14	41.60	98.72	0.54	2.16	0.33
1.50	0.25	160.06	118.51	35.06	42.14	41.55	98.60	0.59	2.36	0.33
1.75	0.25	159.99	118.51	35.00	42.14	41.48	98.43	0.66	2.64	0.33
2.00	0.25	159.93	118.51	34.95	42.14	41.42	98.29	0.72	2.88	0.33
3.00	1.00	159.79	118.51	34.83	42.14	41.28	97.96	0.86	0.86	0.33
24.0	21.00	158.22	118.51	33.51	42.14	39.71	94.23	2.43	0.12	0.32
48.0	24.00	155.92	118.51	31.57	42.14	37.41	88.78	4.73	0.20	0.30
72.0	24.00	153.50	118.51	29.52	42.14	34.99	83.03	7.15	0.30	0.28
96.0	24.00	151.46	118.51	27.80	42.14	32.95	78.19	9.19	0.38	0.26

DRYING MEASUREMENTS FOR SAMPLE C2 – CONTINUED										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, ΔY/ΔT	MOISTURE CONTENT, Ψ (G/CM^3)
120.0	24.00	148.92	118.51	25.66	42.14	30.41	72.16	11.73	0.49	0.24
144.0	24.00	146.79	118.51	23.86	42.14	28.28	67.11	13.86	0.58	0.23
168.0	24.00	144.68	118.51	22.08	42.14	26.17	62.10	15.97	0.67	0.21
192.0	24.00	143.18	118.51	20.82	42.14	24.67	58.54	17.47	0.73	0.20
216.0	24.00	140.00	118.51	18.13	42.14	21.49	51.00	20.65	0.86	0.17
240.0	24.00	137.98	118.51	16.43	42.14	19.47	46.20	22.67	0.94	0.16
264.0	24.00	135.16	118.51	14.05	42.14	16.65	39.51	25.49	1.06	0.13
288.0	24.00	133.65	118.51	12.78	42.14	15.14	35.93	27.00	1.13	0.12
312.0	24.00	131.57	118.51	11.02	42.14	13.06	30.99	29.08	1.21	0.10
336.0	24.00	129.83	118.51	9.55	42.14	11.32	26.86	30.82	1.28	0.09
360.0	24.00	128.25	118.51	8.22	42.14	9.74	23.11	32.40	1.35	0.08
384.0	24.00	127.24	118.51	7.37	42.14	8.73	20.72	33.41	1.39	0.07
408.0	24.00	126.22	118.51	6.51	42.14	7.71	18.30	34.43	1.43	0.06
432.0	24.00	125.08	118.51	5.54	42.14	6.57	15.59	35.57	1.48	0.05
456.0	24.00	118.69	118.51	0.15	42.14	0.18	0.43	41.96	1.75	0.00
480.0	24.00	118.69	118.51	0.15	42.14	0.18	0.43	41.96	1.75	0.00
504.0	24.00	118.67	118.51	0.14	42.14	0.16	0.38	41.98	1.75	0.00
528.0	24.00	118.66	118.51	0.13	42.14	0.15	0.36	41.99	1.75	0.00
552.0	24.00	118.65	118.51	0.12	42.14	0.14	0.33	42.00	1.75	0.00
576.0	24.00	118.58	118.51	0.06	42.14	0.07	0.17	42.07	1.75	0.00
600.0	24.00	118.51	118.51	0.00	42.14	0.00	0.00	42.14	1.76	0.00
SHADED MEASUREMENTS WERE TAKEN AFTER SAMPLE WAS PLACED IN THE OVEN.										

APPENDIX H – DRYING INDEX DATA

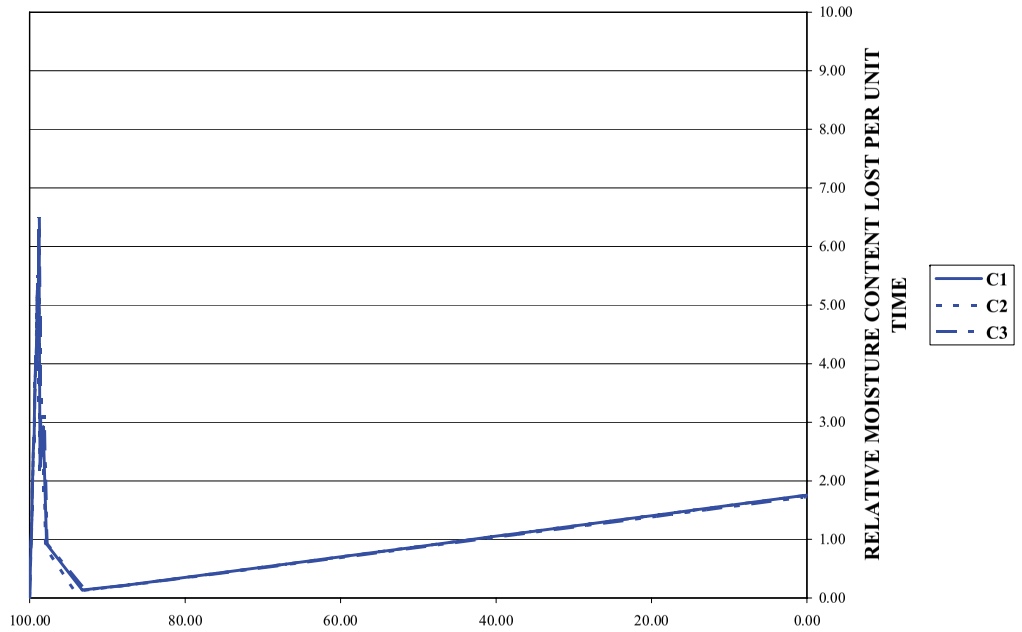
DRYING MEASUREMENTS FOR SAMPLE C3										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, $\Delta Y/\Delta T$	MOISTURE CONTENT, Ψ (G/CM^3)
0.00	0.00	160.45	118.96	34.88	41.49	41.49	100.00	0.00	0.00	0.33
0.08	0.08	160.40	118.96	34.84	41.49	41.44	99.88	0.05	0.62	0.33
0.17	0.09	160.35	118.96	34.79	41.49	41.39	99.76	0.10	1.11	0.33
0.25	0.08	160.28	118.96	34.73	41.49	41.32	99.59	0.17	2.12	0.33
0.33	0.08	160.23	118.96	34.69	41.49	41.27	99.47	0.22	2.75	0.33
0.42	0.09	160.21	118.96	34.68	41.49	41.25	99.42	0.24	2.67	0.33
0.50	0.08	160.17	118.96	34.64	41.49	41.21	99.33	0.28	3.50	0.33
0.58	0.08	160.13	118.96	34.61	41.49	41.17	99.23	0.32	4.00	0.33
0.67	0.09	160.08	118.96	34.57	41.49	41.12	99.11	0.37	4.11	0.33
0.75	0.08	160.04	118.96	34.53	41.49	41.08	99.01	0.41	5.12	0.33
0.83	0.08	160.01	118.96	34.51	41.49	41.05	98.94	0.44	5.50	0.33
0.92	0.09	159.96	118.96	34.47	41.49	41.00	98.82	0.49	5.44	0.33
1.00	0.08	159.93	118.96	34.44	41.49	40.97	98.75	0.52	6.50	0.33
1.25	0.25	159.85	118.96	34.37	41.49	40.89	98.55	0.60	2.40	0.33
1.50	0.25	159.80	118.96	34.33	41.49	40.84	98.43	0.65	2.60	0.33
1.75	0.25	159.74	118.96	34.28	41.49	40.78	98.29	0.71	2.84	0.33
2.00	0.25	159.67	118.96	34.22	41.49	40.71	98.12	0.78	3.12	0.33
3.00	1.00	159.52	118.96	34.10	41.49	40.56	97.76	0.93	0.93	0.32
24.0	21.00	157.48	118.96	32.38	41.49	38.52	92.84	2.97	0.14	0.31
48.0	24.00	155.05	118.96	30.34	41.49	36.09	86.98	5.40	0.22	0.29
72.0	24.00	153.04	118.96	28.65	41.49	34.08	82.14	7.41	0.31	0.27
96.0	24.00	150.42	118.96	26.45	41.49	31.46	75.83	10.03	0.42	0.25

