UNIVERSITY OF SOUTH CAROLINA

Project Manual:: Appendix B Mortar & Brick Analysis

Contract Documents
Historic Horseshoe Wall Restoration
Phase 2

State Project No. H27- Z205
SMHa Project Number 1605
April 27, 2016

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Characterization of Masonry Mortar
Historic Campus Wall
University of South Carolina

by
Denis A. Brosnan, Ph.D., P.E.
July 2, 2014

Executive Summary

Specimens of mortar from the Historic Wall completed in 1836 were characterized as to their chemical and mineralogical composition and for selected physical properties. The purpose was development of information for use in specifications for repair material and to guide restoration activities. Continuing advice and construction monitoring in future restorations are to be provided to the Architectural/Engineering team as restoration progresses.

The brick masonry wall was built before the era of Portland cement production but during a time when lime, hydraulic lime, and "Roman cement" binders were available for use with aggregate (sand) to produce masonry mortars. It is important that repair mortars are compatible with those used in original constructions to ensure the repairs do no harm to the historic materials. To this end, the mortars on the wall were subjected to analytical tests and microscopic examinations.

The mortar binders were found to be similar to contemporary natural (pozzolanic) hydraulic lime with a hydraulic lime to sand volumetric ratio varying between 1:2 and 1:3. The binder was a unique mixture of clay and magnesian lime manufactured to exhibit mineral constituents called pozzolans that impart greater chemical durability to hardened mortars than those composed of only lime binders. Bricks were not examined as a part of characterization activities, as the bricks on the Wall are generally in excellent structural condition for continued service.

Mortar deterioration was observed at the top of the wall in coping courses, near and below ground level in vertical sections. In coping courses, organic acids from vegetation and rain exposure led to partial removal of the carbonate binder and weakening of the mortar. Near and below ground level, dissolved salt in ground water and rising damp facilitated partial removal of the carbonate binder. The results on a microscopic scale are altered mineralogy and increases in porosity/air content.

Restoration of historic masonry is conducted in compliance with the Secretary of the Interior's Standards for the Treatment of Historic Properties which addresses use of compatible materials, use of materials authentic to the structure, and repairs conducted in compliance with the aesthetics of the structure. Use of natural hydraulic lime mortar meeting ASTM Standard C1707 is recommended for restoration of the Wall. These mortars are available or can be produced in both bedding and pointing formulations with colorants added to ensure acceptable aesthetics. Care is advised in consulting with the supplier and/or pre-testing candidate mortars in small field panels prior to repairs to evaluate efflorescence potential and ensure no unexpected costs for masonry cleaning.

Engineering Assessment of Bricks
Historic Campus Wall
University of South Carolina

by
Denis A. Brosnan, Ph.D., P.E.
July 7, 2014

Executive Summary

Specimens of clay bricks from the Historic Wall completed in 1836 were characterized as to their engineering properties that relate to contemporary Standards for brick products. The purpose was development of information for use in specifications for repair material and to guide restoration activities. These bricks were obtained from cataloged achieve specimens held at USC in late 2010.

The bricks were found to be hand molded and produced from weathered shale clay as is found in the Columbia S.C. area[1]. The bricks were found to exhibit saturation coefficients and pore structures that would classify them as Grade SW (Severe Weathering) in contemporary Standards, and replacement bricks meeting Grade SW are strongly recommended. The test results are consistent with the observation of only a few freezing and thawing durability failures or "spalls" on the Wall. Additional brick attributes for repair include use of similar brick sizes, colors, thermal expansion, and surface features as in original construction. Mortar color matching and joint tooling are important in repairs so as to match the aesthetics of the original structure.

Introduction

Four structural clay brick specimens from original construction of the Horseshoe Wall, located in historical archives, were tested for absorption properties according to the method in ASTM C67, *Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile*. These specimens were also tested using Mercury Intrusion Porosimetry (MIP) to further establish their contemporary Grade rating, and they were tested using thermal expansion by dilatometry in order to estimate their firing temperatures.

The purpose of this report is to provide supplemental information for the current preservation activities with the Wall. Bricks meeting ASTM C 216 Grade SW (Severe Weathering) in restoration work were recently recommended[2]. The specimens were tested in the Bishop Materials Laboratory of Clemson University under the certifications attained by that organization relative to the tests.

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[1] The source of bricks was primarily from the John Brown brickyard located by the Congaree River in Columbia, but some bricks were obtained from Charleston, SC. See "University of South Carolina Campus Wall Historic Structure Survey, E. Oswald, J. Betsworth, and J. Zeise, A Report Prepared for Dr. Robert Weyeneth, Spring (2011).

[2] Characterization of Masonry Mortar, Historic Campus Wall, University of South Carolina, Denis A. Brosnan, Ph.D., P.E., July 2, 2014.

Bricks are fundamentally classified under ASTM C 216 by their water absorption characteristics and their compressive strength. The absorption characteristics reflect the pore structure that essentially determines the ability of the bricks to resist the forces involved in freezing and thawing of water saturated bricks. Therefore, much attention in this report is paid to properties that reflect pore structure in characterization of historic bricks.

The qualification of structural clay units in resisting freezing and thawing cycles is judged by comparing water absorption characteristics with criteria in contemporary Standards[3], with tests conducted using the methods in ASTM C 67. While contemporary Standards do not apply to bricks in older masonry structures, the criteria in the Standards represent years of accumulated knowledge on brick masonry and are used in making an engineering estimate of brick performance. To further consider the qualification of the bricks, the pore size and pore volume criteria developed by Maage are employed[4]. Finally, the firing temperature of the bricks was determined using thermal dilatometry[5].

Findings

Photographs of three of the as-received bricks are shown in the Appendix. All appear to be molded bricks based on the weathered shale commonly found in the Columbia area. The three brick were all red to red-yellow in color with typical "porous texture" for molded bricks as shown on fracture surfaces on the as-received photographs.

The absorption properties of the bricks are given in Table 1. The properties are briefly explained as follows:

Cold Water Absorption (CWA) – the weight gain of a dried brick or tile expressed as a percentage increase from the dry weight after immersion in room temperature water for 24-hours. Such treatment typically fills or saturates about 66-68% of the open porosity of the brick.

Boiling Water Absorption (BWA) – the weight gain of a dried brick or tile expressed as a percentage increase from the dry weight after immersion in boiling water for five hours. Such treatment typically fills or saturates over 96% of the open porosity of the brick.

Saturation Coefficient – the quotient of CWA divided by BWA expressed as a fraction. This quantity reflects the fraction of "fine pores" within the brick or tile. Contemporary Standards set a maximum of saturation coefficient was a means of discriminating durable and non-durable bricks.

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[3] ASTM C216, Standard Specification for Facing Brick (Solid Masonry Units Made from Clay or Shale), The American Society for Testing and Materials. ASTM C212, Standard Specification for Structural Clay Facing Tile, The American Society for Testing and Materials

[4] Manfred Maage, *Frost Resistance and Pore Size Distribution of Bricks,* Ziegelindustrie International, 9 (1990) 472-481.

[5] L. Franke and I. Schumann, *Subsequent Determination of the Firing Temperature of Historic Bricks*, Conservation of Historic Brick Structures, Donhead Publishing, ISBN 1 873394 34 9 (1998).

For example, a brick classed as SW (Severe Weathering) in ASTM C216 cannot exceed a saturation coefficient of 0.80 (or 0.78 as an average in a group of five bricks).

The mercury porosimetry results are also given in Table 1. The Maage Index estimates the durability of fired clay bricks based on the total porosity and the fraction (content) of pores greater than three microns in diameter. The Maage Index rating is as follows:

Maage Index	Rating
>70	Frost resistant at normal saturation.
55-70	Unpredictable performance at normal saturation.
<55	Not frost resistant at normal saturation.

The results in Table 1 show all historic bricks to meet the saturation coefficient criteria for Grade SW (Severe Weathering) bricks as provided in contemporary Standard C216. Three of four bricks tested failed to meet the boiling water absorption maximum values for Grade SW bricks, and this is not surprising for bricks that were hand molded in the early 1800's. All of the bricks tested were rated as "durable" by the Maage criteria. These findings are consistent with the observation that there were only a few durability failures on the Wall.

The coefficient of thermal expansion in the interval room temperature to 200^{o}C for three of the specimens were in the approximate range 5.6-5.8 exp (-6)/^{o}C, a normal value range for clay bricks (Table 2)[6]. It is unlikely that sand was added to the local clay for making the bricks using the Columbia weathered shale (sand would increase the thermal expansion coefficient of fired bricks). Note that general matching of the thermal expansion coefficient between new and original bricks is recommended for repairs in historic structures.

Color data is given in Table 3, and it may be compared to as-received photographs of three of the four bricks. Brick 37E exhibits the largest yellow hue (highest b* value), consistent with the fact that this brick exhibits the lowest predicted firing temperature (Table 4). It is noted that brick 37E was previously classed as durable by the absorption and Maage methods despite a "lower" firing temperature.

The firing temperatures of the bricks (Table 4) were estimated using thermal dilatometry to be in the range 1076-1098^{o}C (1969-2008^{o}F). The individual dilatometry curves are given in the Appendix. For comparison purposes, modern facing bricks manufactured in Columbia classed as severe weathering and based on weathered shale are typically exposed to temperatures of about1093^{o}C (2000^{o}F). The values of the historic bricks allow them to be considered as "normally fired" for estimation of their Grade qualification.

[6] The normal range for thermal expansion coefficient for clay bricks is 3.4 – 8.0 exp (-6)/^{o}C per M. Kornmann, Clay Bricks and Rooftiles, Societe de l'industrie minerale, Paris (2007).

Table 1: Standards, Absorption Properties, and Maage Index

Category and Specimen ID	Cold Water Absorption, % (CWA)	Boiling Water Absorption, % (BWA)	Saturation Coefficient (CWA/BWA)	Apparent Porosity. %	Maage Index	Durability Prediction at Normal Saturation
Limit for SW bricks (average)		≤17.0	≤0.78	Not specified.		
Limit for SW bricks (individual)		≤20.0	≤0.80	Not specified.		
Limit for MW bricks (average)		≤22.0	≤0.88	Not specified.		
Limit for MW bricks (individual)		≤25.0	≤0.90	Not specified.		
4W	6.88	11.66	0.59	23.55	138.0	Pass SW CWA/BWA Meets SW by CWA Pass Maage
30W	17.37	22.00	0.79	36.96	213.6	Pass SW CWA/BWA Meets MW by CWA Pass Maage
34E	15.18	20.26	0.75	35.44	205.5	Pass SW CWA/BWA Meets MW by CWA Pass Maage
37E	17.52	22.09	0.79	37.60	75.3	Pass SW CWA/BWA Meets MW by CWA Pass Maage

Table 2: Coefficient of Thermal Expansion by Thermal Dilatometry

Specimen	Value, / ^oC	Comment
4W	5.59exp(-6)	Normal value for clay brick.
30W	5.8exp(-6)	Normal value for clay brick.
34E	5.69exp(-6)	Normal value for clay brick.
37E	1.79exp(-6)	Instrument fault at low temperature influenced result.

Table 3: Color Measurement in the L*a*b* System of Measurement

Specimen	L* (+L indicates lightness)	a* (+a indicates red)	b* (+b indicates yellow)
4W	42.7	14.8	17.3
30W	45.4	17.5	24.1
34E	41.4	13.6	16.9
37E	55.7	16.7	27.7

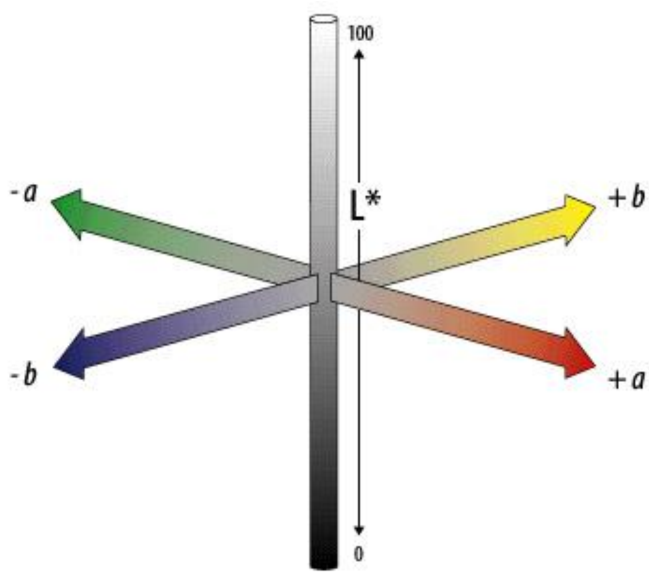


Figure 1: L*a*b* Coordinate System

Table 4: Estimated Firing Temperatures by Deflection in Thermal Dilatometry

Specimen	Value, ^{o}C
4W	1097.6
30W	1085.8
34E	1088.1
37E	1076.0

Conclusions

The absorption and mercury porosimetry indices show all brick tested to be predicted as durable in agreement with practical observations of bricks in the Historic Wall. This supports the recommendation of use of Grade SW bricks for restoration repairs. Other criteria for replacement bricks include:

- Use of replacement molded bricks of the same size as the historic units.
- Color matching of replacement bricks to those bricks in the existing wall with similar surface features to include a smooth texture.
- Use of replacement molded bricks of similar thermal expansion coefficient as those in the historic wall.

While compressive strength was not obtained in this assessment, the bricks in the Wall appear sound and have obviously performed well.

With regards,

Denis A. Brosnan

Denis A. Brosnan, Professor and Consultant
Registered Professional Engineer
SC Registration 13888

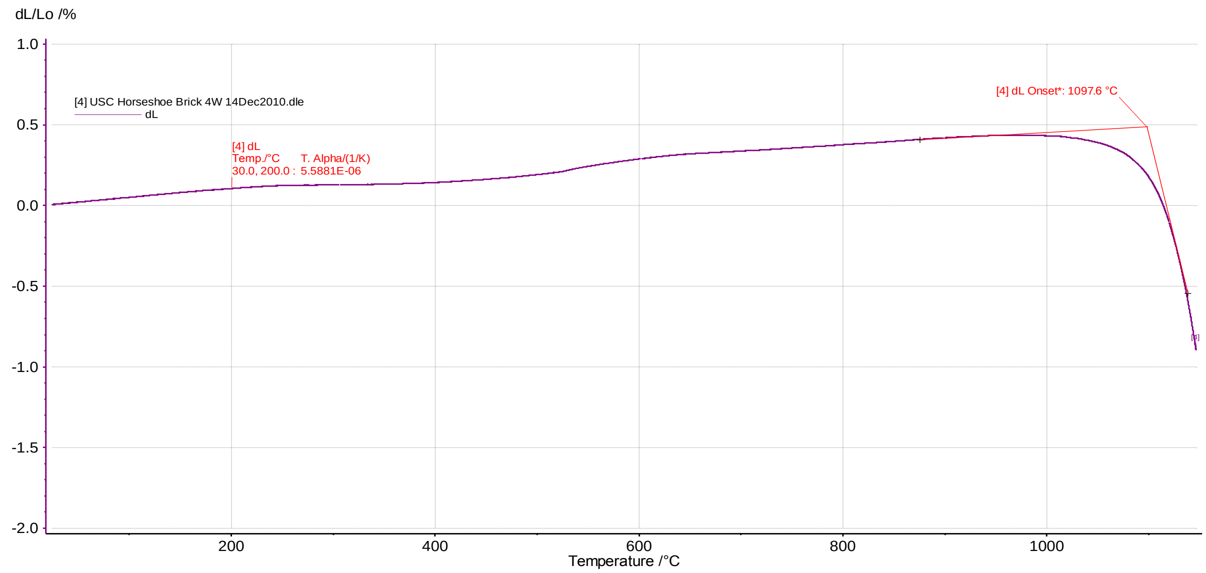
Appendix: Photographs and Additional Data

As-Received Photographs – No Brightness or Contrast Adjustment
No photograph available for Specimen 4W

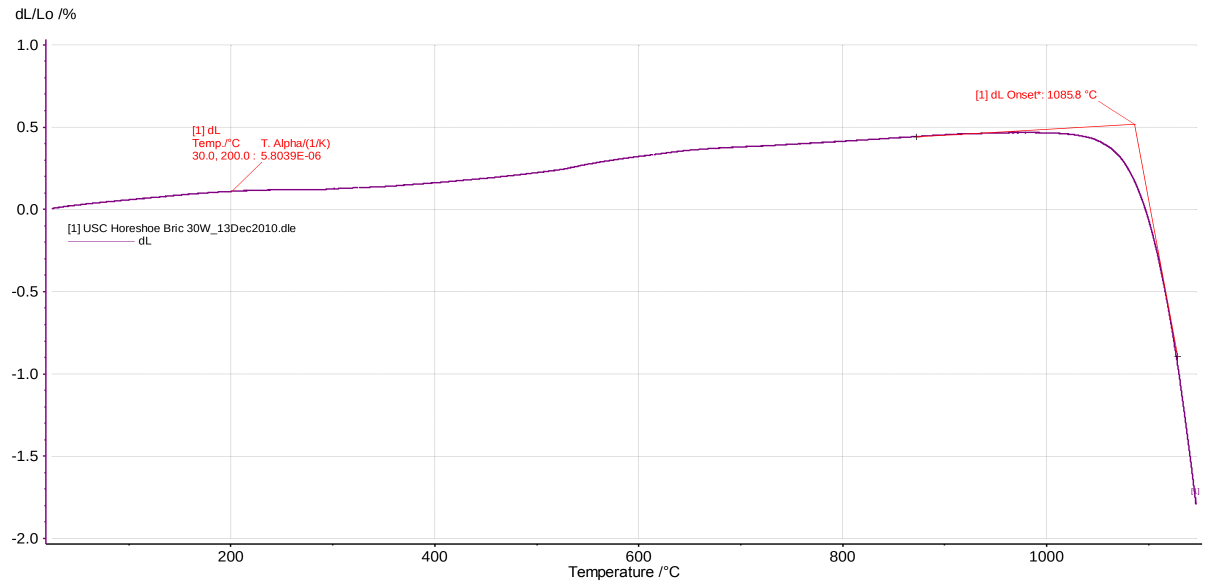

34E
USC Confederate Wall 34E


USC Confederate Wall 37E

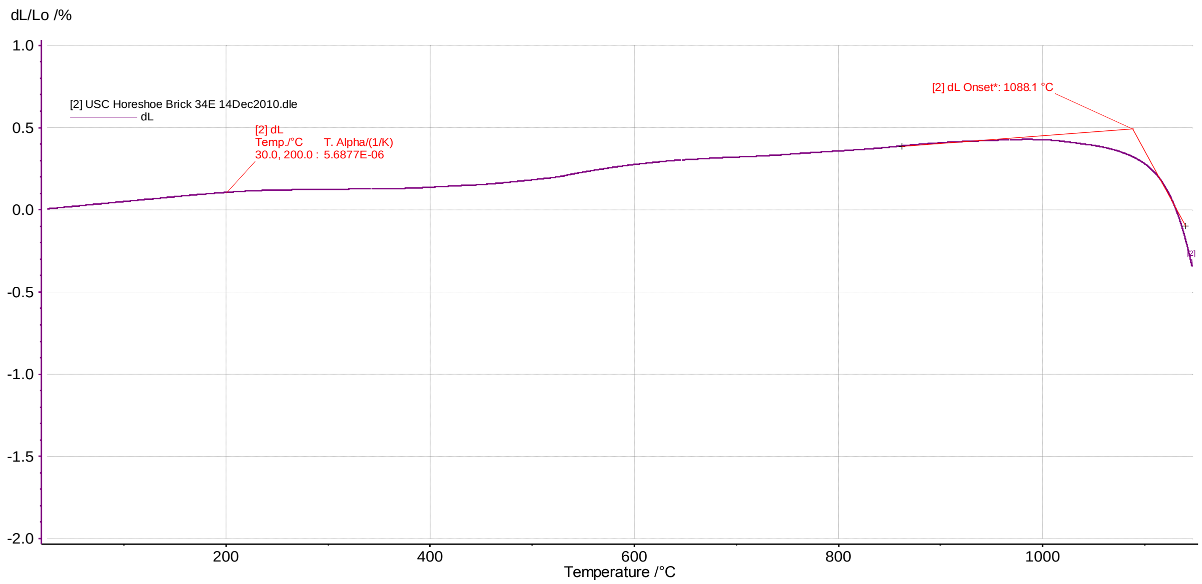
Thermal Expansion Curve – Brick 4W



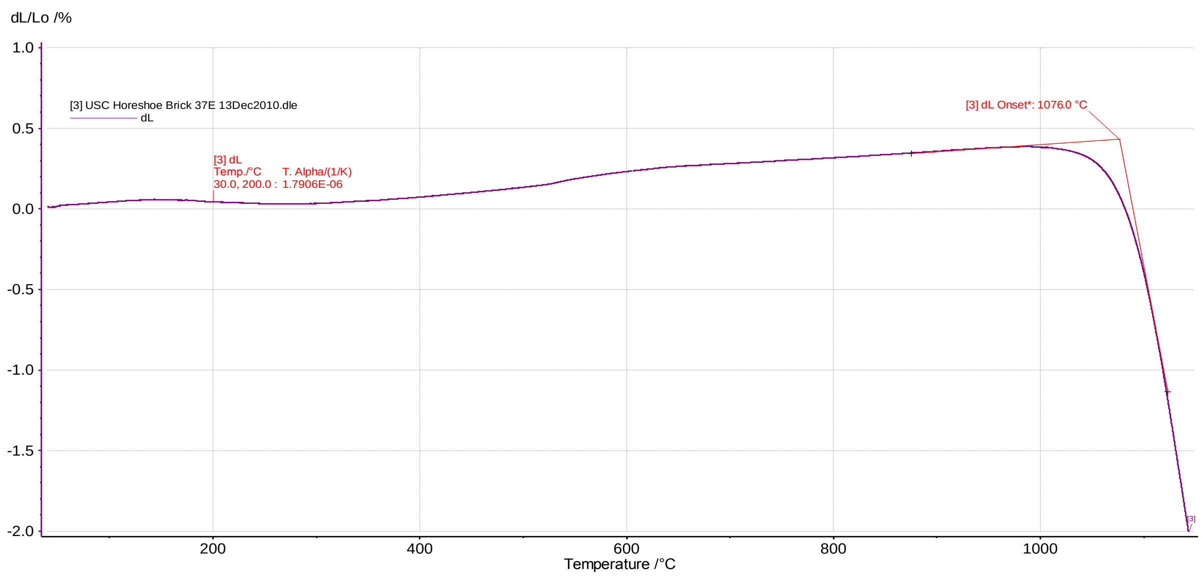
Thermal Expansion Curve – Brick 30W



Thermal Expansion Curve – Brick 34E



Thermal Expansion Curve – Brick 37E



Introduction

The Historic Wall surrounding the Horseshoe at the University of South Carolina Campus was inspected and four specimens of mortar were obtained for characterization on March 13, 2014. For purposes of this report, the inspection was to determine the condition of the wall and to observe any mechanisms of material degradation. General findings on masonry materials were as follows:

- The bricks in original construction were in good structural or sound condition exhibiting only infrequent damage from freezing and thawing or salt exposure. Some bricks were missing in areas of the coping courses, and others were damaged in areas of wall impacts or physical alterations of the wall.

- Many bricks were loose in coping courses where mortar and bricks were discolored by organic matter from overhanging tree growth. Biological growth in mortar joints attested to the wet conditions in the upper courses of the wall. The mortar was solid or not in a powdered condition in upper courses in the wall.

- Mortar recession was observed in lower courses, generally to 24" above ground level, suggesting mortar interaction with salt-laden water in rising damp. The source of salts is the naturally occurring salt in the soil plus environmental sources.

- Mortar was generally in a soft condition below ground level for a distance of 1-2" behind the masonry wall surface; i.e. the mortar was easily removed using a steel tool.

The mortar specimens are identified as follows:

"Greene 1", from the upper interior wall (campus side) on Greene Street by Health Sciences near the corner of Sumter and Greene Streets.

"Greene 2", from below ground on the interior side from a small excavation about 6 courses below ground level, near the corner of Sumter and Greene Streets.

"Sumter 1", from the upper interior wall adjacent to the Caroliniana near the coping courses.

"Sumter 2", from the lower interior wall above ground level but in the area of visible rising damp area of mortar recession, adjacent to the Caroliniana (not from within the small excavation at this location).

The mortar specimens were characterized as to their composition and physical properties in order to develop specifications for repair and restoration. The development of information on the mortar follows dictates the *Secretary of the Interior's Standards for the Treatment of Historic Properties*[1] where attention is prescribed toward use of authentic materials that meet the aesthetics of the historic construction while "doing no harm" to the historic "fabric". In practical terms, this means as masonry mortar used in repair or restoration should (1) exhibit a water vapor permeability

[1] See http://www.nps.gov/history/hps/tps/standguide/

equal to that of the original mortar (so as to avoid moisture accumulation in wall elements) and (2) reasonably match the "stiffness" or modulus of elasticity of the original mortar. It is well known, for example, that stiff repair or repointing mortar based on Portland cement can cause spalling or facial loss from a historic wall due to mismatch of modulus of elasticity with "soft" historic bricks. To meet aesthetic requirements of the Secretary's Standards, repair mortars containing colorants are typically chosen.

The examination of hardened masonry mortar follows methods in ASTM Standards[2]. Because the Historic Wall was completed in 1836, it was known that modern Portland cement binder was unavailable. The possible binders were for masonry mortar were hydraulic lime (as calcium hydroxide), pozzolanic hydraulic lime, and "Roman cement", the latter a material in limited availability especially due to shipment difficulties to Columbia. The remaining potential binders, hydraulic lime and pozzolanic hydraulic lime, dictated special analytical procedures for identification.

For explanation, hydraulic lime as calcium hydroxide, is combined with sand and water to produce masonry mortar that slowly attains a "set" condition by chemical reaction with atmospheric carbon dioxide" in a process called re-carbonation. Pozzolanic hydraulic lime has mineral constituents in addition to calcium hydroxide forming more corrosion resistant substances within masonry mortar than those formed in non-pozzolanic compositions[3]. Pozzolanic hydraulic lime has been known since Roman times, and it is currently sold under ASTM Standards[4]. As a historical note, mortar in Roman constructions in Western Europe, circa AD200, contained pozzolanic hydraulic lime created by mechanical mixtures of hydraulic lime and clay brick dust, as pozzolanic mortar from Italy was not available for construction in Western Europe.

The techniques used in characterization of the mortars are well-known and reported in a number of references[5]. These techniques include X-ray fluorescence spectroscopy or "XRF" for chemical analysis, X-ray diffraction analysis or "XRD" for mineralogy, simultaneous thermal analysis or "STA" to detect carbonate content and presence of trace minerals, water soluble salt determination by ion chromatography or "IC", and density and porosity (air content) of mortar by mercury intrusion porosimetry or "MIP". In addition, mortar was examined by light microscopy or "petrography" and by scanning electron microscopy or "SEM". This report is divided into a non-technical section in the body of the report with detailed information in the Appendix, the latter for the historical record and intended as a resource for researchers and students.

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[2] ASTM C1324 - 10 Standard Test Method for Examination and Analysis of Hardened Masonry Mortar. The American Society for Testing and Materials.

[3] Pozzolanic hydraulic limes are commonly known as "natural hydraulic lime" or "NHL" if produced from argillaceous limestone (without pozzolanic additives).

[4] ASTM C1707 – 11, Standard Specification for Pozzolanic Hydraulic Lime for Structural Purposes.

[5] Brosnan, Denis A., Sanders, John P. and Hart, Stephanie A., "Application of Thermal Analysis in Preservation and Restoration of Historic Masonry Materials, Part A: Characterization of Materials," Journal of Thermal Analysis and Calorimetry (2011) 106:109-115.

Findings

Mortar Batch Proportions

The mortars were found to be comprised of quartz (sand) and calcite (calcium carbonate) by XRD. The quantitative XRD was used to establish the sand content of the mortars while, following usual lab practice, the STA (thermal analysis) data was used to quantify the hydrated lime content[6]. The results of the calculations using the weight to volume conversion methods in ASTM 1324 are given in Table 1.

Table 1: Volumetric Proportions of Mortars

Constituents by Volume	Greene 1	Greene 2	Sumter 1	Sumter 2
Location	Upper Wall	Below Ground	Upper Wall	Lower Wall
Parts Sand	2.12	6.40	2.53	4.04
Parts Hydraulic Lime	1	1*	1	1*

* The result reflects carbonate solution in ground water or rising damp.

As will be discussed below, the relative contents of sand and lime in Greene 2 and Sumter 2 are a result of carbonate removal by salt attack and are therefore not representative of original construction. By contrast, the specimens Greene 1 and Sumter 1 did not experience substantive salt corrosion and they reflect original batch proportions. Because of the small specimen sizes and job site variations during original construction, the actual batch proportions in original mortar are predicted as two to three parts of sand to one part of hydraulic lime.

Binder Identification

The binder or cementitious material in each mortar was found by SEM to be a pozzolanic hydraulic lime composed of a mechanical mixture of hydraulic lime and clay that was blended with sand at the job site by masons. A contemporary blended hydraulic lime is called an *artificial* hydraulic lime. Relics of the clay[7] in the USC mortar exhibit an analysis of Al_2O_3 of 17.65% and SiO_2 of 62.71% or Al_2O_3/ SiO_2 of 0.28 in general agreement with t values of weathered shale used as brick making clays in the Columbia area[8]. The hydraulic lime phase[9] exhibits CaO of 75.80%, MgO of 3.66%, and SiO_2 of 17.86%. The clay to lime ratio varied in the mortar specimens with

[6] The STA data is preferred as it can differentiate carbonate phases in binder from those that may be present in sands when considered with petrographic information.
[7] Spectrum 35.
[8] Personal communication, David McKeown (Hanson Brick) to Denis Brosnan. June 17, 2014. The weathered shale used by Hanson Brick, as-mined, exhibited the following analyses: 15.45-16.86% Al_2O_3, 64.35-65.07% SiO_2, and 0.23-0.26 Al_2O_3/SiO_2. The shale also contained 1.40-2.99% MgO as mined.
[9] Spectrum 37.

specimen "Sumter 2" exhibiting the highest clay content. This just means that masons used "inexact" practices with mortar batches resulting in variations in the actual composition.

The overall composition of the binder in the upper wall specimens is compared to contemporary pozzolanic hydraulic lime in Table 2. While the comparisons do not yield exact matches (per expectations), the similarity of the analyses implies that the Columbia masons were using a formula of clay and lime intended to produce a pozzolanic hydraulic lime.

Table 2: Comparison of Binders by Chemical Analysis (Weight %)

	Greene 1	Sumter 1	NHL 3.5	NHL 5.0
Source	Spectrum 8 SEM, Greene 1	Spectrum 30 SEM. Sumter 1	Va. Lime Works NBRC Lab Report 2/22/10	Va. Lime Works NBRC Lab Report 2/22/10
CaO	73.89	68.49	67.19	66.96
Al_2O_3	3.12	2.05	4.88	4.54
SiO_2	13.22	26.01	21.04	21.17
MgO	7.86	2.52	2.19	2.64
Fe_2O_3	0.88	0.93	1.51	1.54
S	0.62	ND	1.30	1.38
Cl	0.41	ND	0.13	0.11

ND = not detected. NHL specimens tested were from Virginia Lime Works.

The designations NHL 3.5 and NHL 5.0 refer to a minimum compressive strength development of either 3.5 MPa (508 psi) or 5.0 MPa (725 psi) in a mortar mix after 28 days of curing (per BS EN 459-1). Type NHL 3.5 is typically recommended for construction near or below ground level. A type 2.0 is available but not recommended for near ground level. Types NHL 2.0, 3.5, and 5.0 are called weekly, moderately, and eminently hydraulic lime respectfully.

In summary, the binder in all of the USC mortar specimens is an artificial mixture of lime and clay (with sand) producing a pozzolanic hydraulic lime. Since artificial pozzolanic mortars have been known since Roman times, the masons building the wall were aware of the technology of their era and trying to construct a durable wall to last many years.

Deterioration of Mortar in the Wall

Data relative to the carbonate content of the mortars is shown in Table 3. Loss on ignition measures total weight loss between room temperature and 1000^{o}C to include the decomposition of calcium carbonate and any other minerals that decompose as well. The STA data presented is for decomposition only in the interval of carbonate decomposition in the interval 600-800^{o}C.

This data shows a reduction in carbonate content of about 35-50% in the specimens from the outer periphery of the mortar. The removal of carbonate binder was also seen by microscopic methods. The process has been described in the literature by Labelli, et. al[10].

Table 3: Data Illustrating Weight Loss and Carbonate Levels in Mortars*

	Greene 1	Greene 2	Sumter 1	Sumter 2
Location	Upper Wall	Below Ground (% of upper wall)	Upper Wall	Lower Wall (% of upper wall)
Total Weight Loss after 1000°C (LOI), %	13.58	7.32 (53.9% of Greene 1)	12.89	8.46 (65.5% Of Sumter 1)
Weight loss, 20-250°C (organic matter), STA, %	1.03	0.58	0.72	1.89
Calculated Carbonate content from STA. % as $CaCO_3$	20.5	10.7 (52.2% of Greene 1)	17.9	10.6 (59.2% of Sumter 1)

* The carbonate and organic matter both contribute to the total weight loss or LOI.

The data is not specific to the mortar in coping courses on the wall. In that location, organic acids from decay of tree vegetation is responsible for mortar attack. This is supported by the relatively high weight losses on carbon oxidation when comparing specimens Greene 1 and Greene 2; however, other organics, as possible plant growth, were apparently present in Sumter 2 rendering the comparison with Sumter 1 as indecisive.

Further data supporting carbonate removal is shown in Table 4 where the content of water soluble salts extracted at room temperature is reported (by IC). The values are expressed in parts per million of the dry specimen weight (i.e. mg/kg). It is difficult to correlate salt content with position; however, all mortar specimens exhibit water soluble species.

Table 4: Soluble Salts in Mortar Specimens, ppm.

	Greene 1	Greene 2	Sumter 1	Sumter 2
Location	Upper Wall	Below Ground	Upper Wall	Lower Wall
Calcium	6358	953	886	7894
Magnesium	92.9	286	230	31.1
Chloride	1535	20.6	12.4	98.6
Sulfate	4858	53.7	45.8	1295

[10] B. Lubelli, R. van Hees, and C. Groot, The role of sea salts in the occurrence of different damage mechanisms and decay patterns in brick masonry, Construction and Building Materials 18 (2004) 119-124

It is not surprising that carbonate reduction is seen in areas of rising damp or below ground, as this is a very common occurrence in historic mortars. Pozzolanic substances retard such corrosion in mortars, but they do not prevent all carbonate loss. This is why periodic re-pointing is necessary for masonry walls.

Physical Data on Wall Mortars

Physical tests by MIP revealed the density and porosity (air content) of the mortars (Table 5). The values for density and porosity are as expected for hardened mortar except for the values in Sumter 2. The low porosity and high fraction of pores <1 micron in diameter are possibly related to the very high clay content of the binder phase in this specimen.

Table 5: Density and Porosity Data by MIP for Mortars

	Greene 1	Greene 2	Sumter 1	Sumter 2
Location	Upper Wall	Below Ground	Upper Wall	Lower Wall
Bulk density, g/cm^3	1.85	1.72	1.71	1.93
Apparent porosity, volume %	27.08	33.01	30.39	20.10
Fraction of pores <1μ in diameter	17.24	28.80	32.57	57.24

Recommendation on Repair and Replacement Mortar

Mortar based on pozzolanic hydraulic lime meeting ASTM C1707 – 11, *Standard Specification for Pozzolanic Hydraulic Lime for Structural Purposes*, meets all of the Secretary of the Interior's requirements to include authenticity and aesthetics, providing that the mortar is color matched. It should meet specifications for NHL 3.5 in BS EN 459-1, and it should be formulated in sand contents appropriate for either re-pointing or bedding mortar. The choice of NHL 3.5 will approximately match the vapor permeance and stiffness of the original mortar.

Recommendation on Repair Bricks

Repair bricks should be hand molded, size matched, and color matched to those in the Wall, and meet ASTM C216, Grade SW. rated "not effloresced". The bricks should have loosely adherent sand that can be removed as necessary at the job site. Used bricks are not recommended because of their unknown durability per recommendations in the Technical Notes of the Brick Industry Association.

Additional Considerations in Wall Restoration

Evaluation of Efflorescence

Field panels of a size 4 feet by four feet by one course thickness could be constructed behind the existing walls over a solid base using any candidate restoration mortars and exposed to weather for at least 60 days to evaluate efflorescence potential of the mortar. If the solid base is concrete, the field panel should be constructed over flashing to prevent upward movement of calcium into the panel. Removal of efflorescence may involve considerable cost to a restoration project given the need to protect original materials from chemical or physical cleaning methods. An alternative to construction of field panels is consultation with the manufacturer of the natural hydraulic lime to estimate the efflorescence potential.

Aesthetics of Repair and Original Areas/Cleaning

Field panels or manufacturer's samples should be compared to the original masonry with respect to joint color to evaluate whether there will be acceptable aesthetic differences between repair and original wall segments.

Flashing

The current recommendation in Technical Note 29A on Garden Walls (Brick Industry Association) is that through wall flashing is used under the coping materials. Since flashing was not used in the original wall construction, "good judgment" as cited in the BIA Note implies that disturbing existing sound masonry to install coping is inappropriate.

Engineering Evaluation/Tree Roots

Engineering evaluation of the wall should consider the recommendations in Brick Development Association (UK) Guide 12, "Design of Free Standing Walls." Further, the wall should meet criteria in current codes. The engineering evaluation should also consider potential root damage in an overall safety assessment.

Appendix

Photographs by Street Location

Sample Location – Greene 2

Obtaining Greene 2

(Note mortar recession in the lower wall to the left of a pointed area.)

Top Course of Wall by Sumter near Greene
(Note mortar recession and vegetation in coping courses.)

Lower Courses of Wall by Sumter near Greene
(Note mortar recession in lower wall.)

Lower Courses of Wall by Sumter near Pendleton
(Note mortar recession in lower wall.)

Upper Wall by Sumter

Missing Bricks in Coping on Sumter

Excavation on Carolina Library on Sumter – Near location for Sumter 1 and Sumter 2

Wall Opening - Pendleton

Note on Analytical Tests – Methods used in these analyses are described in the following papers:

1. G. Chiari, G. Torroca, and M. Santarelli, Recommendations for Systematic Instrumental Analysis of Ancient Mortars: The Italian Experience, Standards for Preservation and Rehabilitation, ASTM STP 1258, American Society for Testing and Materials, 1996, pp. 275-284.

2. Denis A. Brosnan, Characterization and Degradation of Masonry Mortar in Historic Brick Structures, Journal of Structures, Volume 2014 (2014), Article ID 859879, 7 pages.

Notes on Methods

X-ray Fluorescence Spectroscopy (XRF) – a means of determining the chemical analysis of a specimen by using impinging monochromatic X-rays to excite atomic species in the specimen to produce X-rays of characteristic energy for those species in the specimen. By analyzing the energy of evolved X-rays, the chemical species in the specimen are identified, and the quantity of substances in the specimen is calculated from the intensity of X-rays generated by the specimen. The technique is used in analysis of rocks, cements, and ceramics. The usual convention of reporting the composition of species is in terms of metal oxides. The analysis of specimens in this report by XRF is for specimens after exposure to 1000^oC (oxidized basis).

Loss on Ignition – the weight loss of a specimen after heating in air to 1000^oC expressed as a percentage of the original sample weight. Oxidation of organic matter and mineral decompositions are typical reasons for weight loss.

X-ray Diffraction Analysis (XRD) – the determination of crystalline species in a specimen by observing the diffraction (bending) angle of monochromatic X-rays in a powdered specimen. The quantitative analysis of diffraction angle and intensity of X-rays allows a quantitative mineralogical analysis.

Soluble Anions and Cations – determination of the water soluble salts extracted from a specimen by immersion in deionized water at 20^oC with analysis of the leachate by ion chromatography (IC). The levels of calcium and magnesium from mortars are of interest. Likewise, the presence of anions like sulfate and chloride typically reflect intrusion of the water by ground or sea salts.

Mercury Intrusion Porosimetry (MIP) – mercury porosimetry is a technique for measuring the density, porosity, and pore sizes by intruding mercury into a dried specimen by applying pressure to the mercury surrounding the specimen. The volume of mercury is carefully monitored as pressure is applied to the mercury, and the pore sizes are calculated using the Washburn equation. The MIP technique is well suited for analysis of small irregularly shaped specimens.

Simultaneous Thermal Analysis with Evolved Gas Analysis – the simultaneous observation of weight changes and energy flows on heating of a specimen with detection of gaseous species evolved over the specimen. As an example, the decomposition of calcium carbonate ($CaCO_3$) is typically seen near 800^oC was the CO_2 is released forming a residual of CaO (lime) with a theoretical weight loss of 44.0% of the original weight of the carbonate. More information is available at:

1. Brosnan, Denis A., Sanders, John P. and Hart, Stephanie A., "Application of Thermal Analysis in Preservation and restoration of Historic Masonry Materials, Part A: Characterization of Materials," Journal of Thermal Analysis and Calorimetry (2011) 106:109-115.
2. Denis A. Brosnan, John P. Sanders, and R. Parker Stroble, "Application of Thermal Analysis in Preservation and Restoration of Historic Masonry Materials; Part B, Degradation of Materials", Journal of Thermal Analysis and Calorimetry (2013) 113: 507-510.