DRYING MEASUREMENTS FOR SAMPLE C3 – CONTINUED										
TIME (HOURS)	TIME DIFFERENCE, ΔT (HOURS)	WEIGHT, W_T (G)	DRY WEIGHT, W_D (G)	RESIDUAL WATER CONTENT, Q_I (%)	INITIAL WATER CONTENT, U_0 (G)	WATER CONTENT, U_T (G)	RELATIVE MOISTURE CONTENT, Y (%)	DIFFERENCE IN MOISTURE CONTENT, ΔY	RELATIVE MOISTURE CONTENT LOST/UNIT TIME, $\Delta Y/\Delta T$	MOISTURE CONTENT, Ψ (G/CM^3)
120.0	24.00	146.92	118.96	23.50	41.49	27.96	67.39	13.53	0.56	0.22
144.0	24.00	143.55	118.96	20.67	41.49	24.59	59.27	16.90	0.70	0.20
168.0	24.00	140.43	118.96	18.05	41.49	21.47	51.75	20.02	0.83	0.17
192.0	24.00	138.50	118.96	16.43	41.49	19.54	47.10	21.95	0.91	0.16
216.0	24.00	135.84	118.96	14.19	41.49	16.88	40.68	24.61	1.03	0.14
240.0	24.00	134.43	118.96	13.00	41.49	15.47	37.29	26.02	1.08	0.12
264.0	24.00	132.41	118.96	11.31	41.49	13.45	32.42	28.04	1.17	0.11
288.0	24.00	130.75	118.96	9.91	41.49	11.79	28.42	29.70	1.24	0.09
312.0	24.00	129.85	118.96	9.15	41.49	10.89	26.25	30.60	1.28	0.09
336.0	24.00	128.33	118.96	7.88	41.49	9.37	22.58	32.12	1.34	0.07
360.0	24.00	126.99	118.96	6.75	41.49	8.03	19.35	33.46	1.39	0.06
384.0	24.00	126.15	118.96	6.04	41.49	7.19	17.33	34.30	1.43	0.06
408.0	24.00	125.32	118.96	5.35	41.49	6.36	15.33	35.13	1.46	0.05
432.0	24.00	124.34	118.96	4.52	41.49	5.38	12.97	36.11	1.50	0.04
456.0	24.00	119.19	118.96	0.19	41.49	0.23	0.55	41.26	1.72	0.00
480.0	24.00	119.18	118.96	0.18	41.49	0.22	0.53	41.27	1.72	0.00
504.0	24.00	119.16	118.96	0.17	41.49	0.20	0.48	41.29	1.72	0.00
528.0	24.00	119.15	118.96	0.16	41.49	0.19	0.46	41.30	1.72	0.00
552.0	24.00	119.13	118.96	0.14	41.49	0.17	0.41	41.32	1.72	0.00
576.0	24.00	119.03	118.96	0.06	41.49	0.07	0.17	41.42	1.73	0.00
600.0	24.00	118.96	118.96	0.00	41.49	0.00	0.00	41.49	1.73	0.00
SHADED MEASUREMENTS WERE TAKEN AFTER SAMPLE WAS PLACED IN THE OVEN.										

APPENDIX H – DRYING INDEX DATA

SAMPLE KEY	
A	2 NHL / 1 S / 1 MS / 0% ER
B	2 NHL / 1 S / 1 MS / 5% ER
C	2 NHL / 1 S / 1 MS / 10% ER

DRYING INDEX CURVES FOR SAMPLE GROUP C



APPENDIX I – WATER VAPOR TRANSMISSION DATA

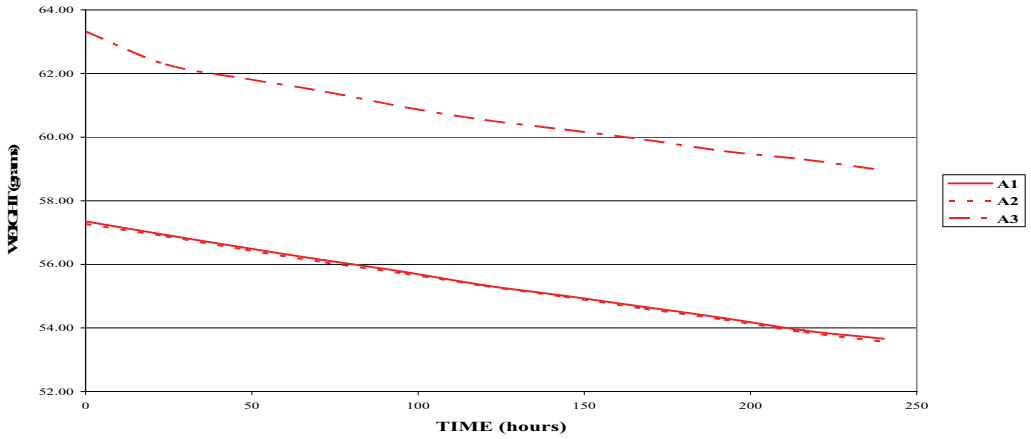
DAILY WEIGHT MEASUREMENTS (GRAMS)											
SAMPLE	DAYS										
	0	1	2	3	4	5	6	7	8	9	10
A1	57.35	56.93	56.52	56.13	55.76	55.34	55.01	54.66	54.31	53.92	53.66
A2	57.27	56.88	56.46	56.06	55.71	55.32	54.98	54.61	54.26	53.87	53.57
A3	63.32	62.29	61.84	61.43	60.94	60.54	60.24	59.92	59.56	59.30	58.96
B1	59.09	58.72	58.32	57.94	57.59	57.21	56.90	56.55	56.25	55.88	55.63
B2	57.55	57.20	56.80	56.42	56.07	55.69	55.41	55.06	54.72	54.31	54.04
B3	58.49	58.14	57.72	57.33	56.97	56.60	56.30	55.98	55.68	55.33	55.08
C1	62.35	62.06	61.63	61.25	60.79	60.44	60.14	59.85	59.51	59.28	58.98
C2	62.26	61.99	61.55	61.16	60.71	60.36	60.05	59.77	59.45	59.20	58.89
C3	62.31	61.95	61.55	61.15	60.76	60.35	60.02	59.65	59.33	58.95	58.67

WATER VAPOR TRANSMISSION CALCULATIONS					
SAMPLE	% WEIGHT LOSS	AVERAGE WEIGHT LOSS	WEIGHT CHANGE (G)	WVT ($G/H \cdot M^2$)	AVERAGE WVT
A1	1.94	1.99	1.40	0.45	0.45
A2	1.92		1.38	0.44	
A3	2.13		1.45	0.46	
B1	1.83	1.50	1.33	0.43	0.36
B2	1.40		1.05	0.34	
B3	1.28		0.95	0.30	
C1	4.95	4.34	3.49	1.12	0.97
C2	4.51		3.03	0.97	
C3	3.57		2.55	0.82	

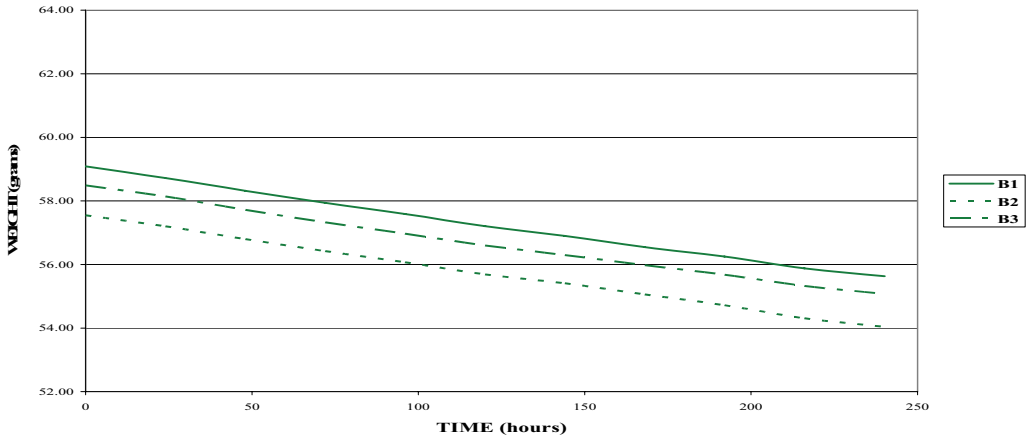
PERMEANCE AND PERMEABILITY CALCULATIONS							
SAMPLE	TIME (H)	S(PA)	$S(R_1-R_2)$	PERMEANCE ($G/PA \cdot S \cdot M^2$)	AVG PERMEANCE	PERMEABILITY (PERM·CM)	AVG PERMEABILITY
A1	240	3.36E+03	1.72E+03	1.92E-07	2.03E-07	2.49E-07	2.64E-07
A2	240	3.36E+03	1.72E+03	1.92E-07		2.50E-07	
A3	240	3.36E+03	1.72E+03	2.26E-07		2.94E-07	
B1	240	3.36E+03	1.72E+03	1.80E-07	1.80E-07	2.33E-07	2.33E-07
B2	240	3.36E+03	1.72E+03	1.82E-07		2.37E-07	
B3	240	3.36E+03	1.72E+03	1.77E-07		2.30E-07	
C1	240	3.36E+03	1.72E+03	1.75E-07	1.80E-07	2.27E-07	2.33E-07
C2	240	3.36E+03	1.72E+03	1.75E-07		2.27E-07	
C3	240	3.36E+03	1.72E+03	1.89E-07		2.46E-07	