Species observed by Thermal Analysis in Historic Mortars

Reaction Temperature °C	Reaction I=endothermic E=exothermic	Species	Species Formula	Reference
75-83	E	Tobermorite	3CaO-2SiO2-xH2O	Dwek, Goncalves (forms ettringite)
50, 100. 160, 430 (major at 430)	E	Nontronite(Smectite-Montmorillonite family)	(CaO1/2Na)O.3Fe2(Si, Al)4O10 (OH)2-nH2O	Frost, Chippera and Bish
60, 266,308, 551 (CO2 and H2O)	E	Iowaite	Mg4Fe(OH)8OCl-3H2O	Frost
120-149	E	Ettringite	3CaO-Al2O3-3CaSO4-31H2O	Anato; Ibrahim et al
120	E	CSH (PC)	C-S-H gel	Alacron-Ruiz in PC, also portlandite (510) and calcite (820); Ibrahim et al
120, 280, 265, 480, 980	E	Nat cement	Lime-metakaolin	Moropoulou
122	E	Gypsum	CaSO4-2H2O	Forms hemihydrate (1/2 H2O) which dehydrates at 127C. Hemihydrate aka bassinite. Dweck, p. 460 in TA of Construction Materials.
210-280	E	Marialite	Varies Na4Al3Si9O24Cl to Na4(ALSi3O8)3(Cl2, CO3, SO4)	Benavides.
100-160	E	Zeolites	Varies	Maichrzak, also 710C
248, 364	E	Iron hydroxide and/or iron sulfate hydrate	FeO(OH); water evolution	Zhao, Corrosion Science 53 (2011) 1646-1658. Seen in in Unitarian Church, Chas, 7/13.
478	E	Iron sulfate (from rust sulfidated)	SO2 evolution	Pong et. al., Thermal decomposition of siderite (2007); Siriwardane et. al., up to 500C. Seen in in Unitarian Church, Chas, 7/13.
486	E	Iron carbonate (from rust carbonation)	CO2 evolution	Seen in in Unitarian Church, Chas, 7/13.
300-400 or 337-499	E	Brucite	Mg(OH)2	Kais, Goncalves
400-460 also cited as 437 or 442	E	Portlandite	Ca(OH)2	Dweck; Ibrahim et al give 450-600 but show as 520C.
~520	E	Aragonite to calcite	CaCO3	Handbook C+P, Antao, Canadian Mineralogist 97 (2012) 707-712.
~573	I	Alpha to Beta Quartz	SiO2	
622, 682, or820	E	Calcite (661-700 in vacuo) [680-800 untrafine]	CaCO3	Dweck, depends on crystallinity (Beruto, TCA 424 (2004) 99-109) [Ren?, JTAC 91 (2008) 867-871 in "The Influence of Morphology pf Ultrafine Calcite on Decomposition Kinmetics]
680-720	E	Magnesite	MgCO3	Liu, JTAC 107 (2012) 407-412
700C + and 900C	E	Sodalite (hauyne)	Na4(Al3Si3)O12Cl	Khajovi

Microscopy – use of traditional techniques using transmitted and reflected light microscopy (petrography) and scanning electron microscopy (SEM). The SEM analysis usually involved phase quantification using energy dispersive X-ray analysis (EDAX), a technique providing chemical analysis of individual features in a specimen microstructure. For more information, see:

1. S. DeHayes and D. Stark, Petrography of Cementitious Materials, ASTM STP 1215, The American Society for Testing and Materials (1994).

2. J. Elsen, Microscopy of Historic Mortars, Cement and Concrete Research 36 (2006), 1416 – 1424.

3. Denis A. Brosnan and John P. Sanders, Microscopic Characterization of Clay Bricks and Its Use in Forensic Analysis, *Annual for the Brick and Tile*, *Structural Ceramics and Clay Pipe Industries*, Bauverlag BV GmbH (2012) 101-115.

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Quantitative X-Ray Fluorescence (Oxidized Basis) Report

04/25/2014

COMPANY INFORMATION			
Name:	Denis Brosnan PO Box 613 Pendleton, SC 29670	Plant:	Denis Brosnan
Report Name:	**Quantitative X-Ray Fluorescence (Oxidized Basis)**	Technician:	Michael Mason

RESULTS

Major Constituents	Unit	*Greene 1* Oxidized 4/24/2014	*Greene 2* Oxidized 4/24/2014	*Sumter 1* Oxidized 4/24/2014	*Sumter 2* Oxidized 4/24/2014	
Al2O3	%	0.80	0.80	0.80	2.32	
SiO2	%	79.64	88.72	80.50	80.95	
Na2O	%	<0.7	<0.7	<0.7	<0.7	
K2O	%	0.05	0.12	0.06	0.10	
MgO	%	2.04	0.65	1.55	0.55	
CaO	%	16.35	8.38	16.00	14.49	
TiO2	%	0.11	0.17	0.10	0.22	
MnO	%	0.02	0.02	0.02	0.03	
Fe2O3	%	0.32	0.46	0.30	0.64	
P2O5	%	0.07	0.07	0.07	0.07	
S	%	<0.05	<0.05	<0.05	<0.05	
Sum of Major Constituents	%	99.40	99.39	99.40	99.37	
Minor Constituents						
Cl	ppm	<250	<250	<250	<250	
V	ppm	<150	<150	<150	<150	
Cu	ppm	38	27	39	34	
Zn	ppm	<20	<20	<20	<20	
Zr	ppm	<20	331	62	130	
Ba	ppm	200	<200	<200	<200	

Lab Reference: 5610.10286,10287,10288,10289

Page 1 of 1

Key Observations:

- CaO (from binder) at expected levels in Greene 1 and Sumter 1, but results for Greene 2 and Sumter 2 suggest CaO depletion.
- Al_2O_3 content higher than expected and "very high" for Sumter 2 – suggesting clay additions to the mortar mix.

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Loss on Ignition Report

04/25/2014

COMPANY INFORMATION			
Name:	Denis Brosnan PO Box 613 Pendleton, SC 29670	Plant:	Denis Brosnan
Report Name:	**Loss on Ignition**	Technician:	Michael Mason

RESULTS

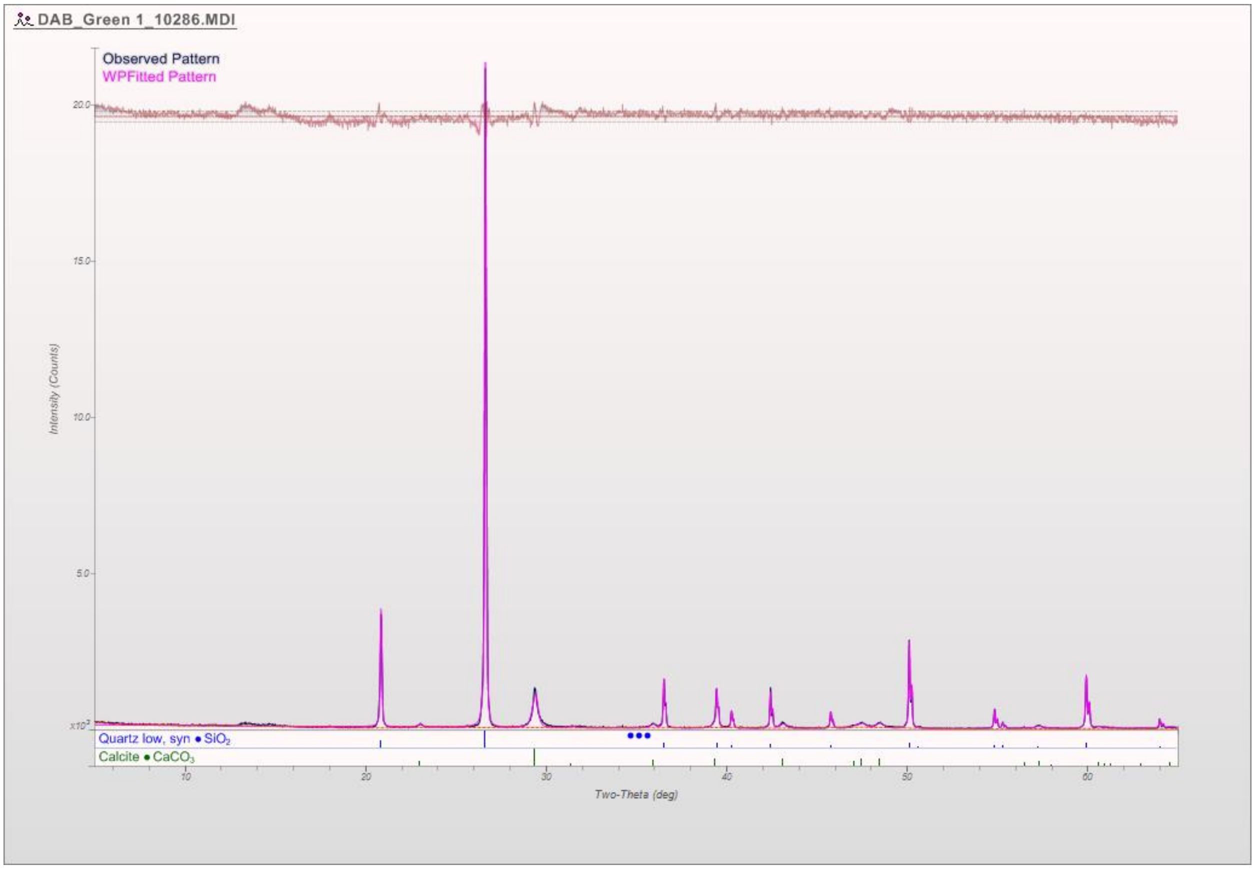
	LOI (%)					Test Date
Greene 1	13.58					4/23/2014
Greene 2	7.32					4/23/2014
Sumter 1	12.89					4/23/2014
Sumter 2	8.46					4/23/2014

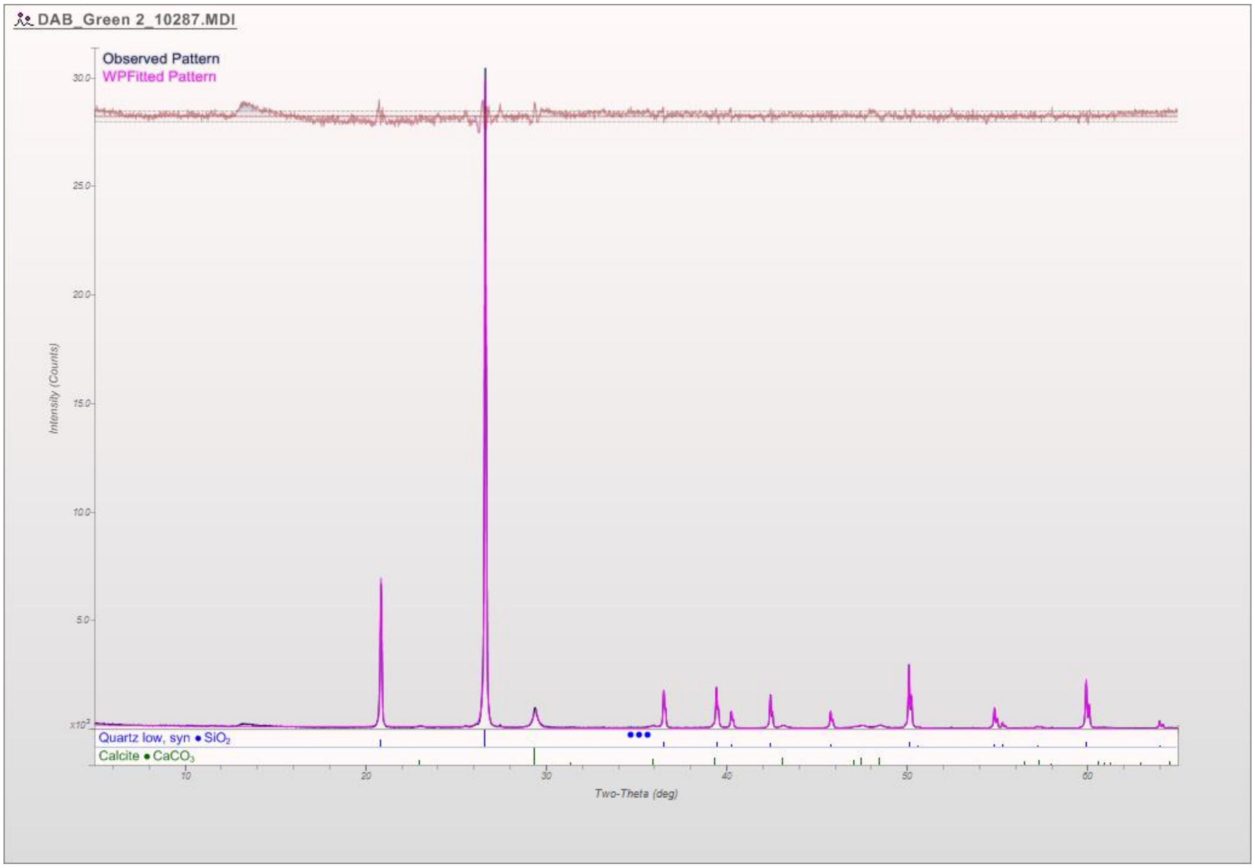
Lab Reference: 5610.10286,10287,10288,10289 Page 1 of 1

Key Observations:

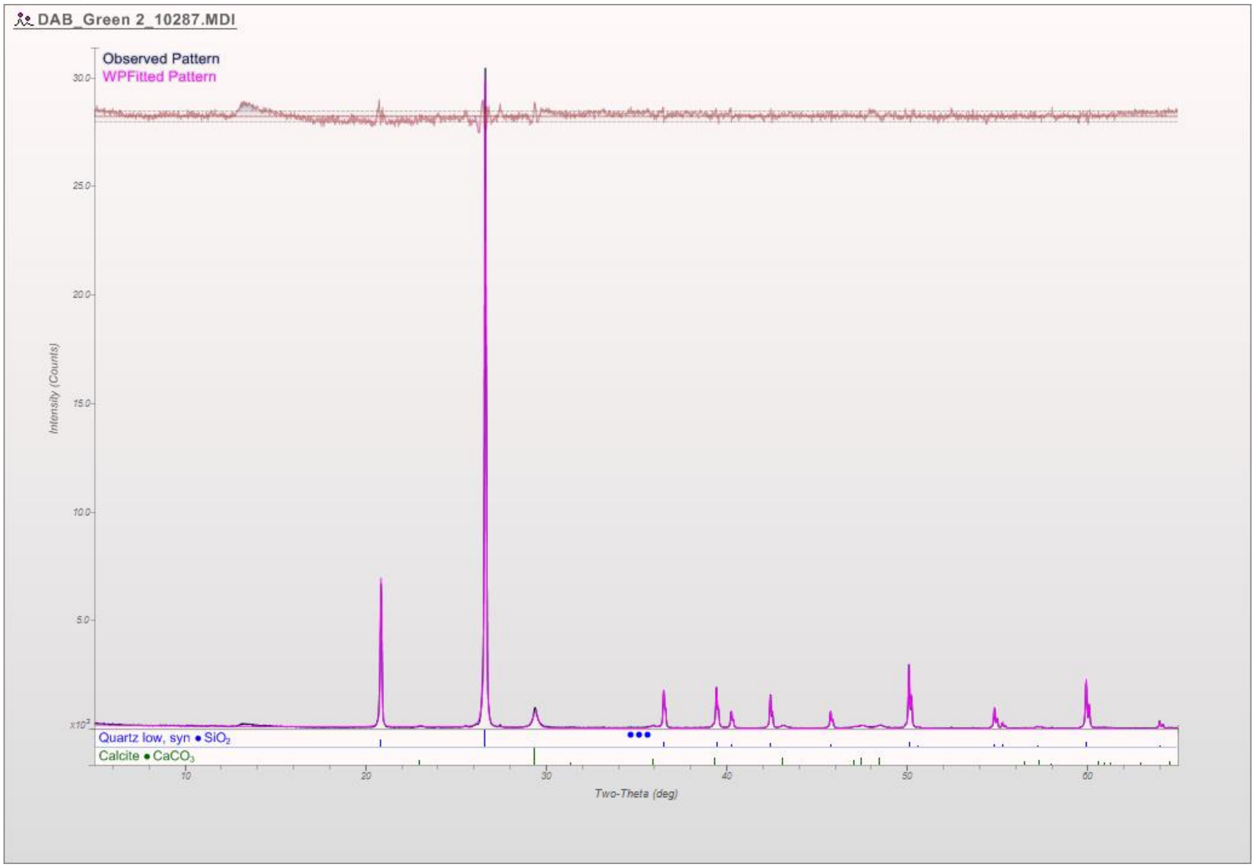
- Lower LOI suggesting carbonate binder depletion in Greene 2 and Sumter 2 as compared to Greene 1 and Sumter 1 respectively. Note that LOI also contains a component due to oxidation of organic matter (carbon).

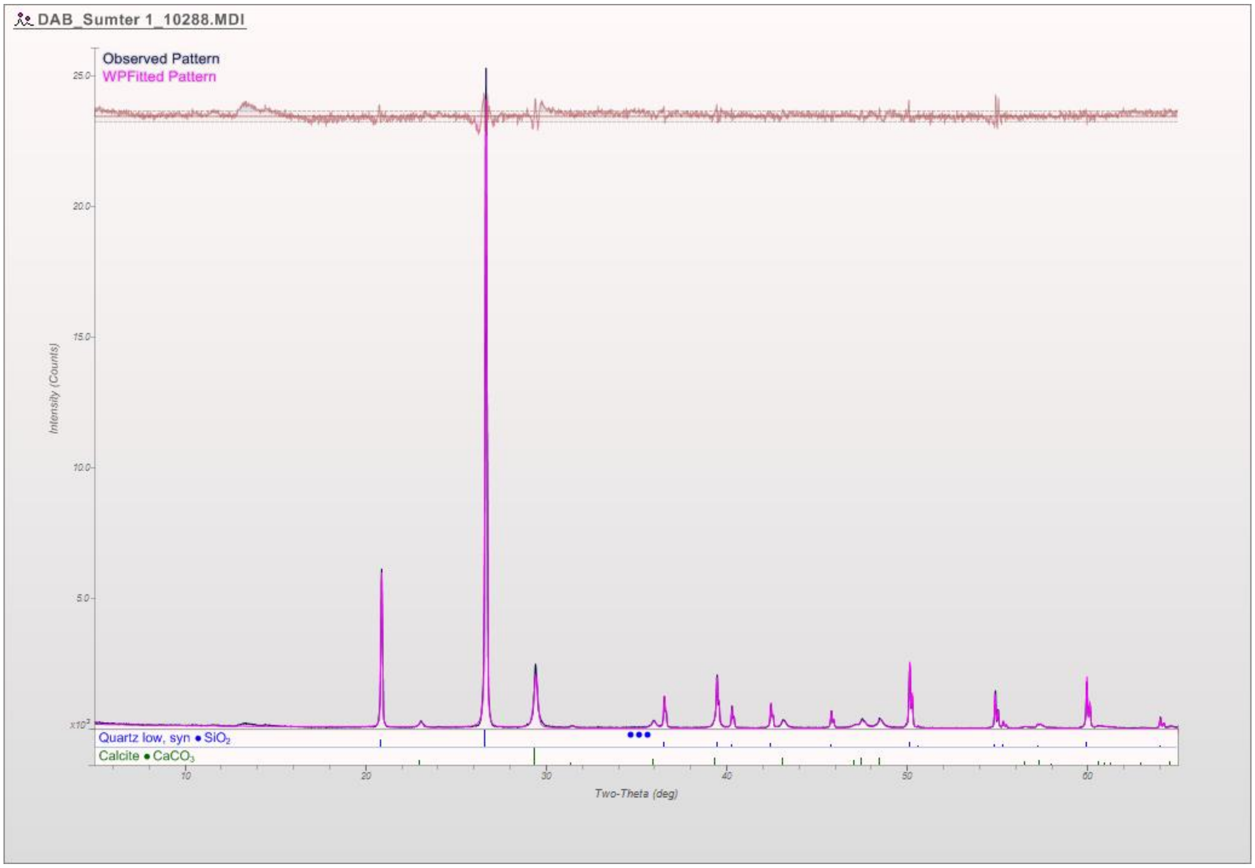
X-ray Diffraction





DAB_Green 2_10287.MDI
Observed Pattern
WPFitted Pattern
Intensity (Counts)
Quartz low, syn • SiO2
Calcite • CaCO3
Two-Theta (deg)


DAB_Green 2_10287.MDI
Observed Pattern
WPFitted Pattern
Intensity (Counts)
x10^3
Quartz low, syn • SiO2
Calcite • CaCO3
Two-Theta (deg)


DAB_Sumter 1_10288.MDI
Observed Pattern
WPFitted Pattern
Intensity (Counts)
x10^3
25.0
20.0
15.0
10.0
5.0
Quartz low, syn • SiO2
Calcite • CaCO3
10
20
30
40
50
60
Two-Theta (deg)

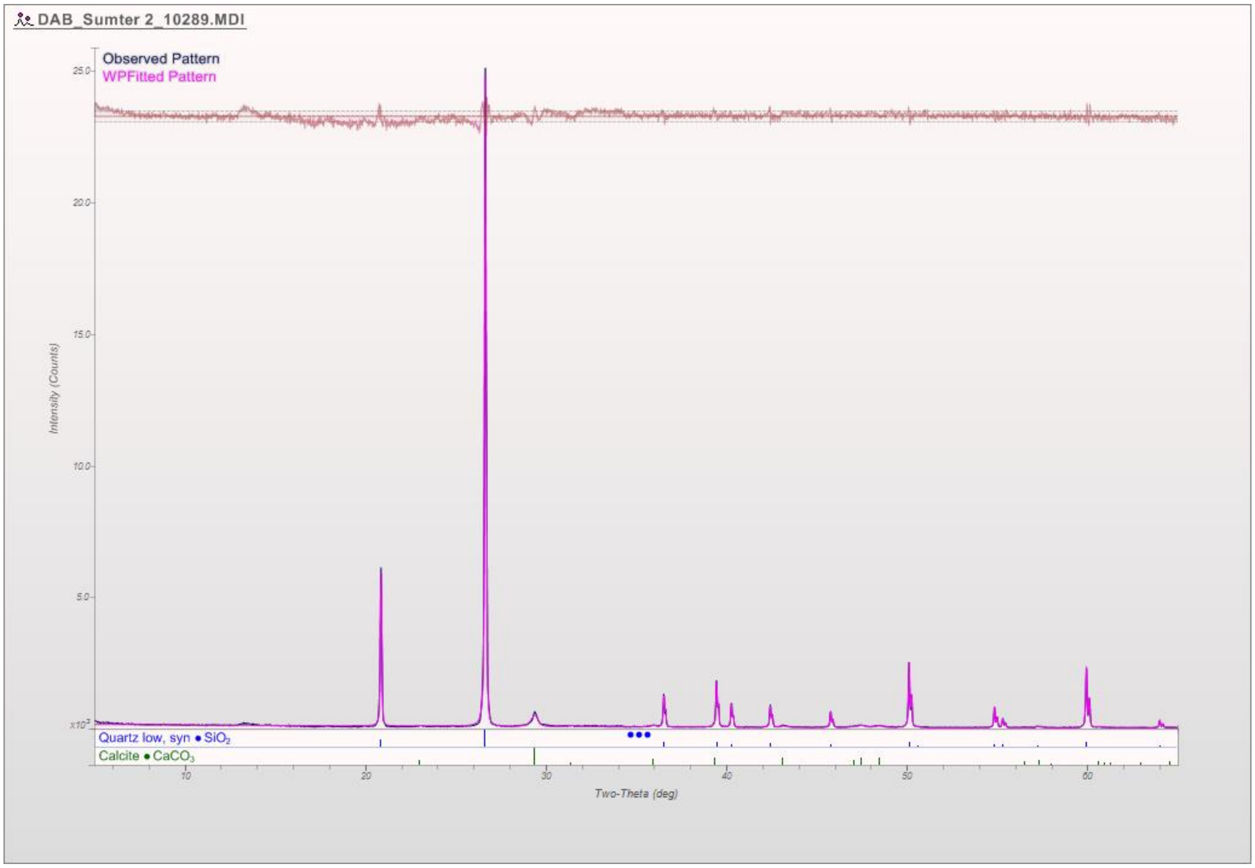


Table 1 – Estimated Phase Content by Whole Pattern Fitting Technique

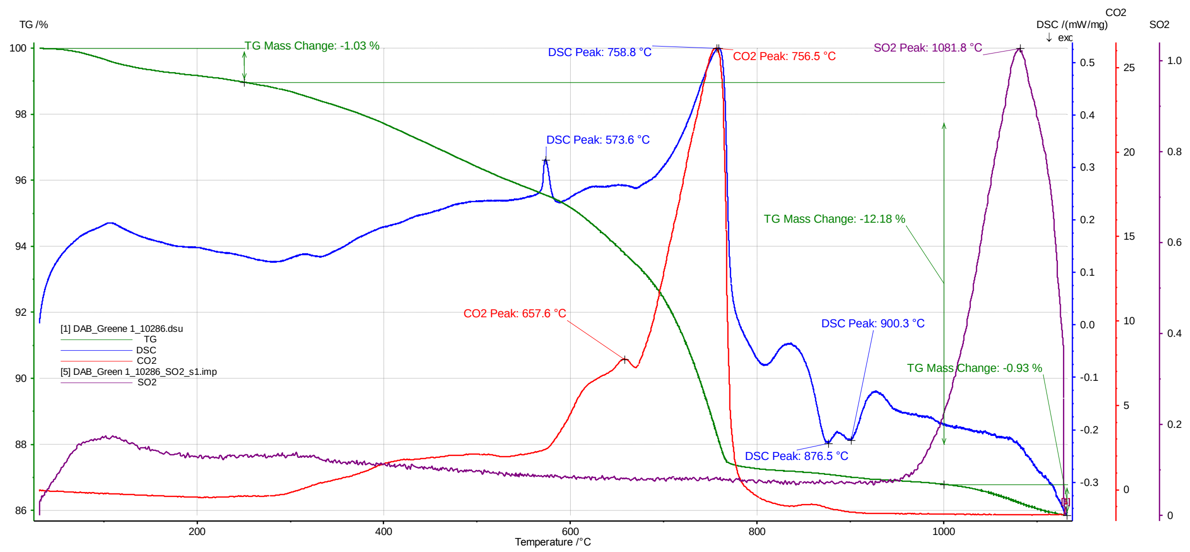
Phase	Green 1 (10286) Wt. % (ESD)	Green 2 (10287) Wt. % (ESD)	Sumter 1 (10288) Wt. % (ESD)	Sumter 2 (10289) Wt. % (ESD)
Quartz	86.1 (2.3)	92.7 (3.0)	91.1 (2.0)	84.2 (2.1)
Calcite	13.0 (0.5)	6.4 (0.4)	6.8 (0.3)	14.9 (0.5)
Amorphous/Other	1.0 (0.6)	0.9 (0.7)	2.1 (0.5)	0.8 (0.5)

Key Observations:

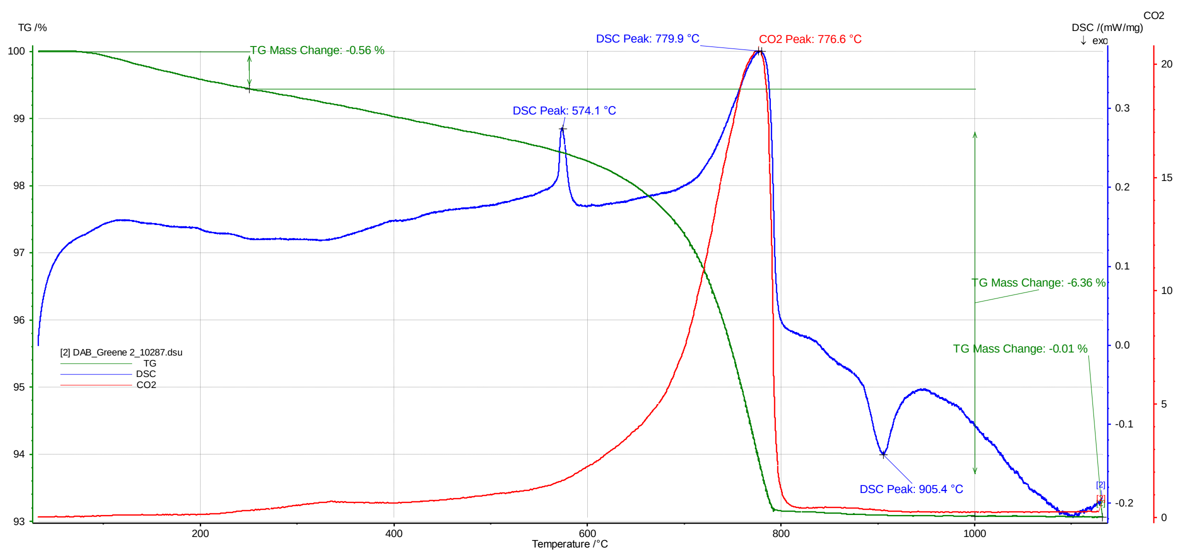
- Major components are calcite (binder) and quartz (sand).

Simultaneous Thermal Analysis with Evolved Gas Analysis

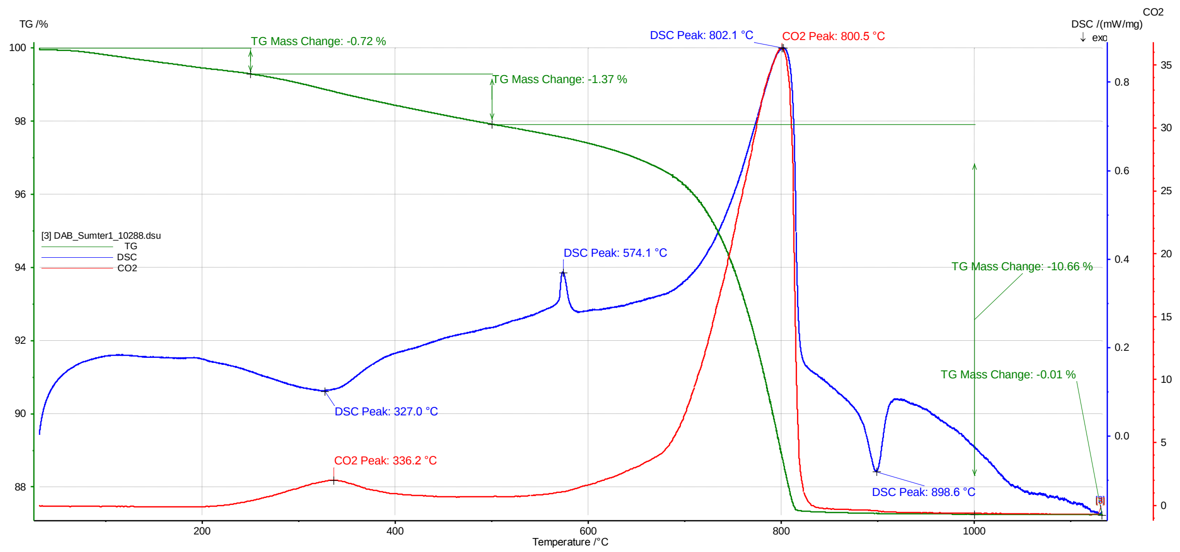
Key: Greene trace is the weight loss (thermogravimetric); Blue trace is the energy change (differential scanning calorimetry, downward peak is exothermic); Red trace is the CO_2 evolution (FTIR detection); and Black trace is the SO_2 evolution (if shown, by FTIR).



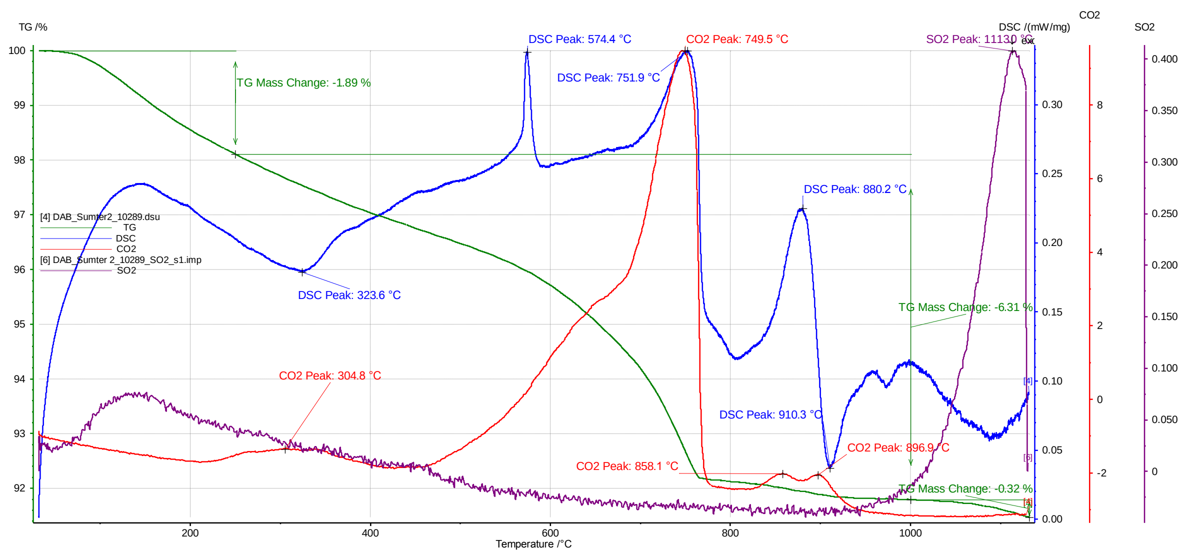
Greene 1



Greene2



Sumter 1



Sumter 2

Key Observations:

- All specimens exhibit the endothermic quartz inversion near 574°C reflecting the sand content of the mortar.
- All specimens exhibit a large endothermic peak with CO_2 evolution near 750-800°C reflecting the carbonate binder decomposition.
- The weight loss below 200°C is likely due to ettringite decomposition. This phase is commonly found in mortars.
- All mortars exhibit CO_2 evolution in the area of 350-400°C reflecting oxidation of organic matter forming CO_2.

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Soluble Anions and Cations Report

04/25/2014

COMPANY INFORMATION			
Name:	Denis Brosnan PO Box 613 Pendleton, SC 29670	Plant:	Denis Brosnan
Report Name:	**Soluble Anions and Cations**	Technician:	Michael Mason

RESULTS					
	Greene 1	**Greene 2**	**Sumter 1**	**Sumter 2**	
Cations	**Sample Concentration (ppm)**	**Sample Concentration (ppm)**	**Sample Concentration (ppm)**	**Sample Concentration (ppm)**	
Lithium					
Sodium	2,061	19.7	9.3	14.5	
Ammonium	20.7	3.9	8.7	9.5	
Potassium	995	23.2	44.1	70.8	
Magnesium	92.9	286	230	31.1	
Calcium	6,358	953	886	7,894	
Barium					
Anions	**Sample Concentration (ppm)**	**Sample Concentration (ppm)**	**Sample Concentration (ppm)**	**Sample Concentration (ppm)**	
Fluoride	11.0	11.5	16.0	11.8	
Chloride	1,535	20.6	12.4	98.6	
Nitrite				4.3	
Bromide					
Nitrate	6,202	3.4	1.2	207	
Phosphate	19.6				
Sulfate	4,858	53.7	45.8	1,295	

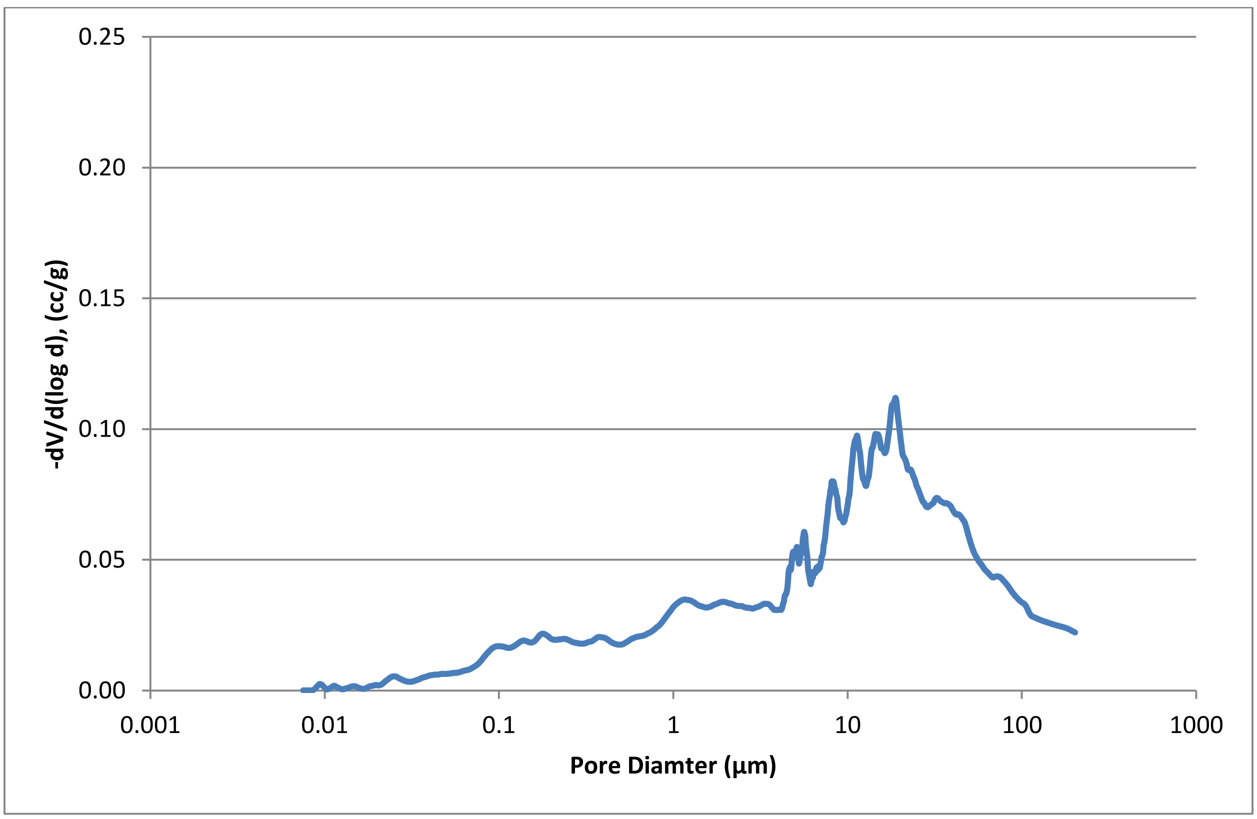
Lab Reference: 5610.10286,10287,10288,10289

Key Observation:

- All mortars contain water soluble salts.
- Salt content trends are not consistent with position on the wall perhaps reflecting environmental factors.

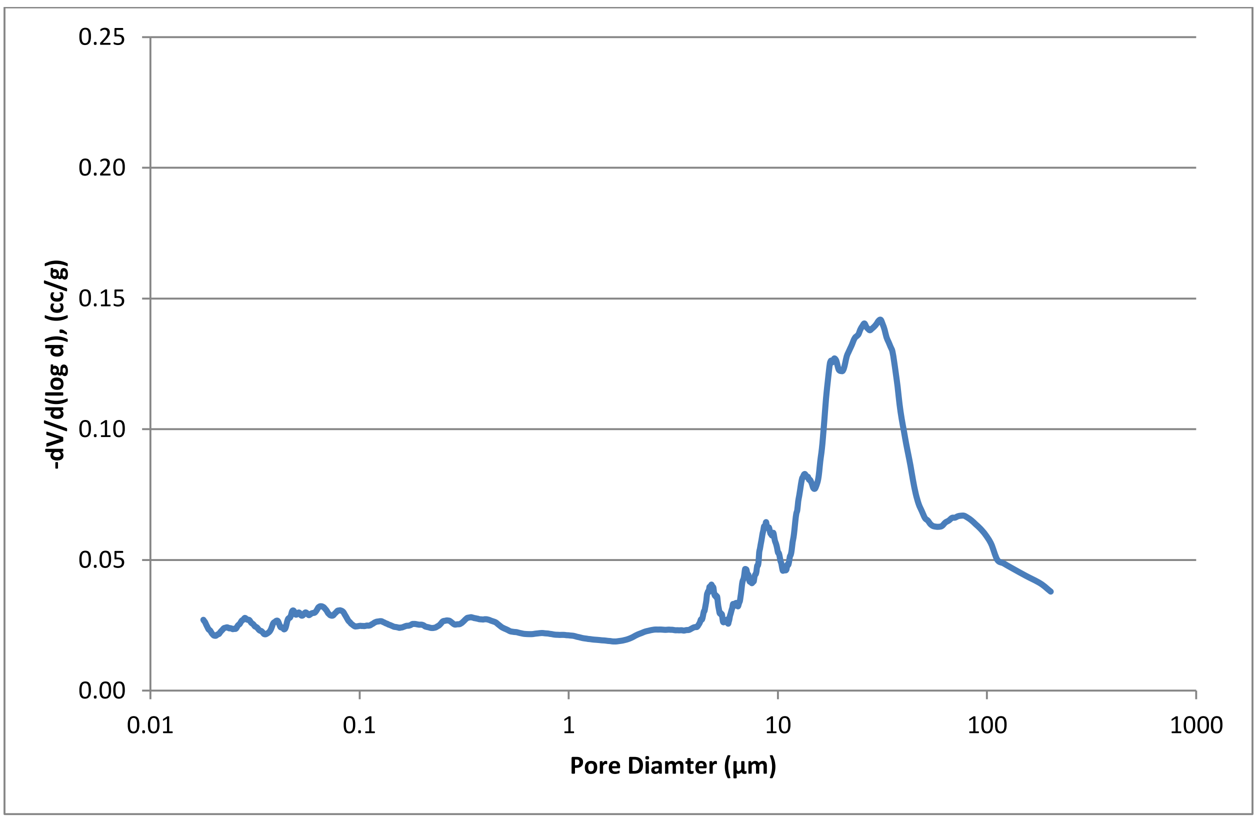
Mercury Intrusion Porosimetry
(MIP)
Greene 1
NBRC 5610/10286

Property	Unit	
Total Intrusion Volume	ml/g	0.147
Median Pore Diameter	microns	11.780
Bulk Density	g/cc	1.85
Apparent Density	g/cc	2.11
Porosity	%	27.08
Total Surface Area	m^2/g	0.92
Permeability (Accounting for Tortuosity Effects)	nm^2	0.36
Pores >3 Microns	%	72.04
Pores >10 Microns	%	54.61
Pores 10-1 Microns	%	28.15
Pores <1 Microns	%	17.24