APPENDIX I – WATER VAPOR TRANSMISSION DATA

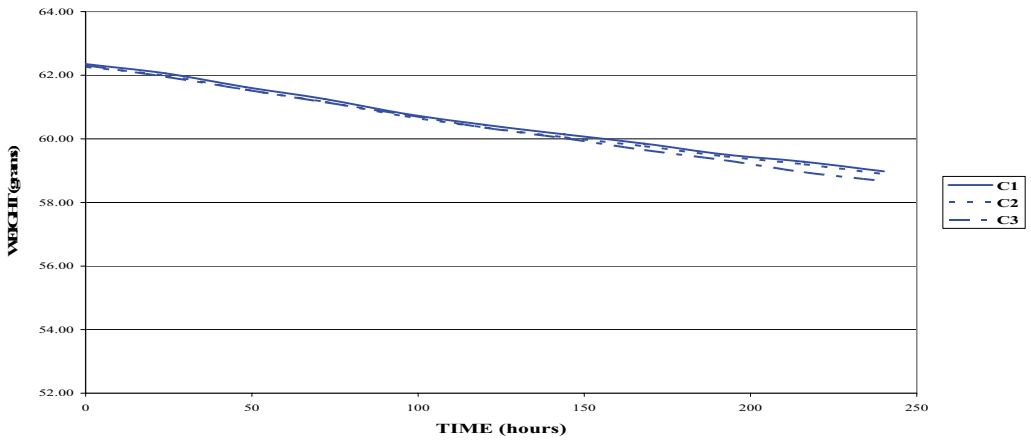
WATER VAPOR TRANSMISSION WEIGHT CHANGE FOR SAMPLE GROUP A



WATER VAPOR TRANSMISSION WEIGHT CHANGE FOR SAMPLE GROUP B

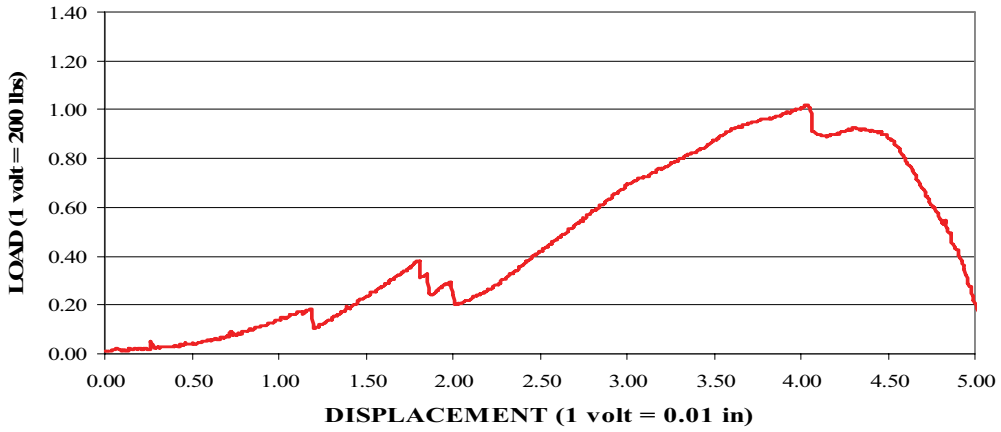


WATER VAPOR TRANSMISSION WEIGHT CHANGE FOR SAMPLE GROUP C

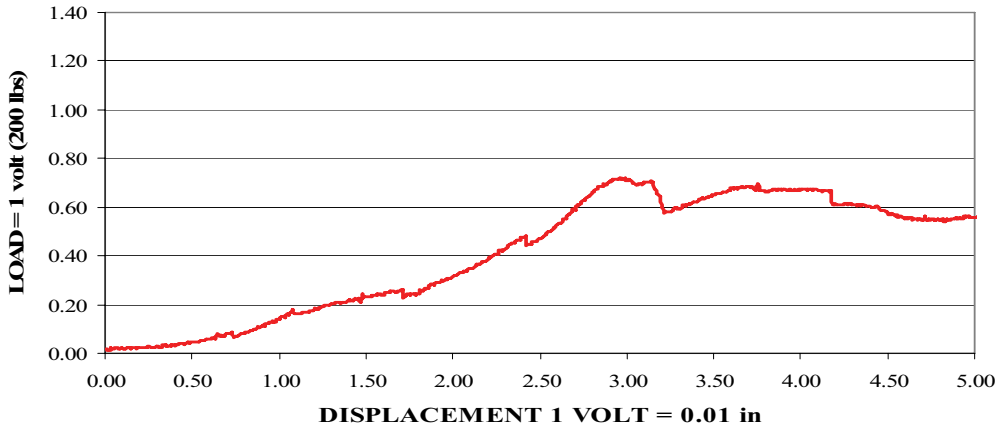


APPENDIX J – SPLITTING TENSILE STRENGTH DATA

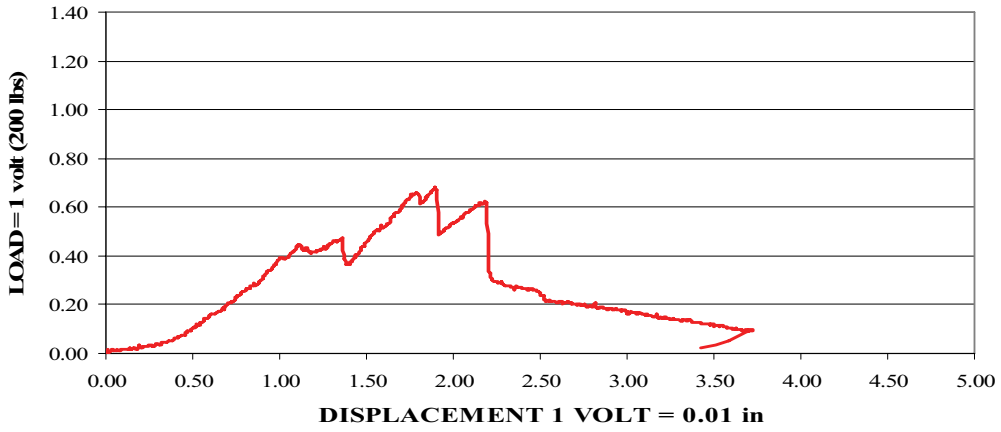
A1 SPLITTING TENSILE STRENGTH TEST (SPEED 0.02 IN/MIN)



A2 SPLITTING TENSILE STRENGTH TEST (SPEED 0.02 IN/MIN)

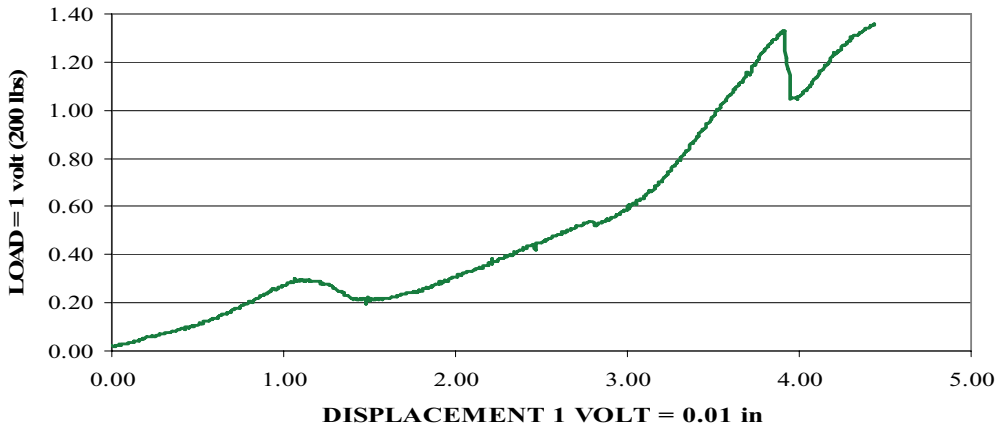


A3 SPLITTING TENSILE STRENGTH TEST (SPEED 0.02 IN/MIN)

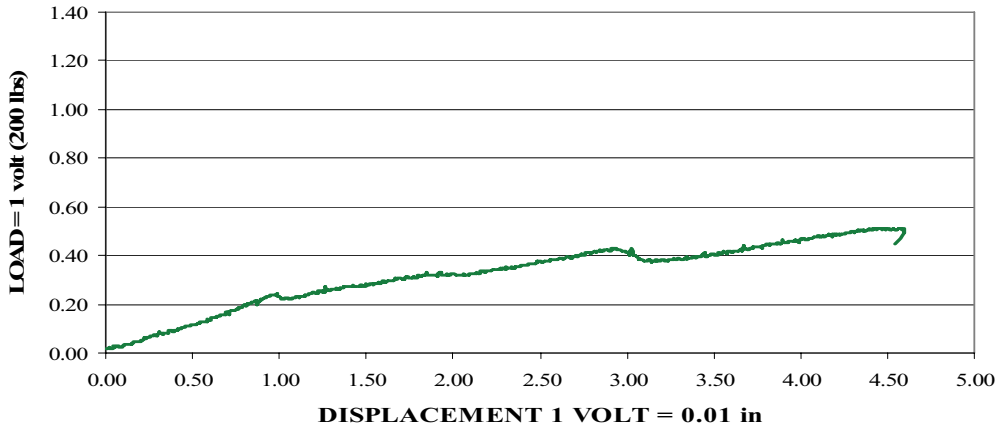


APPENDIX J – SPLITTING TENSILE STRENGTH DATA

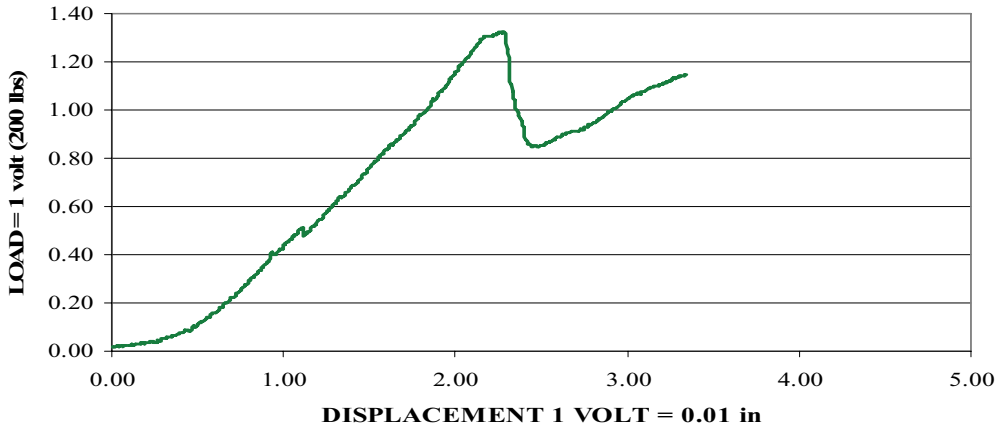
B1 SPLITTING TENSILE STRENGTH TEST (SPEED 0.02 IN/MIN)



B2 SPLITTING TENSILE STRENGTH TEST (SPEED 0.02 IN/MIN)

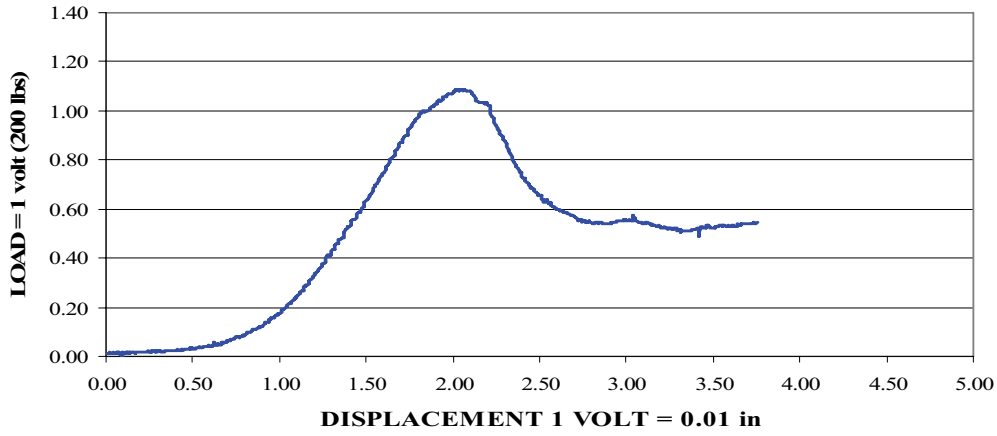


B3 SPLITTING TENSILE STRENGTH TEST (SPEED 0.02 IN/MIN)

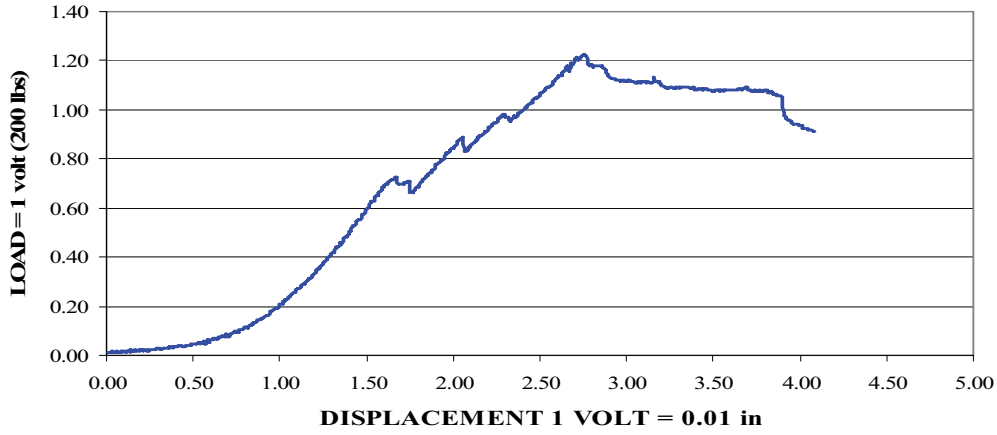


APPENDIX J – SPLITTING TENSILE STRENGTH DATA

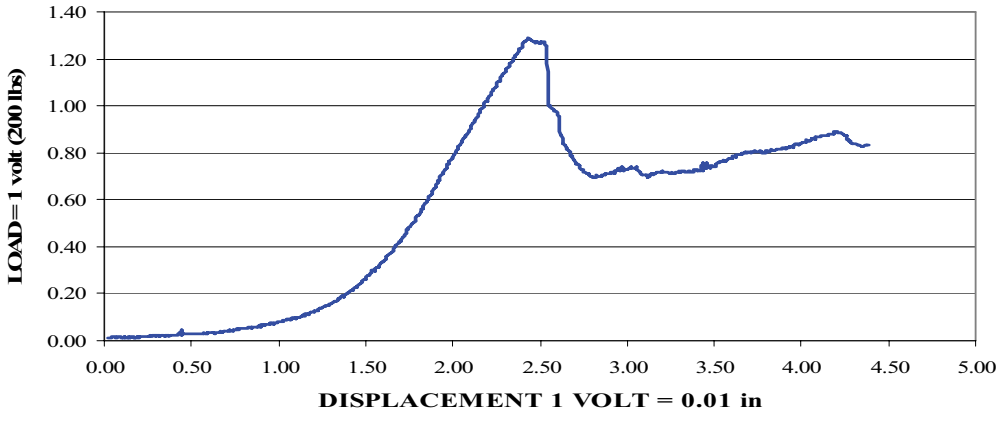
C1 SPLITTING TENSILE STRENGTH TEST (SPEED 0.02 IN/MIN)



C2 SPLITTING TENSILE STRENGTH TEST (SPEED 0.02 IN/MIN)

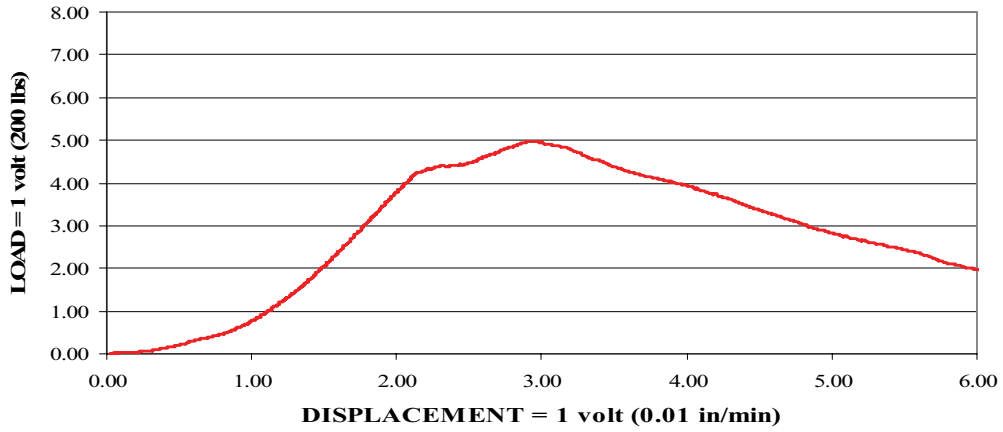


C3 SPLITTING TENSILE STRENGTH TEST (SPEED 0.02 IN/MIN)

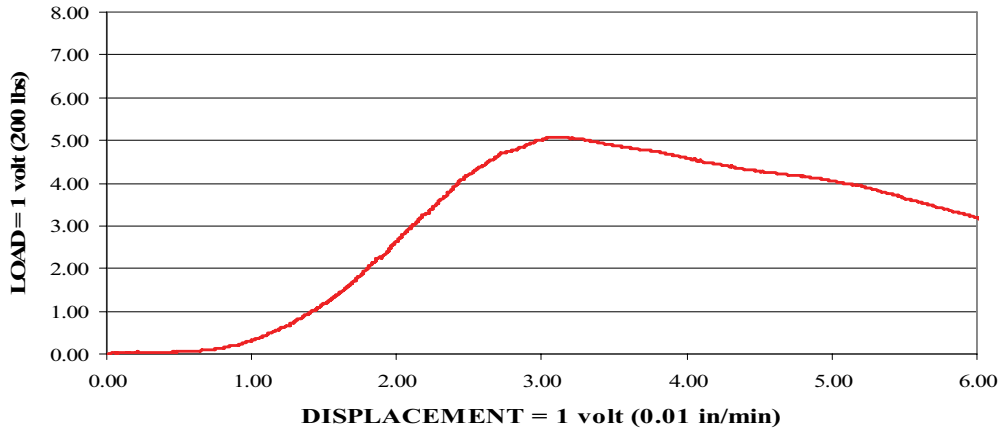


APPENDIX K – COMPRESSIVE STRENGTH DATA

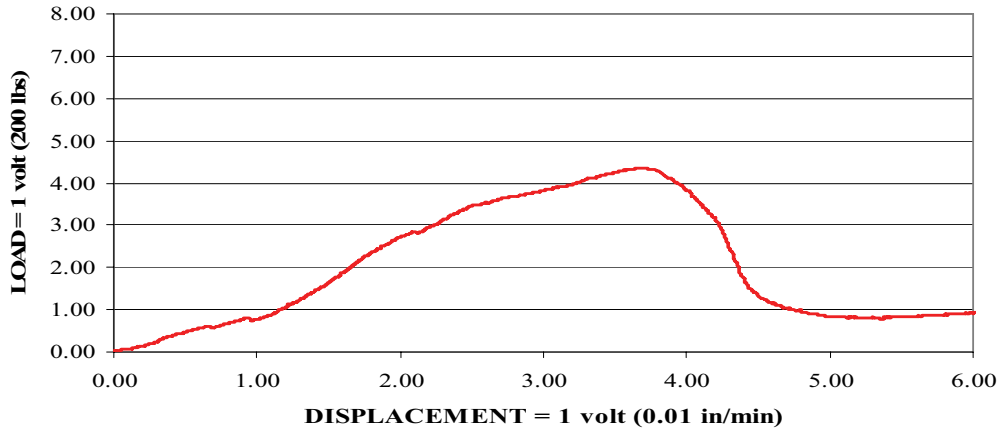
A1 COMPRESSIVE STRENGTH TEST (SPEED 0.02 IN/MIN)



A2 COMPRESSIVE STRENGTH TEST (SPEED 0.02 IN/MIN)