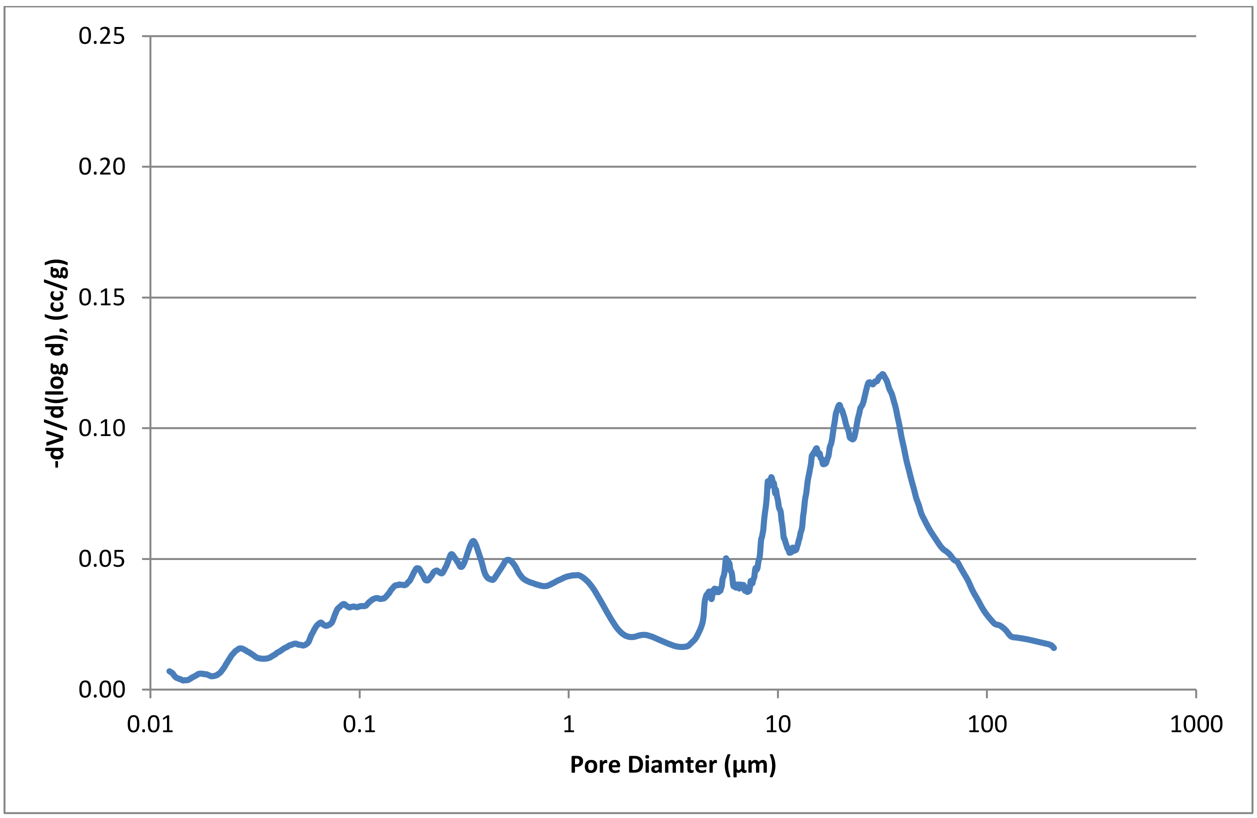
Greene 2
NBRC 5610/10287

Property	Unit	
Total Intrusion Volume	ml/g	0.191
Median Pore Diameter	microns	15.090
Bulk Density	g/cc	1.72
Apparent Density	g/cc	2.07
Porosity	%	33.01
Total Surface Area	m^2/g	6.51
Permeability (Accounting for Tortuosity Effects)	nm^2	0.02
Pores >3 Microns	%	66.02
Pores >10 Microns	%	56.11
Pores 10-1 Microns	%	15.08
Pores <1 Microns	%	28.80



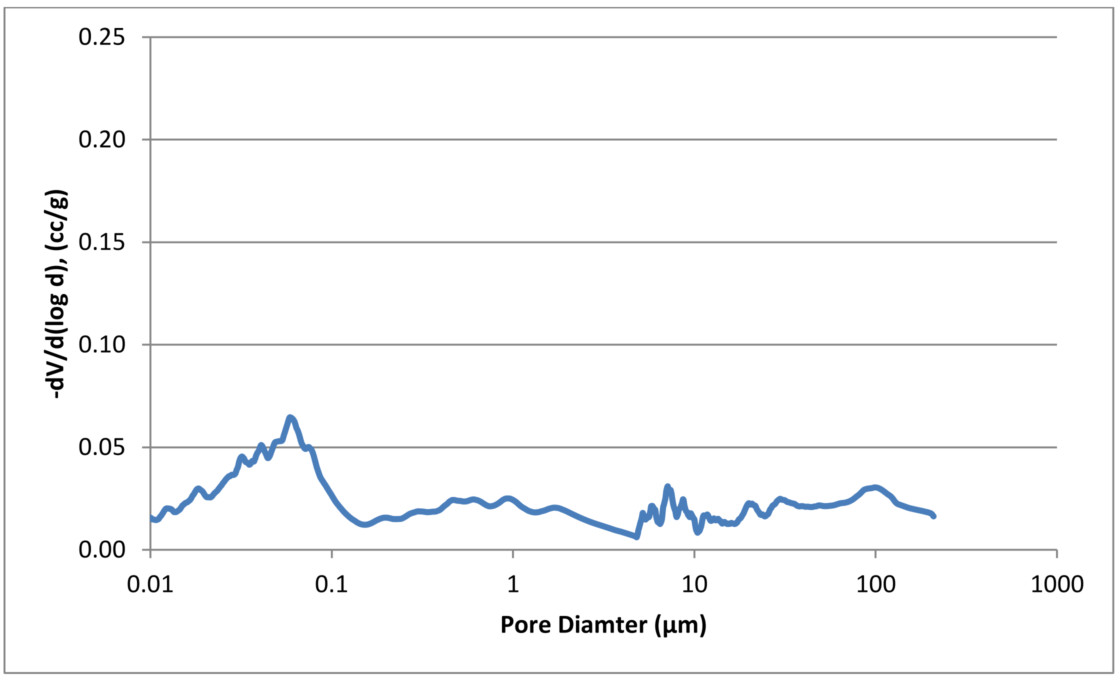
Sumter 1
NBRC 5610/10288

Property	Unit	
Total Intrusion Volume	ml/g	0.178
Median Pore Diameter	microns	9.228
Bulk Density	g/cc	1.71
Apparent Density	g/cc	1.97
Porosity	%	30.39
Total Surface Area	m^2/g	2.38
Permeability (Accounting for Tortuosity Effects)	nm^2	0.09
Pores >3 Microns	%	59.73
Pores >10 Microns	%	48.55
Pores 10-1 Microns	%	18.88
Pores <1 Microns	%	32.57



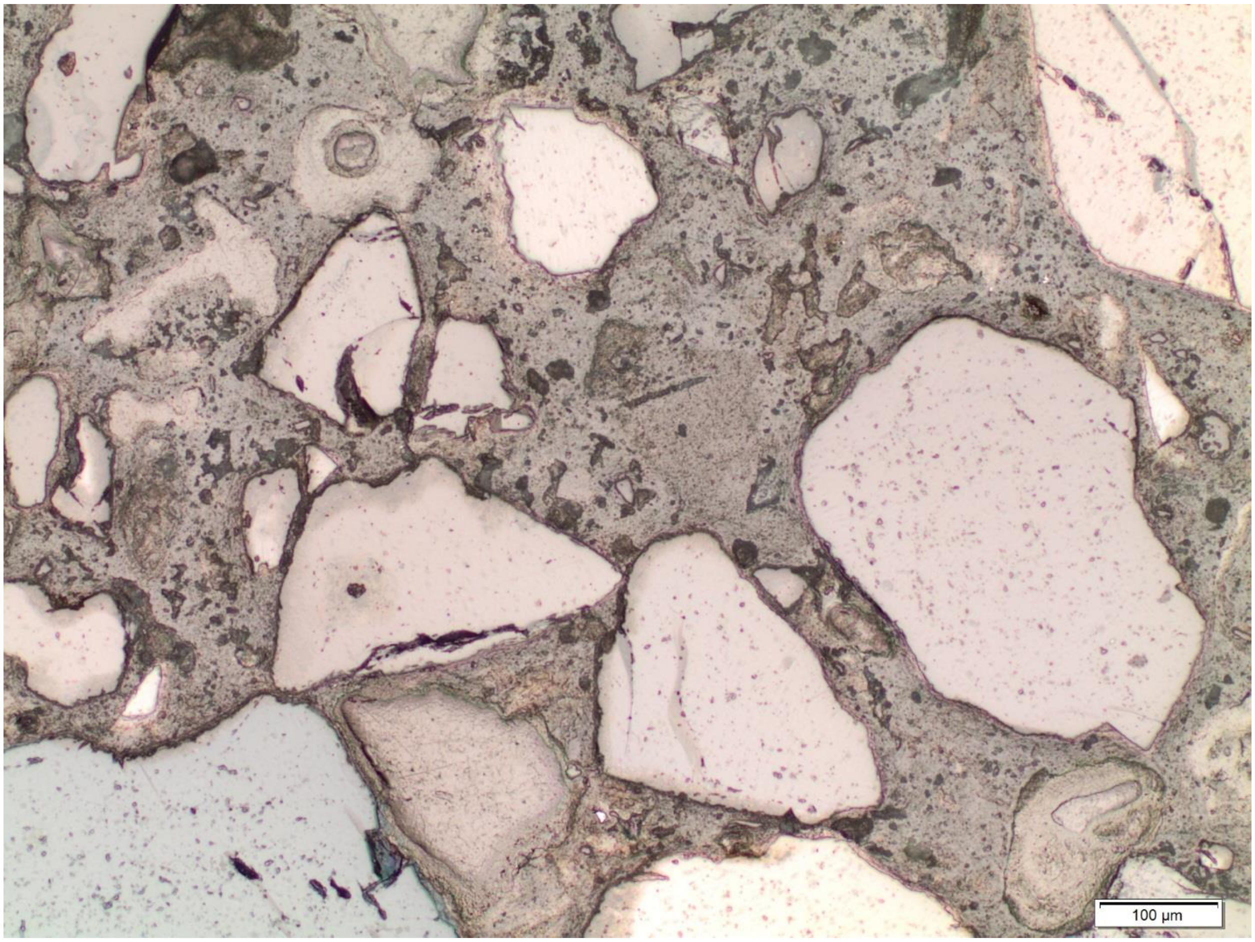
Sumter 2
NBRC 5610/10289

Property	Unit	
Total Intrusion Volume	ml/g	0.104
Median Pore Diameter	microns	0.475
Bulk Density	g/cc	1.93
Apparent Density	g/cc	2.04
Porosity	%	20.10
Total Surface Area	m^2/g	6.68
Permeability (Accounting for Tortuosity Effects)	nm^2	0.00
Pores >3 Microns	%	34.30
Pores >10 Microns	%	26.76
Pores 10-1 Microns	%	16.01
Pores <1 Microns	%	57.24

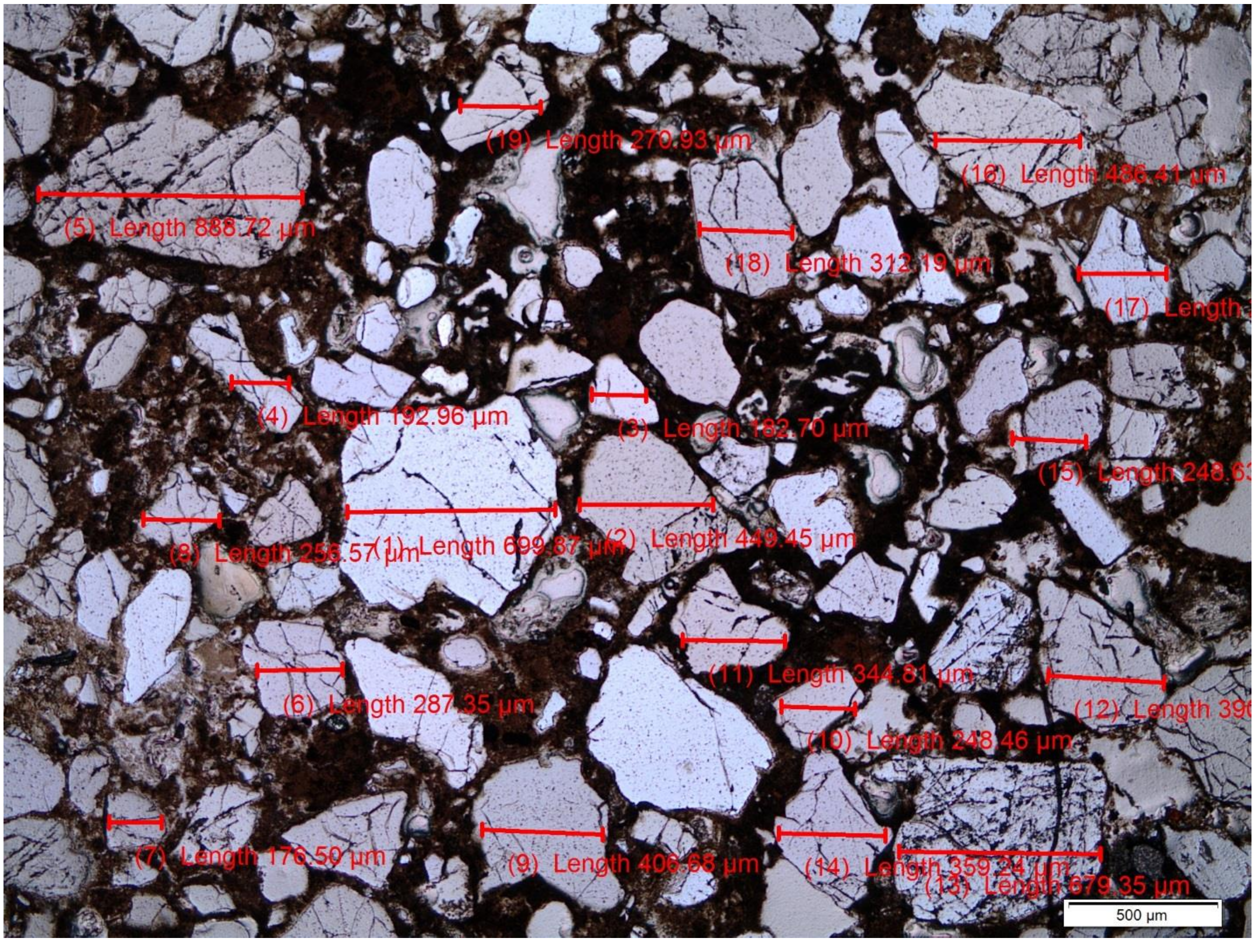


Key Observations:

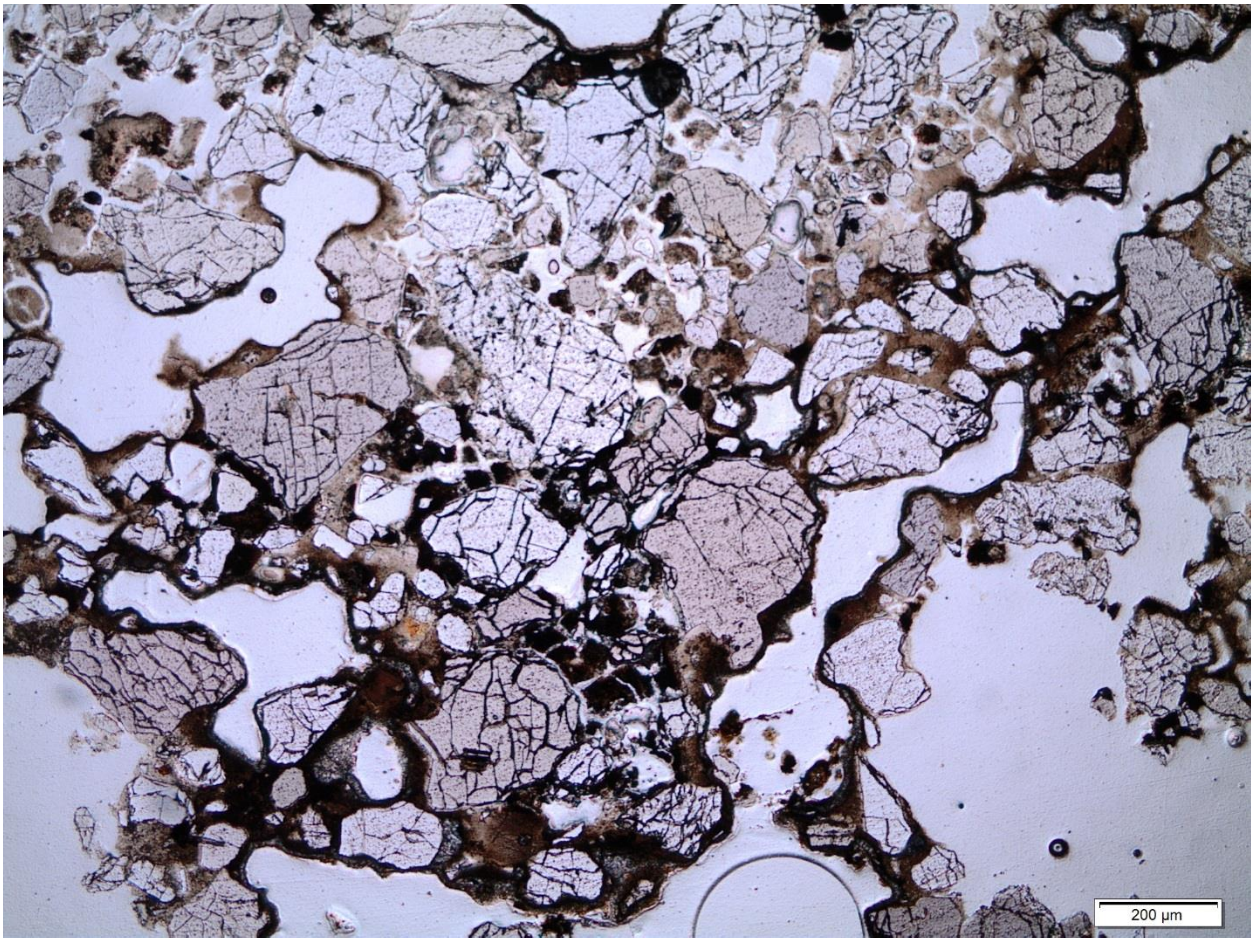
- Mortars Greene 1, Greene2, and Sumter 1 exhibit expected porosities and fractions of porosity <1 micron.
- Mortar Sumter 2 exhibits a lower than expected porosity and a higher than expected fraction of pores >1 micron (perhaps reflecting the high clay content of the parent batch).



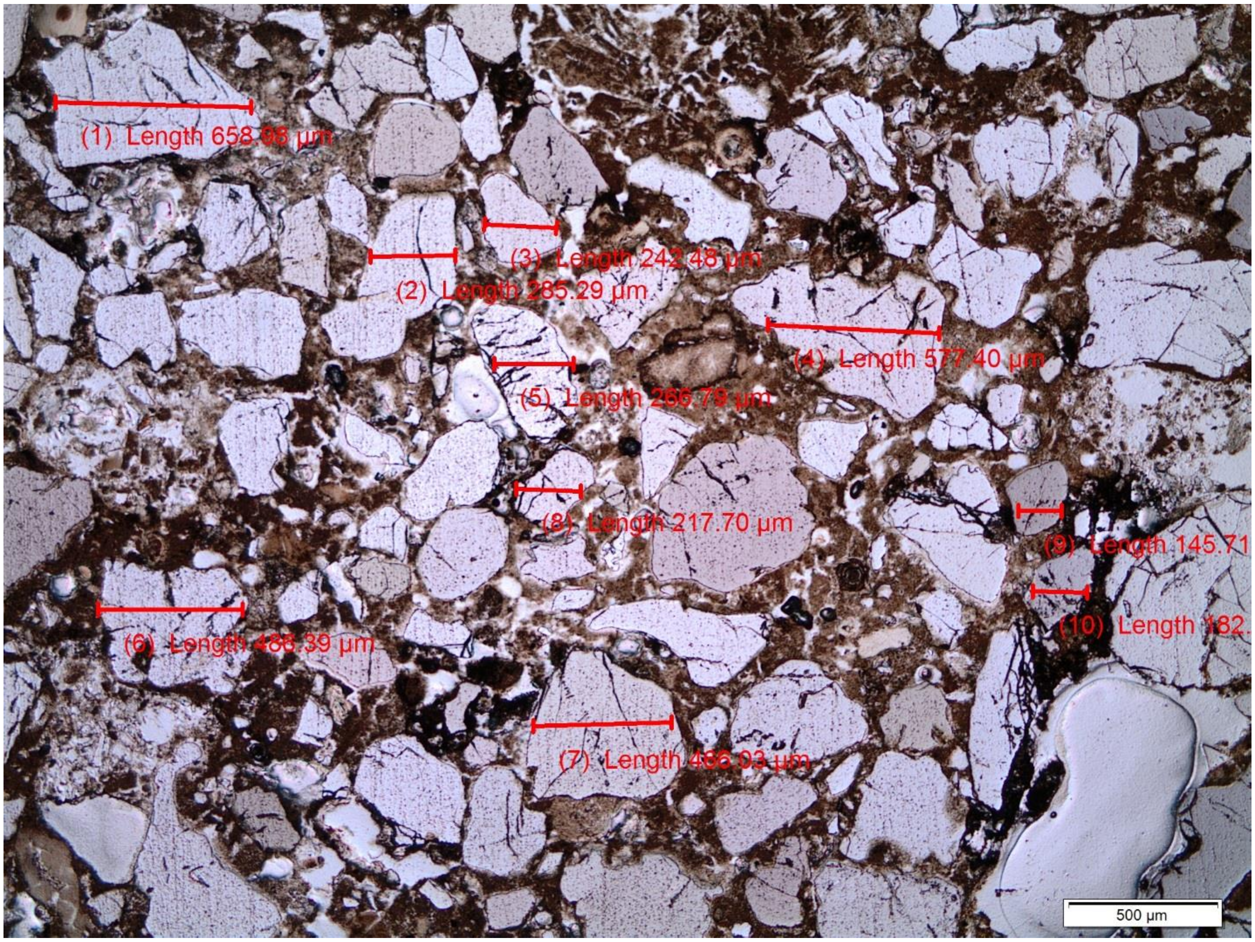
Specimen Greene 1 – Angular and Rounded Sand (Quartz) Crystals Surrounded by Binder Phase. Reflected light.



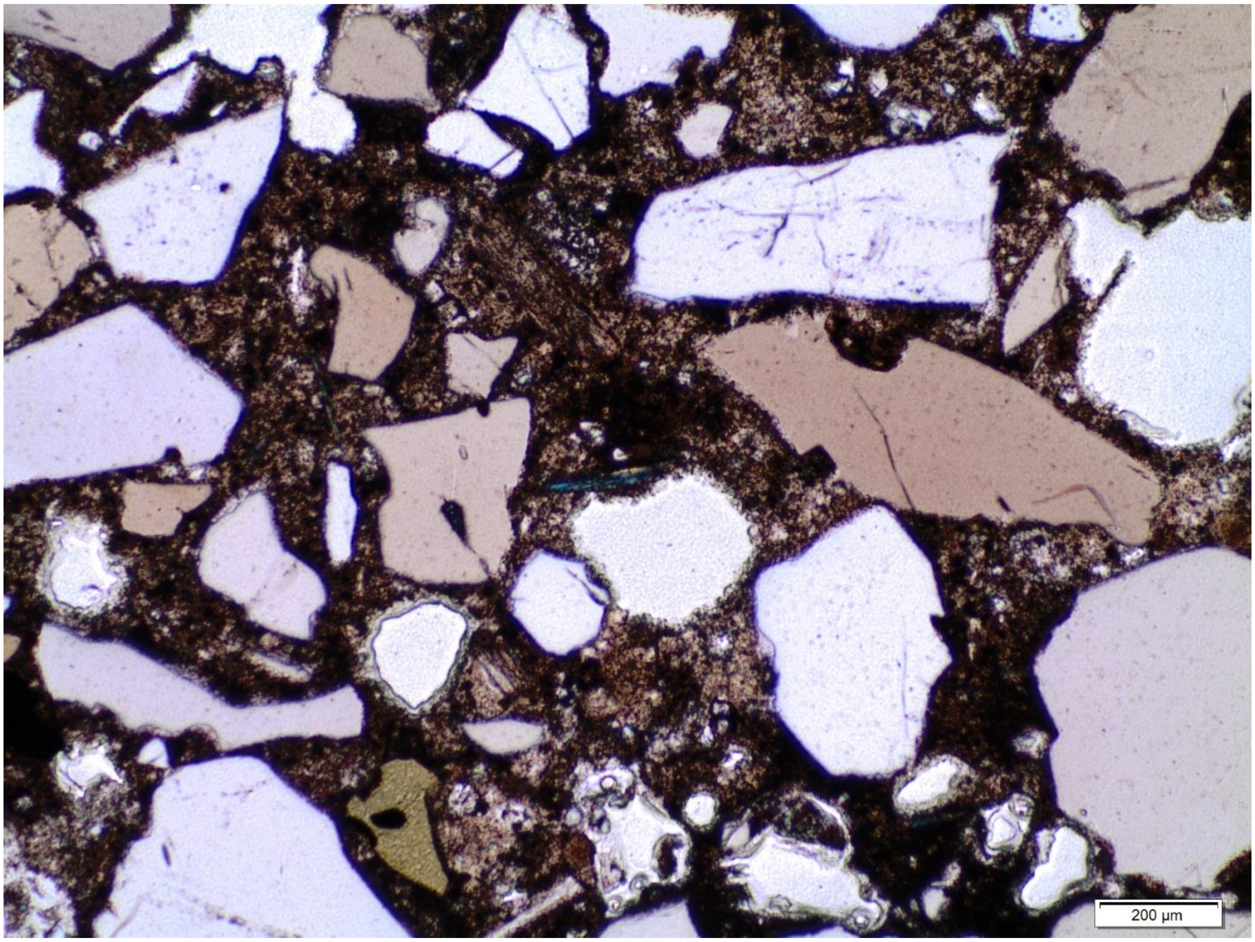
Specimen Greene 1 in Transmitted Light with Measurement of Sand Sizes (in micrometers or microns, μm)



Specimen Sumter 2 (by transmitted light) – Sand (Quartz) Crystals with Dispersed Dark Binder Phase with Considerable Porosity (white areas and "channels"). The level of porosity is likely due to partial removal of carbonate binder by intruding salt-laden water.



Specimen Sumter 1 in Transmitted Light with Measurement of Sand Sizes (in micrometers or microns, μm)



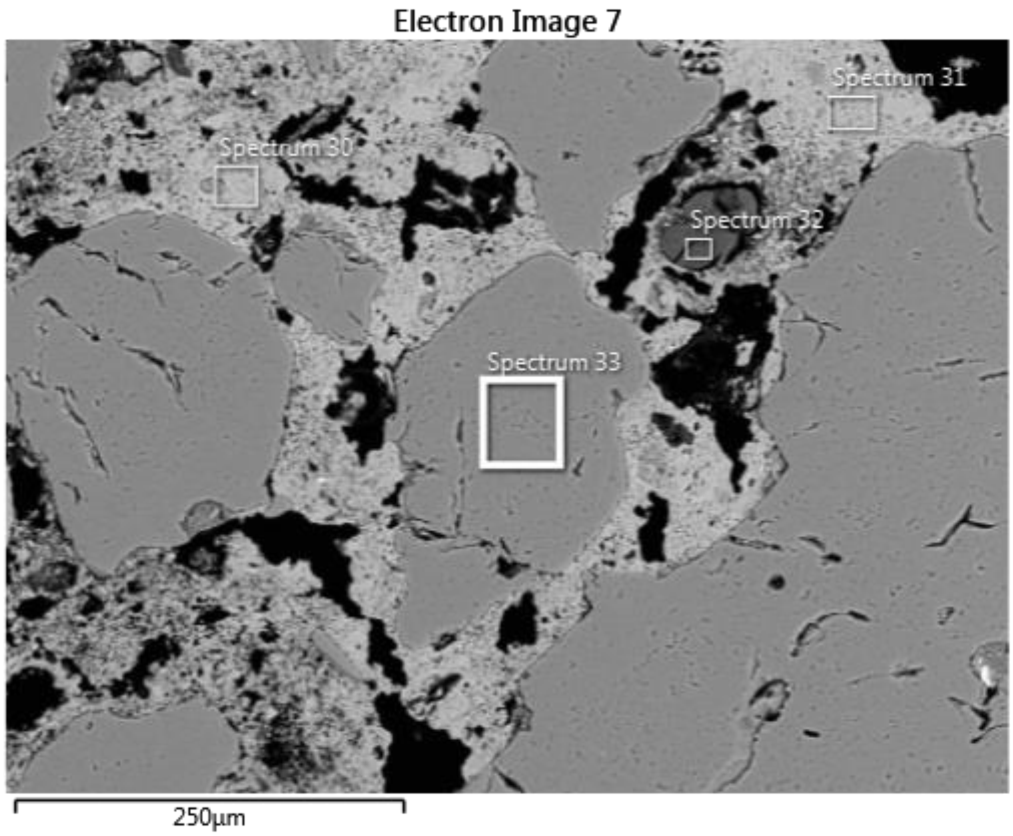
Sumter 2 (Transmitted Light)

Key Observations:

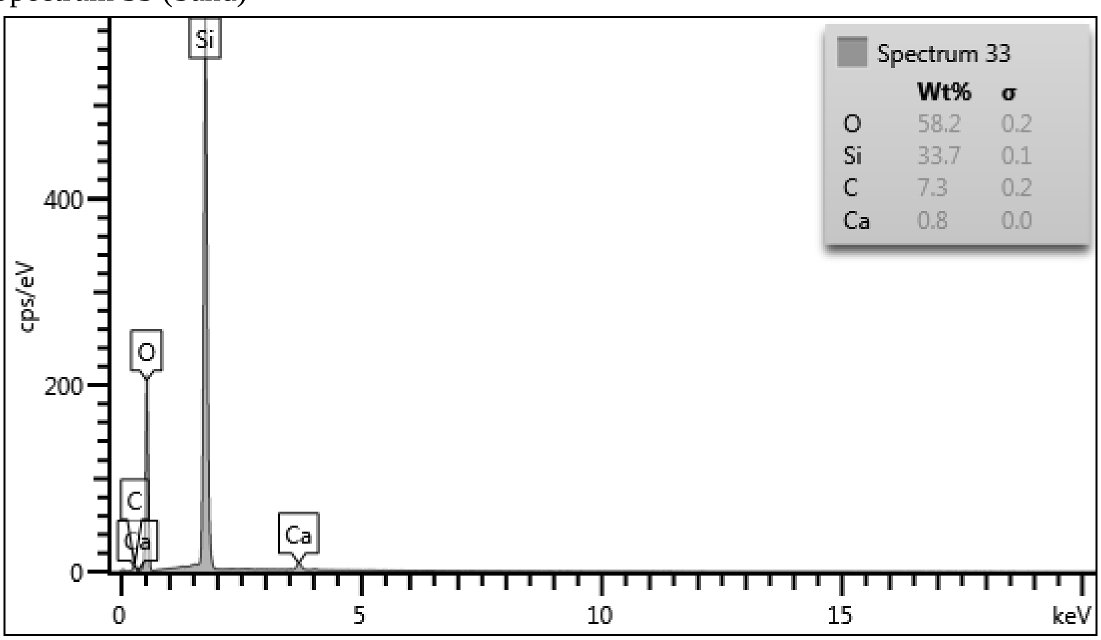
- Sand particle sizes are consistent with those expected in masonry bedding mortars.
- The binder phase contains small opaque or "black" particles, as seen in transmitted light photomicrographs. One object of SEM work was to identify these particles.
- Residual lime agglomerates were not seen in the microstructures suggesting reasonably efficient mixing of mortar constituents.

Scanning Electron Microscopy/EDAX

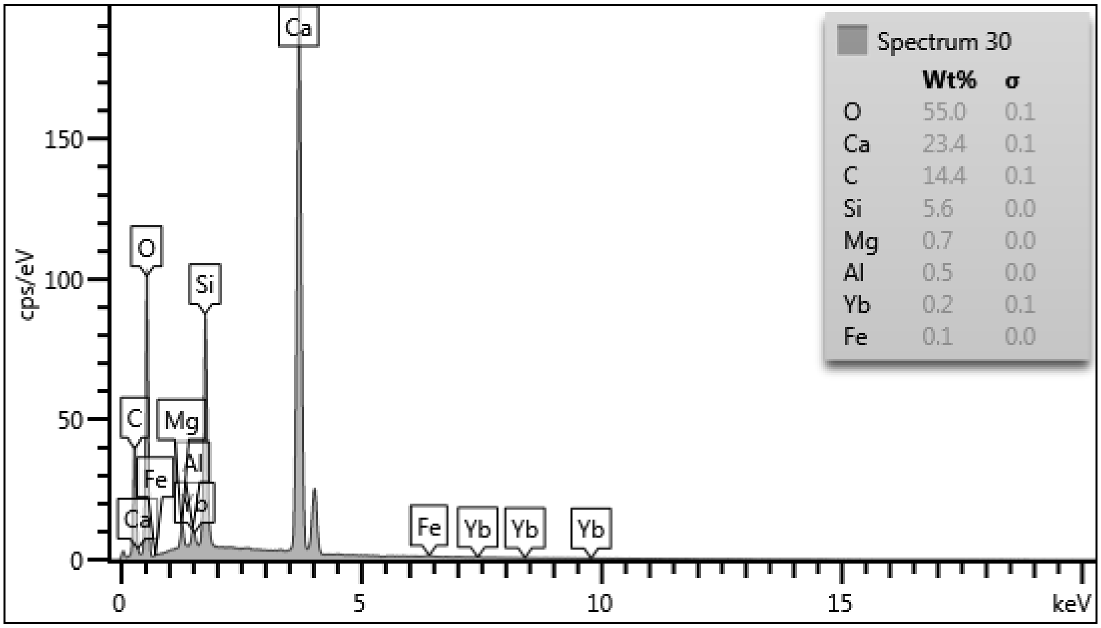
Sumter 1 (Area 2) – Sand (Spectrum 33) and Binder (Spectrum 30)



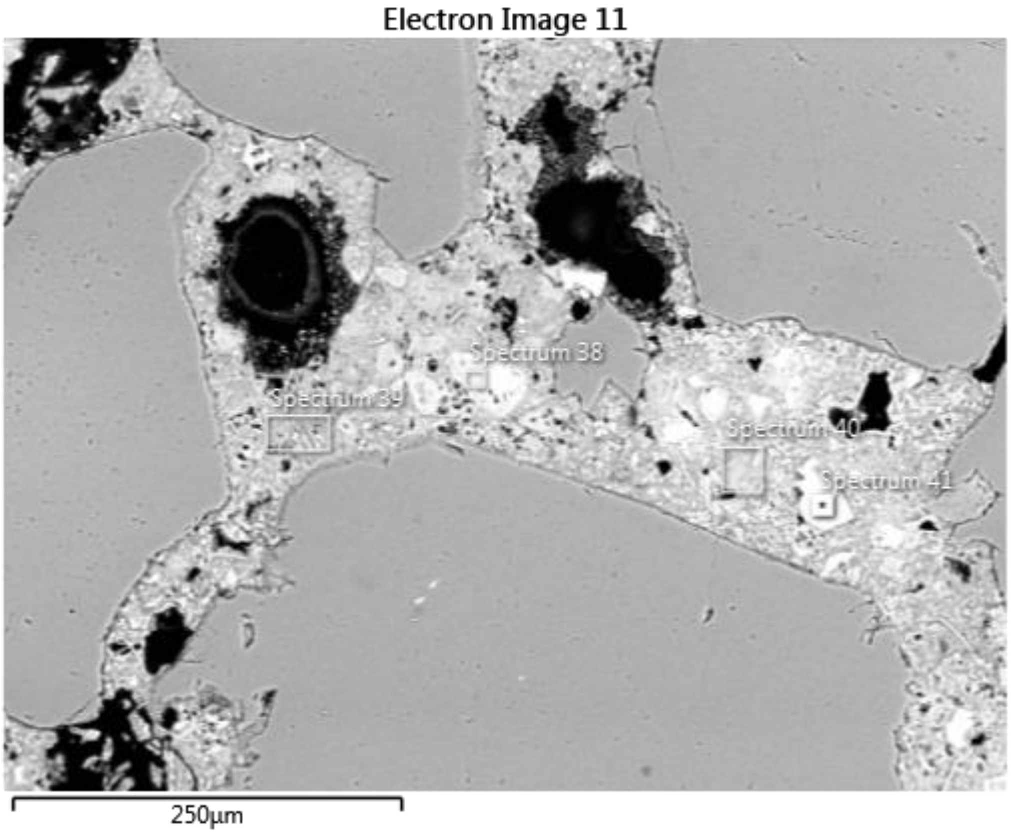
Spectrum 33 (Sand)



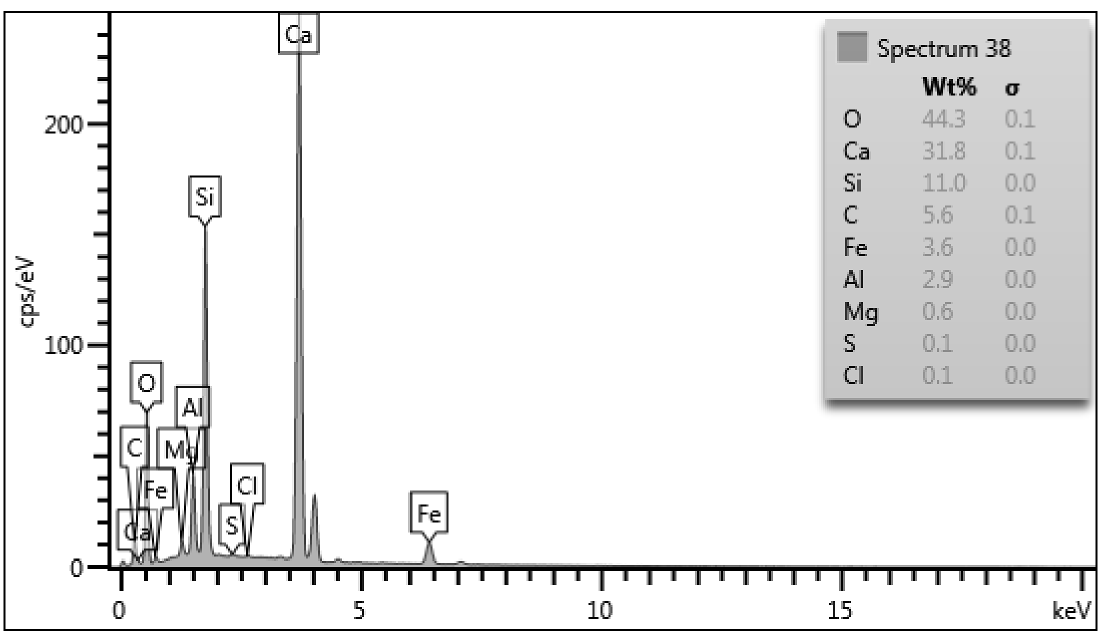
Spectrum 30 (Binder Phase)



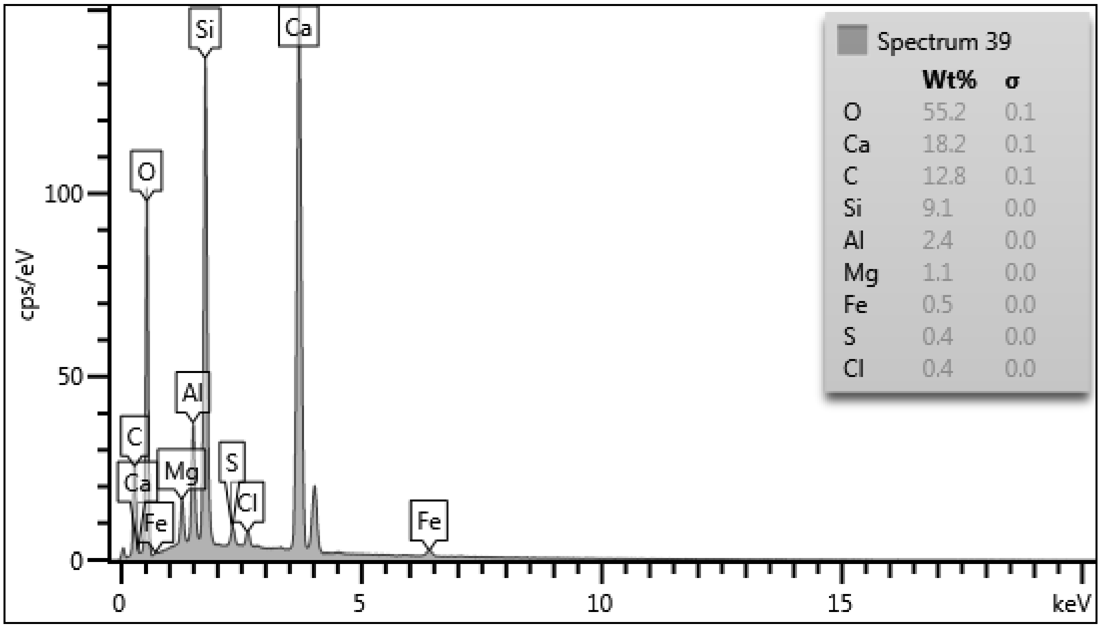
Sumter 2 – Sand (Grey Particles) with Lime Binder (Spectra 39 and 40) with Clay (Spectrum 38)