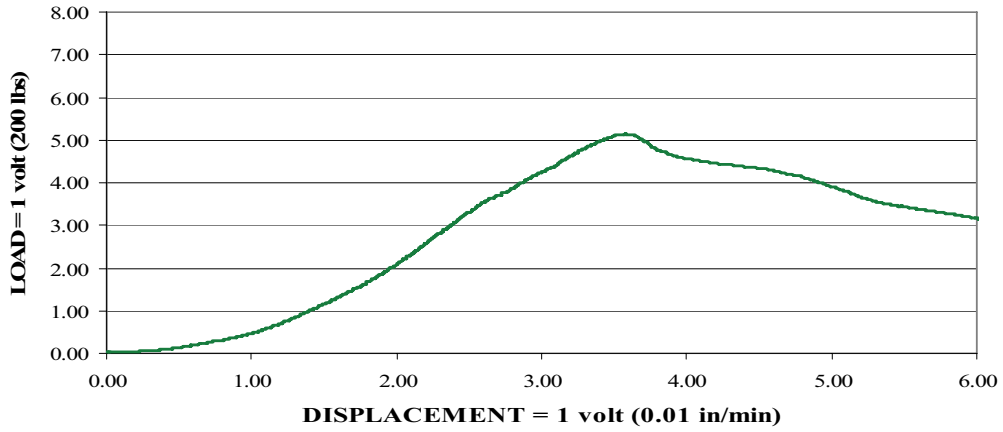


A3 COMPRESSIVE STRENGTH TEST (SPEED 0.02 IN/MIN)

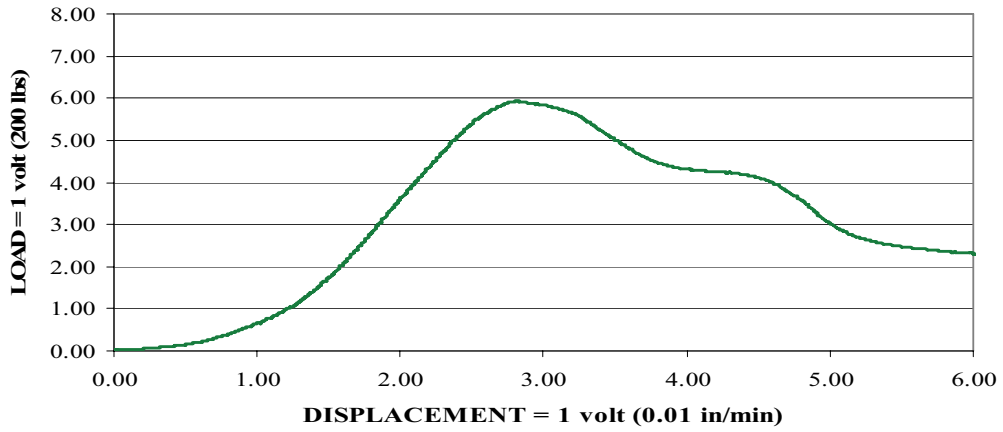


APPENDIX K – COMPRESSIVE STRENGTH DATA

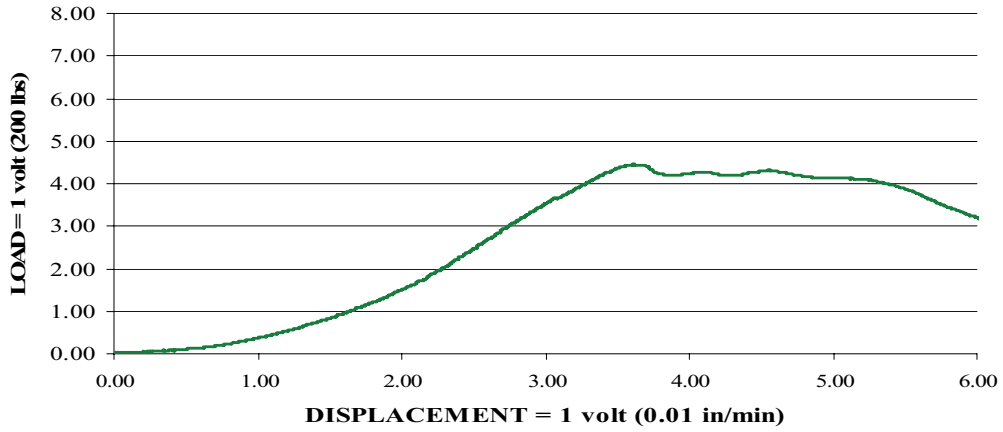
B1 COMPRESSIVE STRENGTH TEST (SPEED 0.02 IN/MIN)



B2 COMPRESSIVE STRENGTH TEST (SPEED 0.02 IN/MIN)

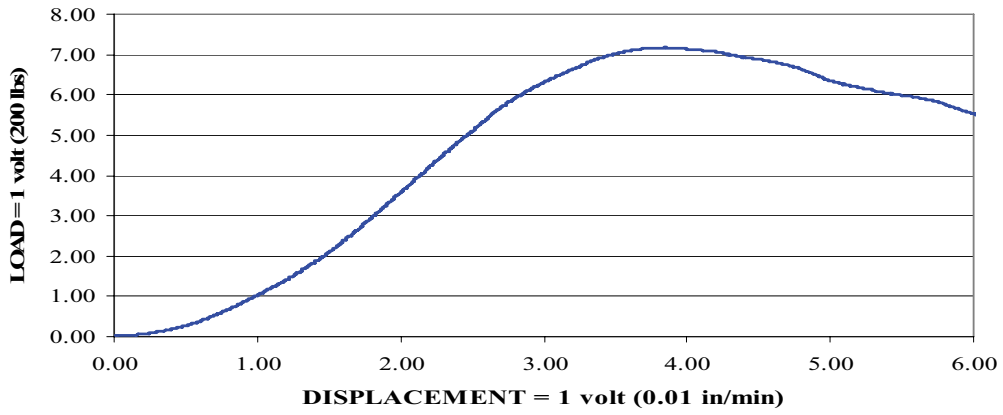


B3 COMPRESSIVE STRENGTH TEST (SPEED 0.02 IN/MIN)

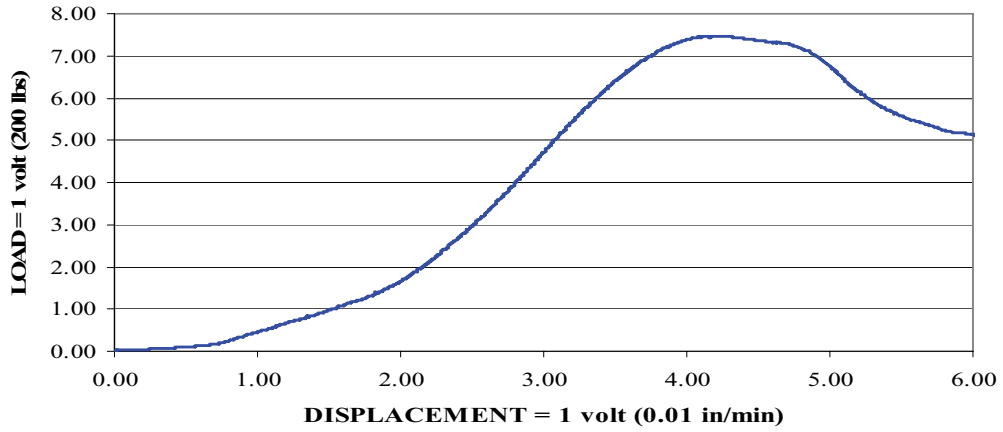


APPENDIX K – COMPRESSIVE STRENGTH DATA

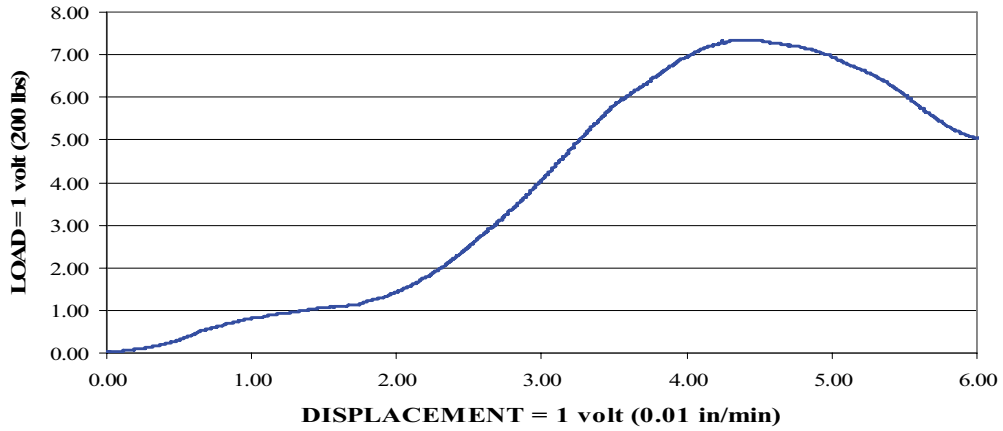
C1 COMPRESSIVE STRENGTH TEST (SPEED 0.02 IN/MIN)



C2 COMPRESSIVE STRENGTH TEST (SPEED 0.02 IN/MIN)



C3 COMPRESSIVE STRENGTH TEST (SPEED 0.02 IN/MIN)



APPENDIX L – FROST RESISTANCE DATA

SAMPLE KEY	
A	2 NHL / 1 S / 1 MS / 0% ER
B	2 NHL / 1 S / 1 MS / 5% ER
C	2 NHL / 1 S / 1 MS / 10% ER

BULK VOLUME CALCULATIONS							
SAMPLE	INITIAL WEIGHT IN AIR (G)	INITIAL WEIGHT IN WATER (G)	INITIAL BULK VOLUME	AFTER 4 CYCLES			
				WEIGHT IN AIR (G)	WEIGHT IN WATER (G)	BULK VOLUME (G)	% BULK VOLUME RETAINED
A1	166.71	41.41	125.30	168.45	43.69	124.76	99.57
A2	164.70	40.65	124.05	166.70	42.55	124.15	100.08
A3	167.16	42.76	124.40	168.89	45.24	123.65	99.40
B1	165.01	39.91	125.10	165.66	40.23	125.43	100.26
B2	159.65	38.42	121.23	160.94	39.72	121.22	99.99
B3	160.22	38.68	121.54	160.96	38.72	122.24	100.58
C1	162.84	39.69	123.15	164.20	41.09	123.11	99.97
C2	161.89	39.20	122.69	163.25	40.93	122.32	99.70
C3	161.02	39.21	121.81	161.75	40.70	121.05	99.38

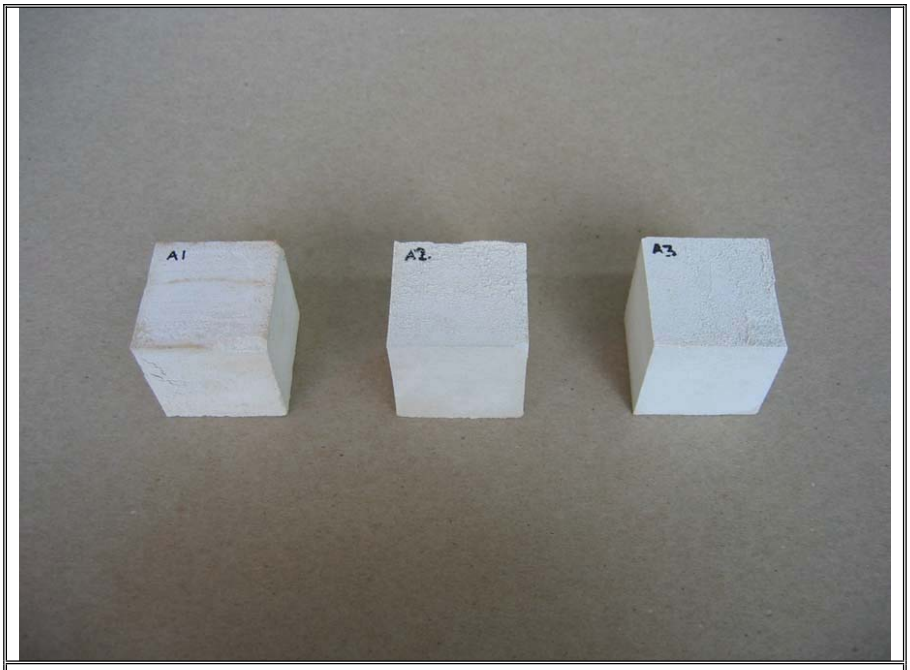
BULK VOLUME CALCULATIONS							
SAMPLE	INITIAL WEIGHT IN AIR (G)	INITIAL WEIGHT IN WATER (G)	INITIAL BULK VOLUME	AFTER 8 CYCLES			
				WEIGHT IN AIR (G)	WEIGHT IN WATER (G)	BULK VOLUME (G)	% BULK VOLUME RETAINED
A1	166.71	41.41	125.30	169.75	44.64	125.11	99.85
A2	164.70	40.65	124.05	167.95	43.70	124.25	100.16
A3	167.16	42.76	124.40	170.05	45.43	124.62	100.18
B1	165.01	39.91	125.10	166.88	41.72	125.16	100.05
B2	159.65	38.42	121.23	162.38	40.88	121.50	100.22
B3	160.22	38.68	121.54	162.24	40.60	121.64	100.08
C1	162.84	39.69	123.15	165.66	42.20	123.46	100.25
C2	161.89	39.20	122.69	164.73	42.20	122.53	99.87
C3	161.02	39.21	121.81	163.62	41.98	121.64	99.86

APPENDIX L – FROST RESISTANCE DATA

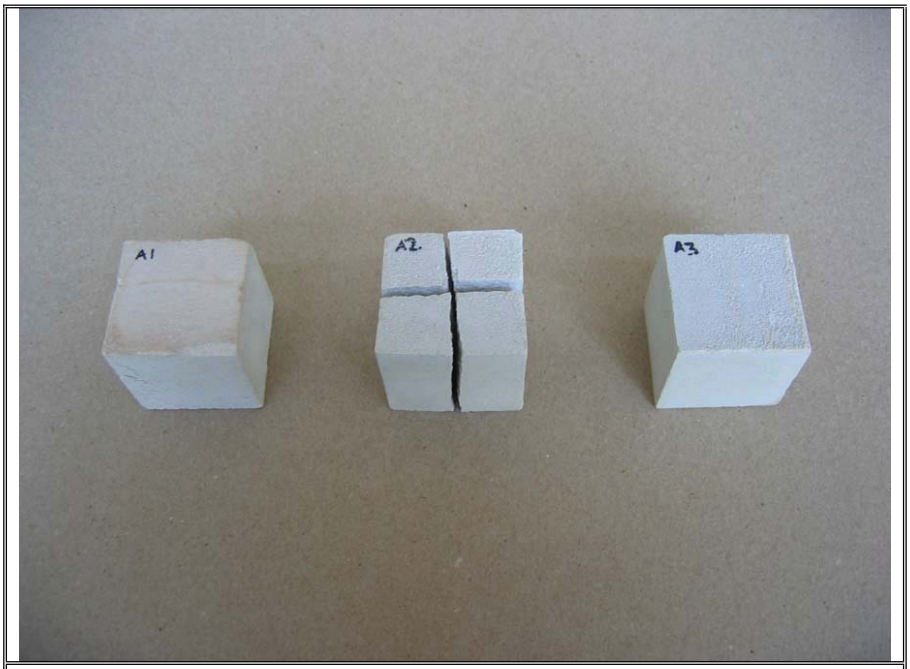
SAMPLE KEY	
A	0% acrylic
B	5% acrylic
C	10% acrylic

BULK VOLUME CALCULATIONS							
SAMPLE	INITIAL WEIGHT IN AIR (G)	INITIAL WEIGHT IN WATER (G)	INITIAL BULK VOLUME	AFTER 12 CYCLES			
				WEIGHT IN AIR (G)	WEIGHT IN WATER (G)	BULK VOLUME (G)	% BULK VOLUME RETAINED
A1	166.71	41.41	125.30	171.12	45.86	125.26	99.97
A2	164.70	40.65	124.05	168.21	44.61	123.60	99.64
A3	167.16	42.76	124.40	171.18	46.33	124.85	100.36
B1	165.01	39.91	125.10	167.69	42.42	125.27	100.14
B2	159.65	38.42	121.23	163.28	41.74	121.54	100.26
B3	160.22	38.68	121.54	163.10	41.16	121.94	100.33
C1	162.84	39.69	123.15	166.46	42.98	123.48	100.27
C2	161.89	39.20	122.69	165.66	42.90	122.76	100.06
C3	161.02	39.21	121.81	164.53	42.80	121.73	99.93

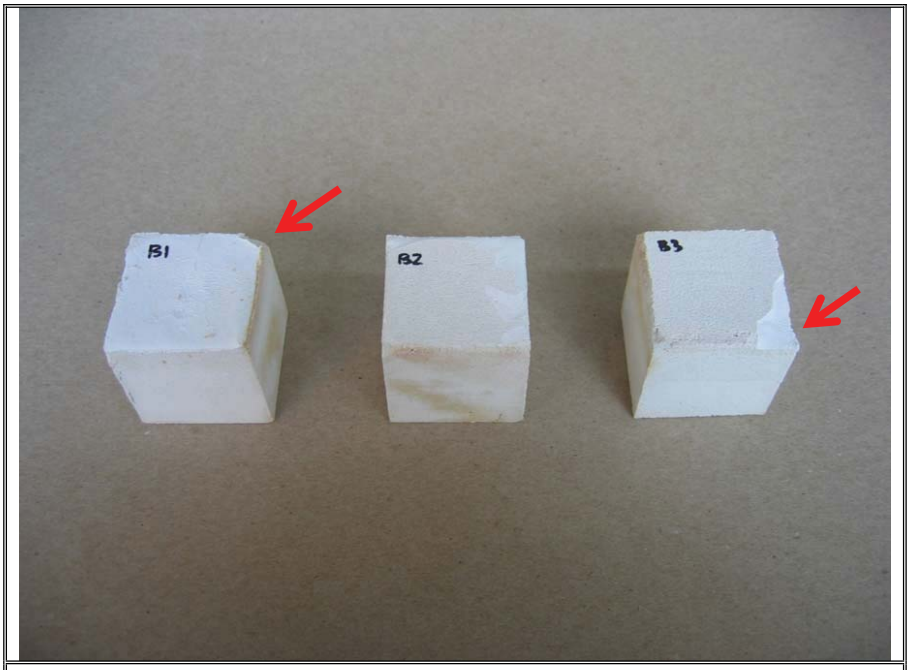
BULK VOLUME CALCULATIONS							
SAMPLE	INITIAL WEIGHT IN AIR (G)	INITIAL WEIGHT IN WATER (G)	INITIAL BULK VOLUME	AFTER 15 CYCLES			
				WEIGHT IN AIR (G)	WEIGHT IN WATER (G)	BULK VOLUME (G)	% BULK VOLUME RETAINED
A1	166.71	41.41	125.30	171.66	45.96	125.70	100.32
A2	164.70	40.65	124.05	171.02	44.80	126.22	101.75
A3	167.16	42.76	124.40	171.61	46.69	124.92	100.42
B1	165.01	39.91	125.10	167.88	42.60	125.28	100.14
B2	159.65	38.42	121.23	163.42	41.70	121.72	100.40
B3	160.22	38.68	121.54	163.06	41.45	121.61	100.06
C1	162.84	39.69	123.15	166.74	43.55	123.19	100.03
C2	161.89	39.20	122.69	165.85	43.20	122.65	99.97
C3	161.02	39.21	121.81	164.93	43.15	121.78	99.98