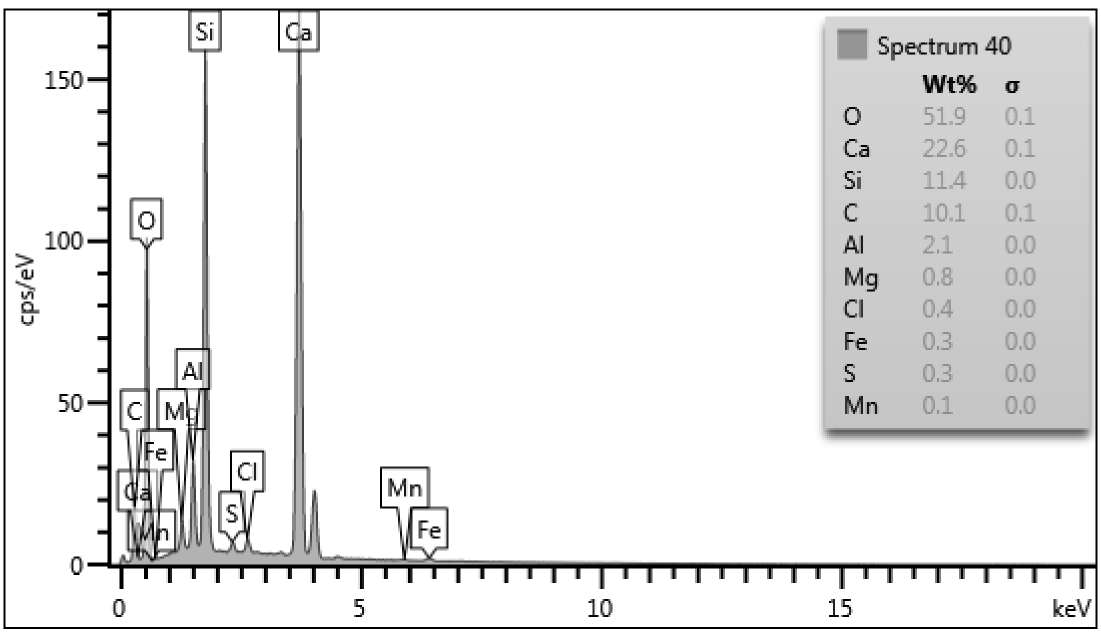
Spectrum 38 (Clay in Binder Phase)



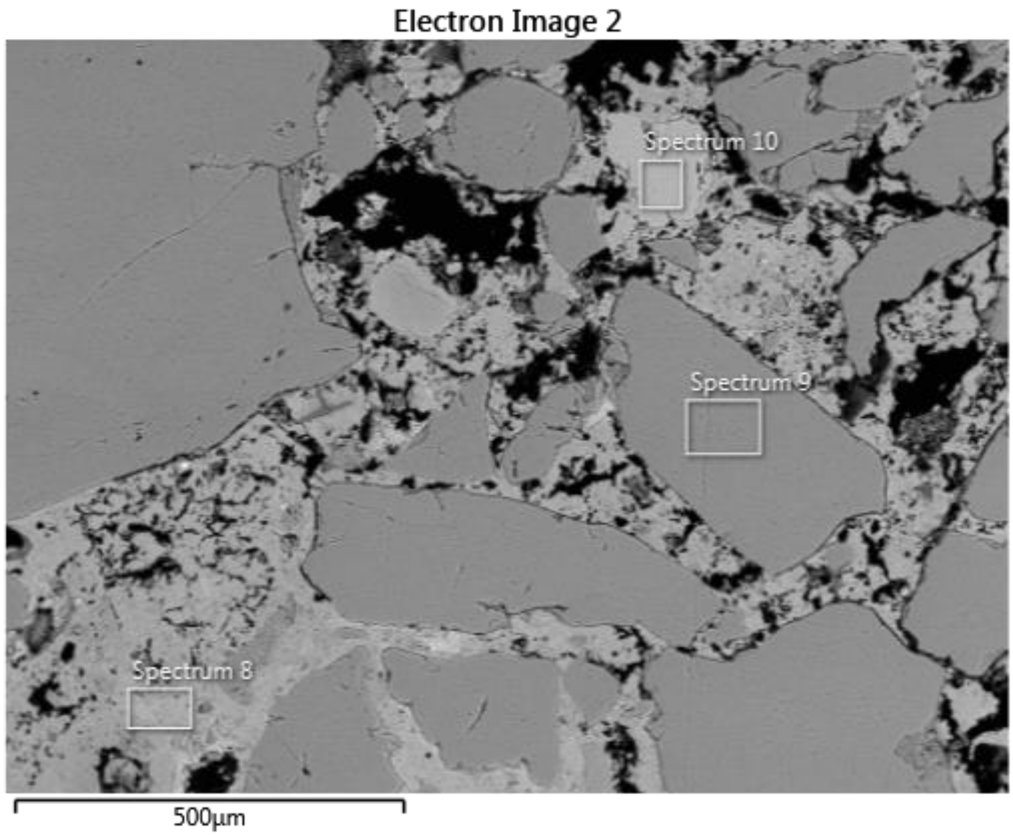
Spectrum 39 (Lime Rich Area in Binder Phase)



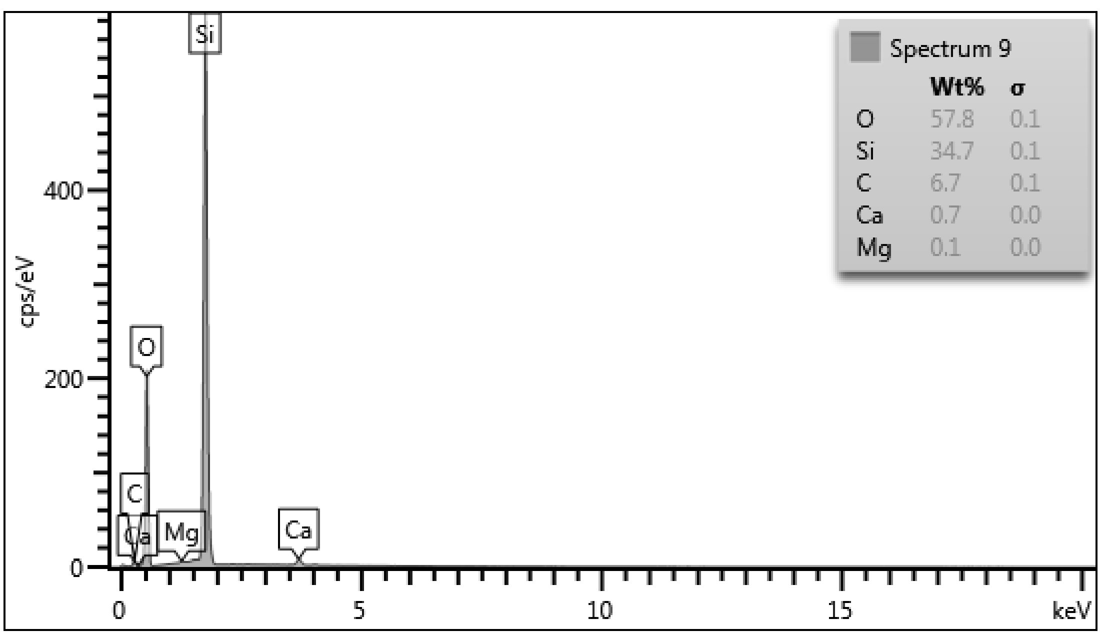
Spectrum 40 (Lime Rich Area in Binder Phase)



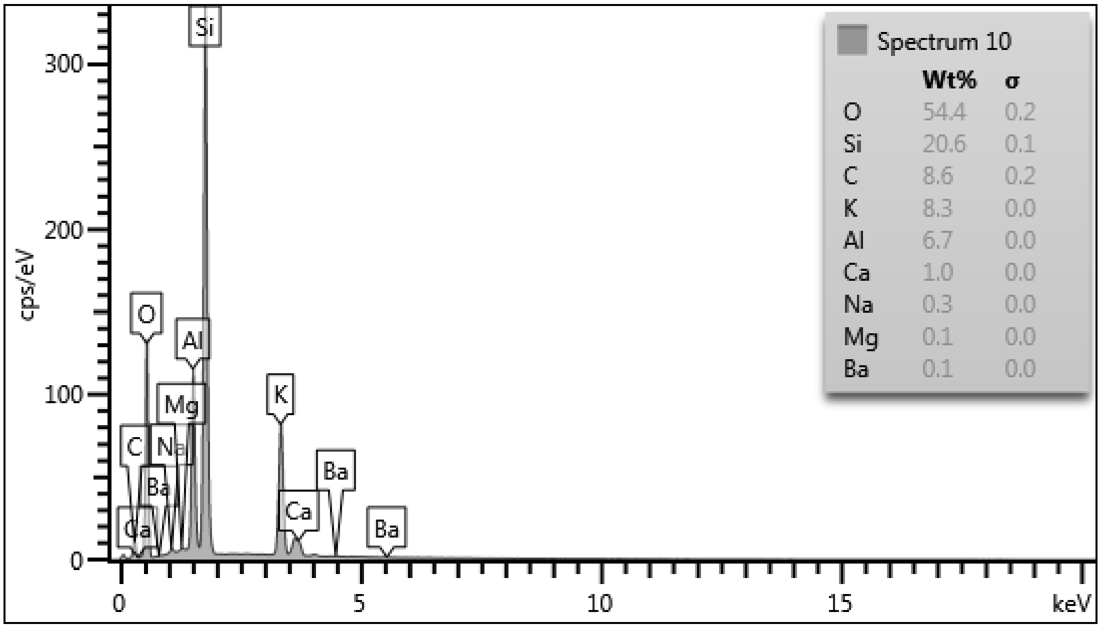
Greene 1 – Sand (Spectrum 9) and Clay in Binder phase (Spectrum 10)



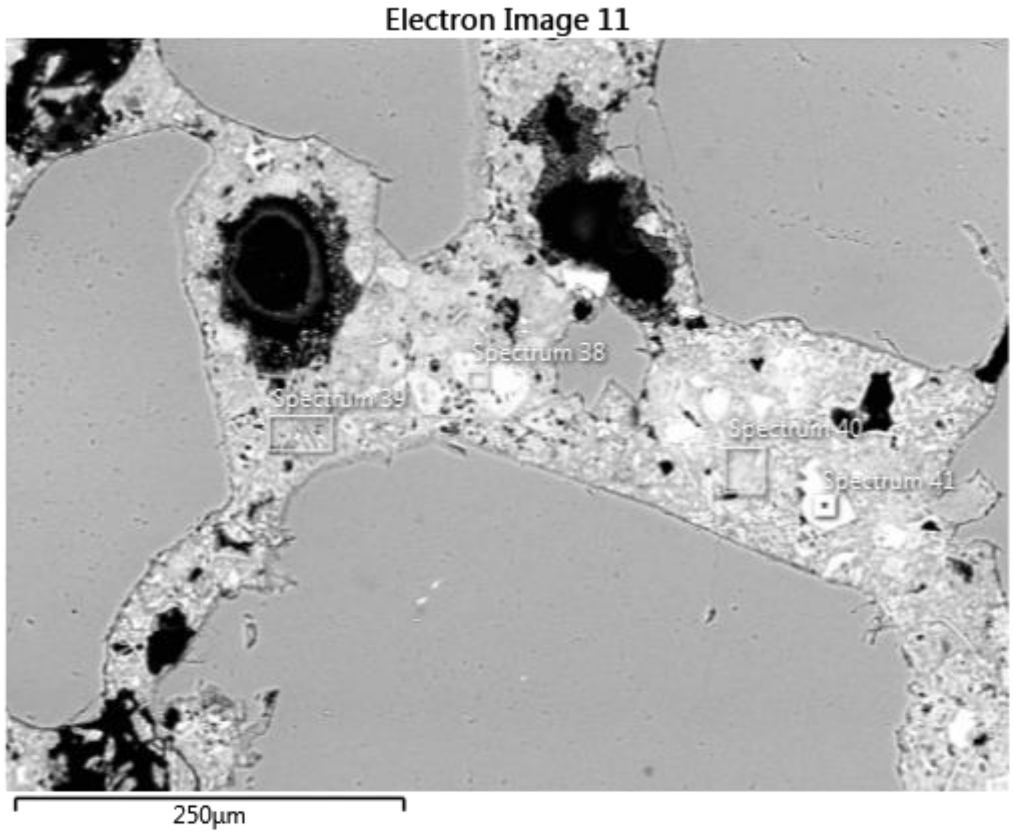
Spectrum 9 (Sand)



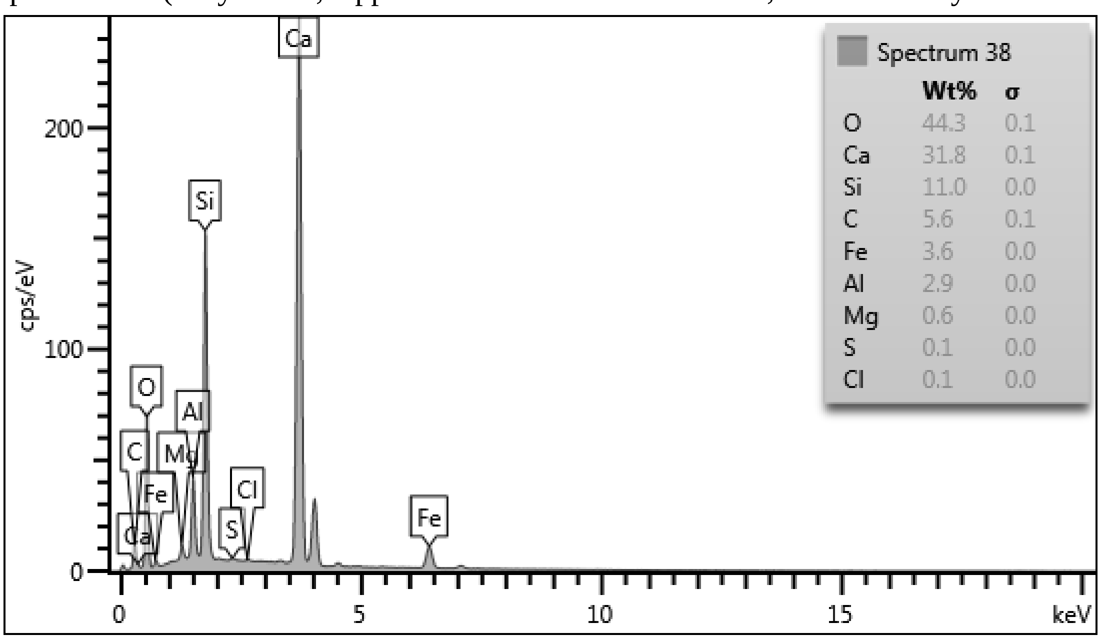
Spectrum 10 (Clay in Binder Phase)



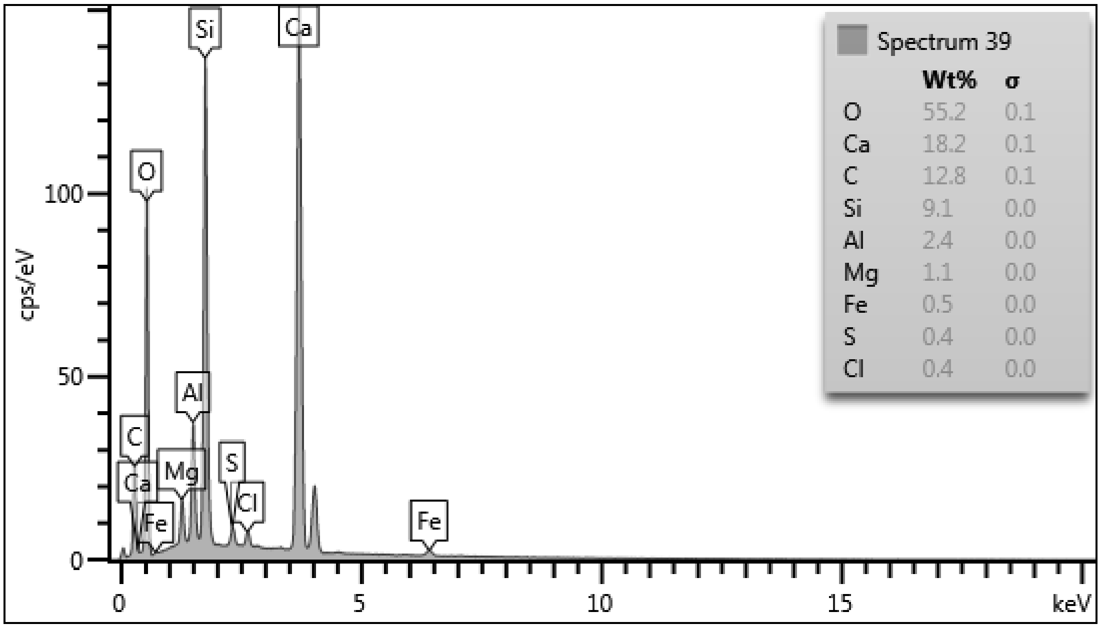
Greene 2 – Sand (Quartz) and Binder (dark and white phases, Spectra 39 and 40) with Pores (Black)



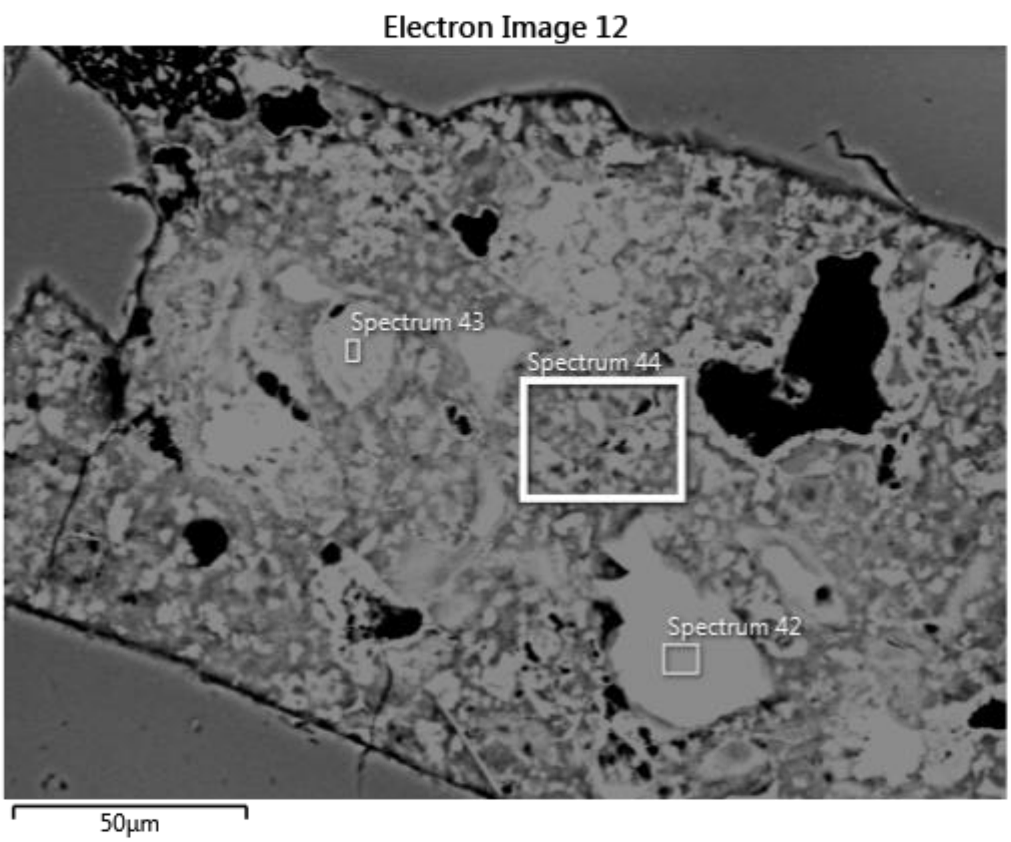
Spectrum 38 (Clay Phase, Appears white due to iron content, surrounded by Lime Rich Binder)



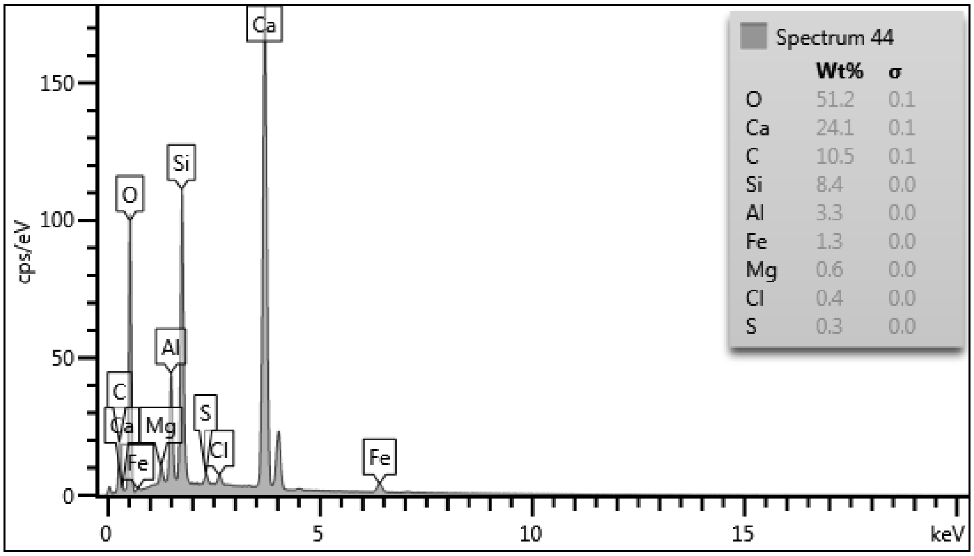
Spectrum 39 (Lime Rich Area in Binder Phase)



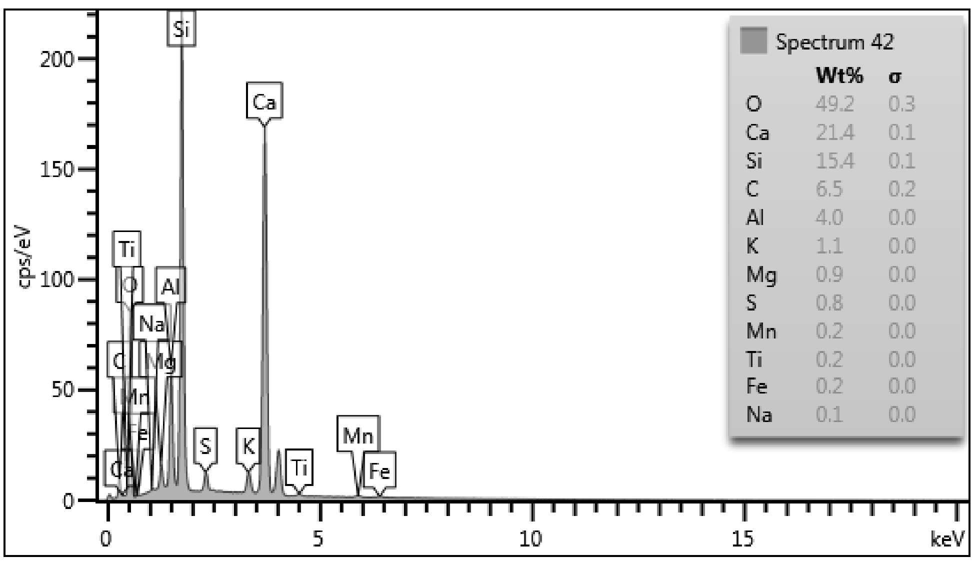
Higher Magnification – Greene 2



Spectrum 44 (Lime Rich Area in Binder)



Spectrum 42 (Clay in Binder)



Key Observations:

- The SEM/EDAX examination identified shale clay as a constituent of the binder phase. These relics appear as "white" in the SEM in backscattered electron image mode due to their iron content, but they are opaque or black when observed by petrography (in transmitted light microscopy).
- The reader is cautioned that polishing to create microscopic sections can "smear" constituents over one another affecting the EDAX results for chemical analysis. In practical terms, the analysis of the lime rich areas of the binder may reflect aluminum content from the clay, etc.