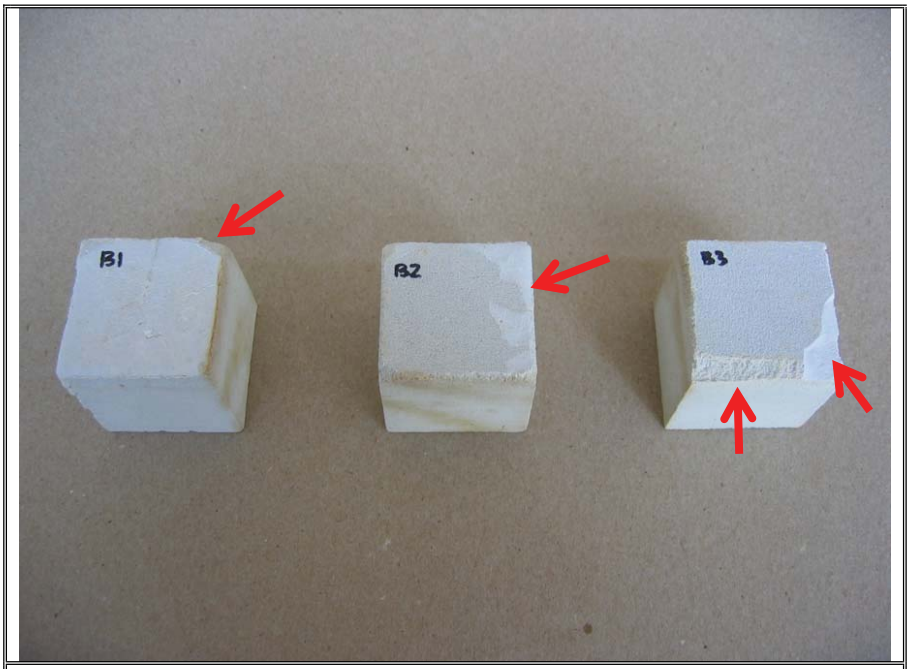
Sample Group A before 6-hour immersion and first freeze/thaw cycle.



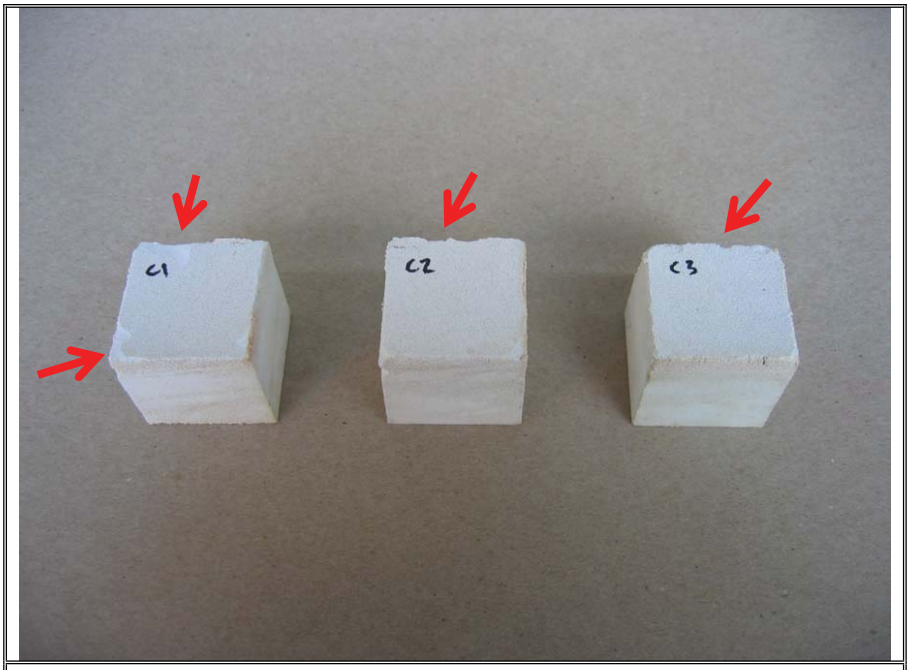
Sample Group A after 6-hour immersion and 15 freeze/thaw cycles.
The only appreciable changes are the 2 vertical cracks in Sample A2.



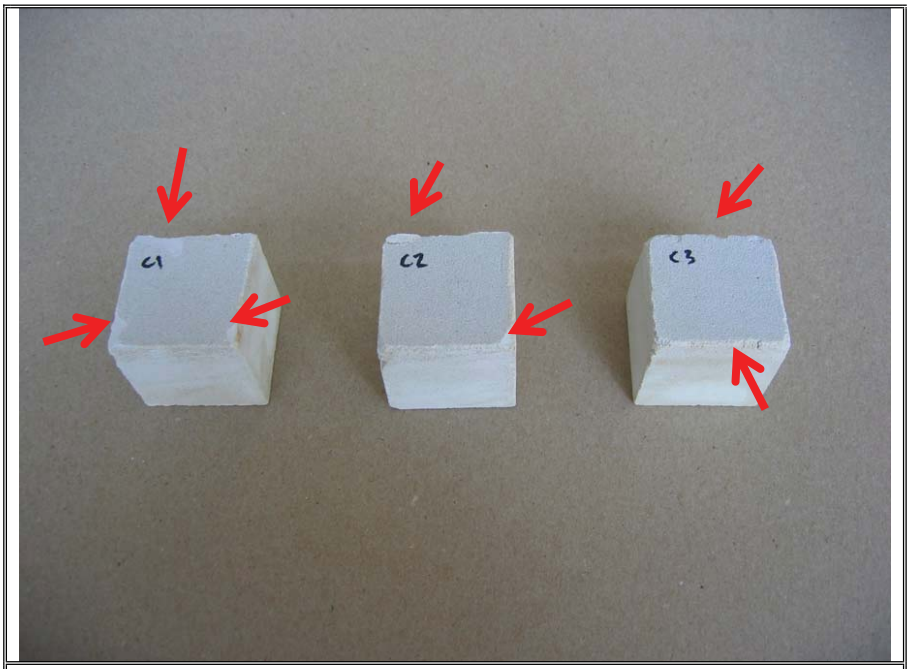
Sample Group B before 6-hour immersion and first freeze/thaw cycle.
Note chips on sample edges.



Sample Group B after 6-hour immersion and 15 freeze/thaw cycles.
Note further erosion of the edges on these samples.



Sample Group C before 6-hour immersion and first freeze/thaw cycle.
Note chips on sample edges.



Sample Group C after 6-hour immersion and 15 freeze/thaw cycles.
Note further erosion of the edges on these samples.

APPENDIX M – SALT CRYSTALLIZATION DATA

SAMPLE KEY	
A	2 NHL / 1 S / 1 MS / 0% ER
B	2 NHL / 1 S / 1 MS / 5% ER
C	2 NHL / 1 S / 1 MS / 10% ER

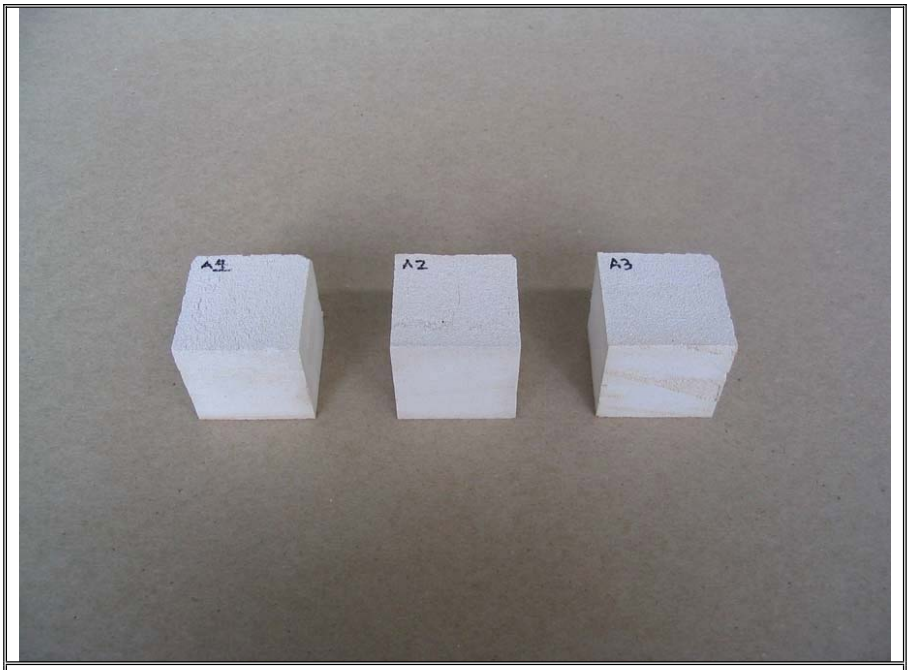
WEIGHT MEASUREMENTS AND WEIGHT CHANGE CALCULATIONS							
SAMPLE	INITIAL WEIGHT (G)	CYCLE 2		CYCLE 4		CYCLE 6	
		WEIGHT (G)	WEIGHT CHANGE (%)	WEIGHT (G)	WEIGHT CHANGE (%)	WEIGHT (G)	WEIGHT CHANGE (%)
A1	120.32	151.57	25.97	157.56	30.95	167.10	38.88
A2	119.72	147.55	23.25	153.16	27.93	162.84	36.02
A3	118.62	146.54	23.54	153.59	29.48	162.48	36.98
B1	120.73	141.56	17.25	143.87	19.17	153.85	27.43
B2	116.43	135.43	16.32	139.27	19.62	146.96	26.22
B3	120.38	140.91	17.05	146.12	21.38	151.22	25.62
C1	120.21	144.00	19.79	143.29	19.20	143.93	19.73
C2	120.19	141.32	17.58	144.22	19.99	143.86	19.69
C3	120.17	141.28	17.57	144.10	19.91	141.94	18.12