About the Author

Denis A. Brosnan is the Bishop Chair in Materials Science and Engineering at Clemson University. He specializes in forensic analysis of ceramic materials. For the last fifteen years, he has concentrated on forensics of building materials with important projects at the Smithsonian Institution, numerous buildings on the National Register, historic fortifications at National Parks including Fort Sumter National Monument, and historic buildings in Charleston, SC.

He is proud to be the father of two graduates of the University of South Carolina, and he considers it a particular honor to work on the Historic Wall at the Horseshoe.

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6277-600 Carolina Commons Drive, PMB 330
Fort Mill, SC 29707

Engineering Assessment of Bricks
Historic Campus Wall
University of South Carolina
by
Denis A. Brosnan, Ph.D., P.E.
July 7, 2014

Executive Summary

Specimens of clay bricks from the Historic Wall completed in 1836 were characterized as to their engineering properties that relate to contemporary Standards for brick products. The purpose was development of information for use in specifications for repair material and to guide restoration activities. These bricks were obtained from cataloged achieve specimens held at USC in late 2010.

The bricks were found to be hand molded and produced from weathered shale clay as is found in the Columbia S.C. area[1]. The bricks were found to exhibit saturation coefficients and pore structures that would classify them as Grade SW (Severe Weathering) in contemporary Standards, and replacement bricks meeting Grade SW are strongly recommended. The test results are consistent with the observation of only a few freezing and thawing durability failures or "spalls" on the Wall. Additional brick attributes for repair include use of similar brick sizes, colors, thermal expansion, and surface features as in original construction. Mortar color matching and joint tooling are important in repairs so as to match the aesthetics of the original structure.

Introduction

Four structural clay brick specimens from original construction of the Horseshoe Wall, located in historical archives, were tested for absorption properties according to the method in ASTM C67, *Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile*. These specimens were also tested using Mercury Intrusion Porosimetry (MIP) to further establish their contemporary Grade rating, and they were tested using thermal expansion by dilatometry in order to estimate their firing temperatures.

The purpose of this report is to provide supplemental information for the current preservation activities with the Wall. Bricks meeting ASTM C 216 Grade SW (Severe Weathering) in restoration work were recently recommended[2]. The specimens were tested in the Bishop Materials Laboratory of Clemson University under the certifications attained by that organization relative to the tests.

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[1] The source of bricks was primarily from the John Brown brickyard located by the Congaree River in Columbia, but some bricks were obtained from Charleston, SC. See "University of South Carolina Campus Wall Historic Structure Survey, E. Oswald, J. Betsworth, and J. Zeise, A Report Prepared for Dr. Robert Weyeneth, Spring (2011).

[2] Characterization of Masonry Mortar, Historic Campus Wall, University of South Carolina, Denis A. Brosnan, Ph.D., P.E., July 2, 2014.

Bricks are fundamentally classified under ASTM C 216 by their water absorption characteristics and their compressive strength. The absorption characteristics reflect the pore structure that essentially determines the ability of the bricks to resist the forces involved in freezing and thawing of water saturated bricks. Therefore, much attention in this report is paid to properties that reflect pore structure in characterization of historic bricks.

The qualification of structural clay units in resisting freezing and thawing cycles is judged by comparing water absorption characteristics with criteria in contemporary Standards[3], with tests conducted using the methods in ASTM C 67. While contemporary Standards do not apply to bricks in older masonry structures, the criteria in the Standards represent years of accumulated knowledge on brick masonry and are used in making an engineering estimate of brick performance. To further consider the qualification of the bricks, the pore size and pore volume criteria developed by Maage are employed[4]. Finally, the firing temperature of the bricks was determined using thermal dilatometry[5].

Findings

Photographs of three of the as-received bricks are shown in the Appendix. All appear to be molded bricks based on the weathered shale commonly found in the Columbia area. The three brick were all red to red-yellow in color with typical "porous texture" for molded bricks as shown on fracture surfaces on the as-received photographs.

The absorption properties of the bricks are given in Table 1. The properties are briefly explained as follows:

Cold Water Absorption (CWA) – the weight gain of a dried brick or tile expressed as a percentage increase from the dry weight after immersion in room temperature water for 24-hours. Such treatment typically fills or saturates about 66-68% of the open porosity of the brick.

Boiling Water Absorption (BWA) – the weight gain of a dried brick or tile expressed as a percentage increase from the dry weight after immersion in boiling water for five hours. Such treatment typically fills or saturates over 96% of the open porosity of the brick.

Saturation Coefficient – the quotient of CWA divided by BWA expressed as a fraction. This quantity reflects the fraction of "fine pores" within the brick or tile. Contemporary Standards set a maximum of saturation coefficient was a means of discriminating durable and non-durable bricks.

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[3] ASTM C216, Standard Specification for Facing Brick (Solid Masonry Units Made from Clay or Shale), The American Society for Testing and Materials. ASTM C212, Standard Specification for Structural Clay Facing Tile, The American Society for Testing and Materials

[4] Manfred Maage, *Frost Resistance and Pore Size Distribution of Bricks,* Ziegelindustrie International, 9 (1990) 472-481.

[5] L. Franke and I. Schumann, *Subsequent Determination of the Firing Temperature of Historic Bricks*, Conservation of Historic Brick Structures, Donhead Publishing, ISBN 1 873394 34 9 (1998).

For example, a brick classed as SW (Severe Weathering) in ASTM C216 cannot exceed a saturation coefficient of 0.80 (or 0.78 as an average in a group of five bricks).

The mercury porosimetry results are also given in Table 1. The Maage Index estimates the durability of fired clay bricks based on the total porosity and the fraction (content) of pores greater than three microns in diameter. The Maage Index rating is as follows:

Maage Index	Rating
>70	Frost resistant at normal saturation.
55-70	Unpredictable performance at normal saturation.
<55	Not frost resistant at normal saturation.

The results in Table 1 show all historic bricks to meet the saturation coefficient criteria for Grade SW (Severe Weathering) bricks as provided in contemporary Standard C216. Three of four bricks tested failed to meet the boiling water absorption maximum values for Grade SW bricks, and this is not surprising for bricks that were hand molded in the early 1800's. All of the bricks tested were rated as "durable" by the Maage criteria. These findings are consistent with the observation that there were only a few durability failures on the Wall.

The coefficient of thermal expansion in the interval room temperature to 200^{o}C for three of the specimens were in the approximate range 5.6-5.8 exp (-6)/^{o}C, a normal value range for clay bricks (Table 2)[6]. It is unlikely that sand was added to the local clay for making the bricks using the Columbia weathered shale (sand would increase the thermal expansion coefficient of fired bricks). Note that general matching of the thermal expansion coefficient between new and original bricks is recommended for repairs in historic structures.

Color data is given in Table 3, and it may be compared to as-received photographs of three of the four bricks. Brick 37E exhibits the largest yellow hue (highest b* value), consistent with the fact that this brick exhibits the lowest predicted firing temperature (Table 4). It is noted that brick 37E was previously classed as durable by the absorption and Maage methods despite a "lower" firing temperature.

The firing temperatures of the bricks (Table 4) were estimated using thermal dilatometry to be in the range 1076-1098^{o}C (1969-2008^{o}F). The individual dilatometry curves are given in the Appendix. For comparison purposes, modern facing bricks manufactured in Columbia classed as severe weathering and based on weathered shale are typically exposed to temperatures of about1093^{o}C (2000^{o}F). The values of the historic bricks allow them to be considered as "normally fired" for estimation of their Grade qualification.

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[6] The normal range for thermal expansion coefficient for clay bricks is 3.4 – 8.0 exp (-6)/^{o}C per M. Kornmann, Clay Bricks and Rooftiles, Societe de l'industrie minerale, Paris (2007).

Table 1: Standards, Absorption Properties, and Maage Index

Category and Specimen ID	Cold Water Absorption, % (CWA)	Boiling Water Absorption, % (BWA)	Saturation Coefficient (CWA/BWA)	Apparent Porosity. %	Maage Index	Durability Prediction at Normal Saturation
Limit for SW bricks (average)		≤17.0	≤0.78	Not specified.		
Limit for SW bricks (individual)		≤20.0	≤0.80	Not specified.		
Limit for MW bricks (average)		≤22.0	≤0.88	Not specified.		
Limit for MW bricks (individual)		≤25.0	≤0.90	Not specified.		
4W	6.88	11.66	0.59	23.55	138.0	Pass SW CWA/BWA Meets SW by CWA Pass Maage
30W	17.37	22.00	0.79	36.96	213.6	Pass SW CWA/BWA Meets MW by CWA Pass Maage
34E	15.18	20.26	0.75	35.44	205.5	Pass SW CWA/BWA Meets MW by CWA Pass Maage
37E	17.52	22.09	0.79	37.60	75.3	Pass SW CWA/BWA Meets MW by CWA Pass Maage

Table 2: Coefficient of Thermal Expansion by Thermal Dilatometry

Specimen	Value, / ^{o}C	Comment
4W	5.59exp(-6)	Normal value for clay brick.
30W	5.8exp(-6)	Normal value for clay brick.
34E	5.69exp(-6)	Normal value for clay brick.
37E	1.79exp(-6)	Instrument fault at low temperature influenced result.

Table 3: Color Measurement in the L*a*b* System of Measurement

Specimen	L* (+L indicates lightness)	a* (+a indicates red)	b* (+b indicates yellow)
4W	42.7	14.8	17.3
30W	45.4	17.5	24.1
34E	41.4	13.6	16.9
37E	55.7	16.7	27.7

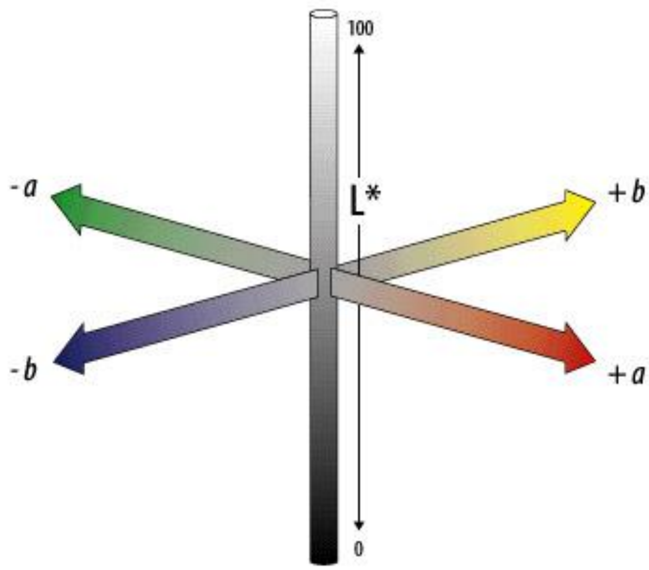


Figure 1: L*a*b* Coordinate System

Table 4: Estimated Firing Temperatures by Deflection in Thermal Dilatometry

Specimen	Value, ^{o}C
4W	1097.6
30W	1085.8
34E	1088.1
37E	1076.0

Conclusions

The absorption and mercury porosimetry indices show all brick tested to be predicted as durable in agreement with practical observations of bricks in the Historic Wall. This supports the recommendation of use of Grade SW bricks for restoration repairs. Other criteria for replacement bricks include:

- Use of replacement molded bricks of the same size as the historic units.
- Color matching of replacement bricks to those bricks in the existing wall with similar surface features to include a smooth texture.
- Use of replacement molded bricks of similar thermal expansion coefficient as those in the historic wall.

While compressive strength was not obtained in this assessment, the bricks in the Wall appear sound and have obviously performed well.

With regards,

Denis A. Brosnan

Denis A. Brosnan, Professor and Consultant
Registered Professional Engineer
SC Registration 13888

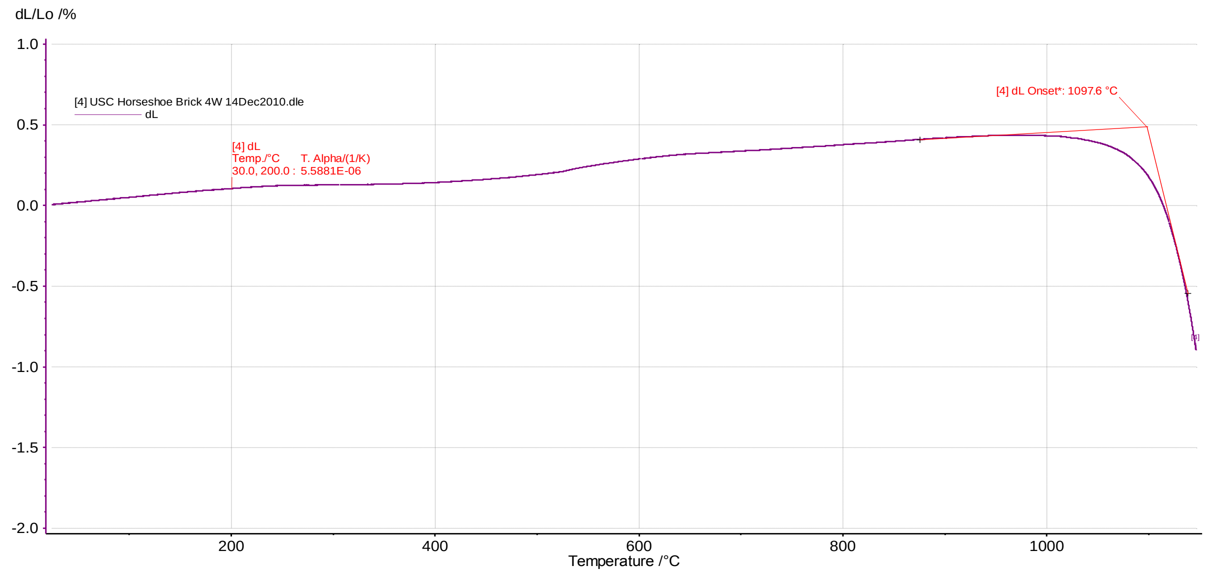
Appendix: Photographs and Additional Data

As-Received Photographs – No Brightness or Contrast Adjustment
No photograph available for Specimen 4W

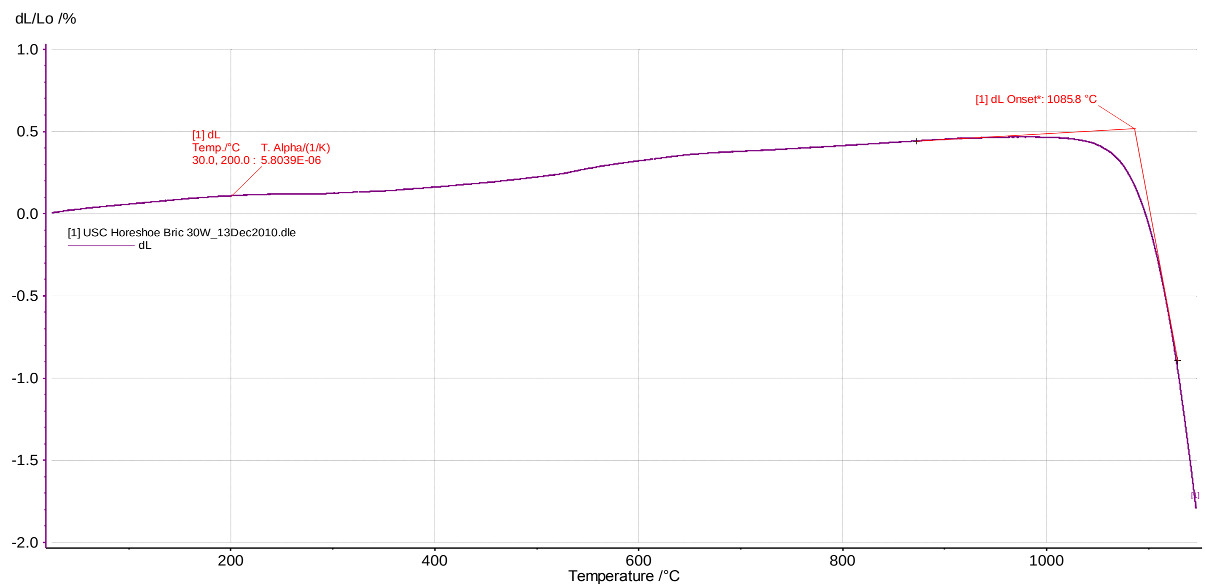

34E
USC Confederate Wall 34E


USC Confederate Wall 37E

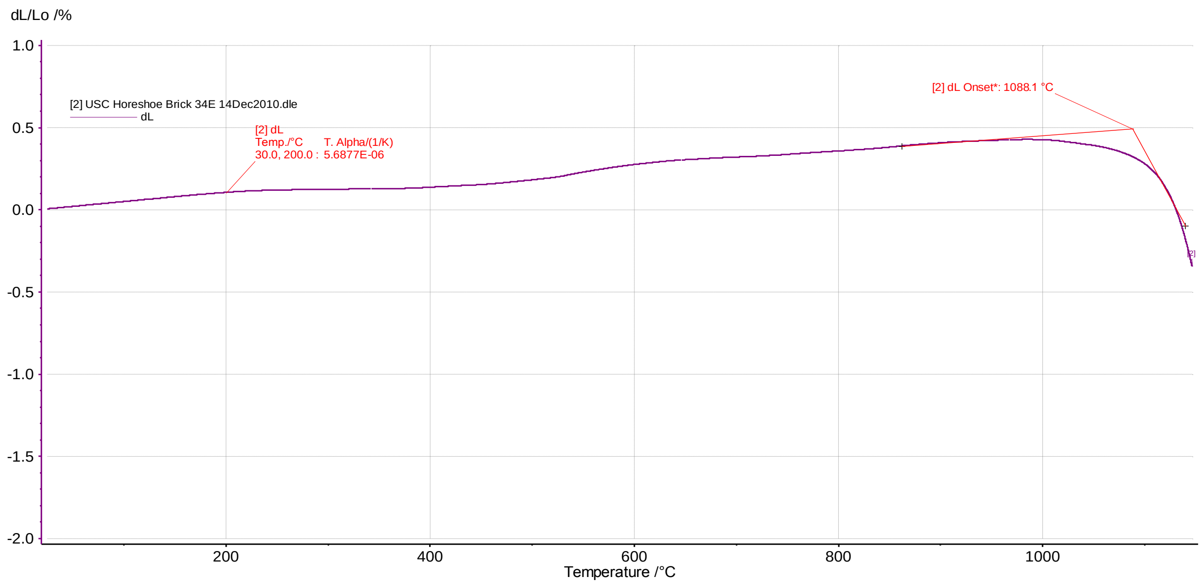
Thermal Expansion Curve – Brick 4W



Thermal Expansion Curve – Brick 30W



Thermal Expansion Curve – Brick 34E



Thermal Expansion Curve – Brick 37E