WEIGHT MEASUREMENTS AND WEIGHT CHANGE CALCULATIONS							
SAMPLE	INITIAL WEIGHT (G)	CYCLE 8		CYCLE 10		CYCLE 12	
		WEIGHT (G)	WEIGHT CHANGE (%)	WEIGHT (G)	WEIGHT CHANGE (%)	WEIGHT (G)	WEIGHT CHANGE (%)
A1	120.32	168.88	40.36	169.98	41.27	169.73	41.07
A2	119.72	164.71	37.58	165.98	38.64	161.97	35.29
A3	118.62	161.70	36.32	162.45	36.95	144.53	21.84
B1	120.73	159.78	32.34	108.57	-10.07	0.00	-100.00
B2	116.43	152.97	31.38	154.10	32.35	106.50	-8.53
B3	120.38	156.37	29.90	148.01	22.95	0.00	-100.00
C1	120.21	145.22	20.81	146.98	22.27	138.16	14.93
C2	120.19	145.87	21.37	147.19	22.46	138.23	15.01
C3	120.17	142.64	18.70	143.84	19.70	0.00	-100.00

APPENDIX M – SALT CRYSTALLIZATION DATA

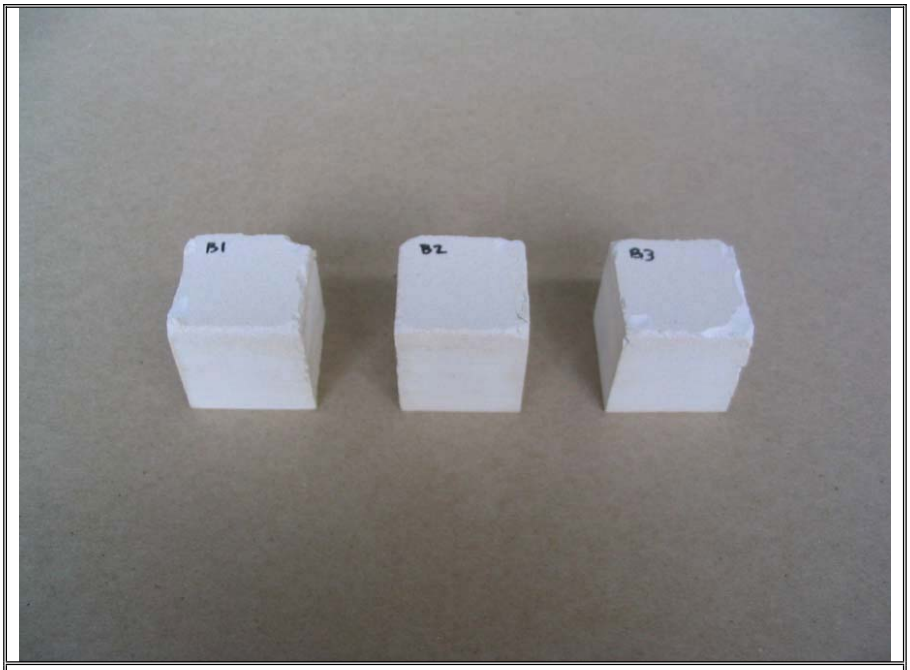
SAMPLE KEY	
A	2 NHL / 1 S / 1 MS / 0% ER
B	2 NHL / 1 S / 1 MS / 5% ER
C	2 NHL / 1 S / 1 MS / 10% ER

WEIGHT MEASUREMENTS AND WEIGHT CHANGE CALCULATIONS							
SAMPLE	INITIAL WEIGHT (G)	CYCLE 14		CYCLE 15		AFTER TAP WATER IMMERSION & DRYING	
		WEIGHT (G)	WEIGHT CHANGE (%)	WEIGHT (G)	WEIGHT CHANGE (%)	WEIGHT (G)	WEIGHT CHANGE (%)
A1	120.32	170.29	41.53	171.47	42.51	129.33	7.49
A2	119.72	150.98	26.11	0	-100.00	0	-100.00
A3	118.62	143.89	21.30	143.22	20.74	109.84	-7.40
B1	120.73	0	-100.00	0	-100.00	0	-100.00
B2	116.43	0	-100.00	0	-100.00	0	-100.00
B3	120.38	0	-100.00	0	-100.00	0	-100.00
C1	120.21	127.82	6.33	118.4	-1.51	94.78	-21.15
C2	120.19	0	-100.00	0	-100.00	0	-100.00
C3	120.17	0	-100.00	0	-100.00	0	-100.00



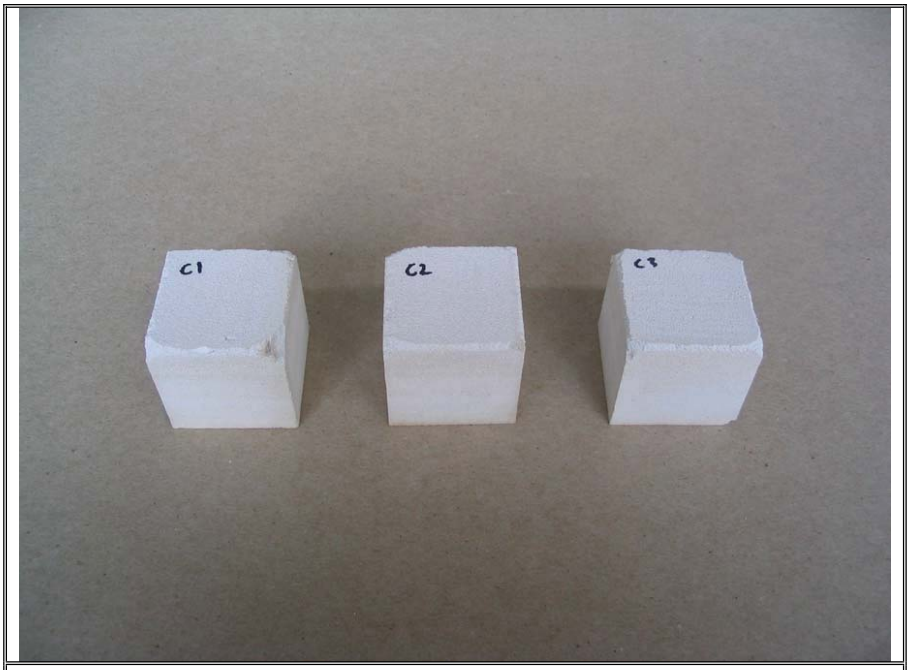
Sample Group A before first immersion in 10% sodium sulfate solution, 7-day immersion in tap water, and drying in oven.

Sample Group A after 14 immersion cycles in 10% sodium sulfate solution, 7-day immersion in tap water, and drying in oven. A1 has visible cracks, A2 is split vertically, and A3 exhibits notable erosion and cracking.



Sample Group B before first immersion in 10% sodium sulfate solution, 7-day immersion in tap water, and drying in oven.

Sample B2 after 12 immersion cycles in 10% sodium sulfate solution, 7-day immersion in tap water, and drying in oven. B1 and B3 failed after the 10th cycle after cracking in half. B1 exhibited significant disaggregation around its center.



Sample Group C before first immersion in 10% sodium sulfate solution, 7-day immersion in tap water, and drying in oven.

Sample C1 after 14 immersion cycles in 10% sodium sulfate solution, 7-day immersion in tap water, and drying in oven. C3 disintegrated after the 10^{th} cycle. C2 failed after the 12^{th} cycle.

APPENDIX N – MATERIAL SUPPLIERS

CHEMTECH SPECIALTIES
5700 Tacony Street
Philadelphia, PA 19135
215.537.1000 / 800.423.7423
www.chemtechspecialties.com
(1) 50 lb bag of 3M G-3500 ceramic microspheres, purchased at an unknown date

HOME DEPOT
1651 South Columbus Boulevard
Philadelphia, PA 19148
215.218.0600
www.homedepot.com
Buckets, paint mixing attachment, plumber's putty.

DURHAM GEO SLOPE INDICATOR
2175 West Park Court
Stone Mountain, GA 30087
770.465.7557
www.durhamgeo.com
(1) Grout flow cone, model C-242

GEORGE F. KEMPF SUPPLY COMPANY
5800 Lindbergh Boulevard
Philadelphia, PA 19143
215.724.8000
(1) 100 lb bag of Mason's Sand, purchased D December 2004.

EL REY STUCCO COMPANY
50 Rio Grande Boulevard
Denver, CO 80223
303.534.3536 / 888.463.5739
www.elrey.com
(1) 5 Gallon bucket of Superior Additive 200

PENNSYLVANIA LIME WORKS
P.O. Box 151
Milford Square, PA 18935
215.536.6706
www.palimeworks.com
(2) 55 lb bags of St. Astier NHL 3.5, purchased December 2004.

FISHER SCIENTIFIC
Liberty Lane
Hampton, NH 03842
800.766.7000
www.fishersci.com
All laboratory supplies unless otherwise noted.

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