Forensic Evaluation of Masonry Materials
Castle Pinckney, Charleston Harbor, SC

by

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Executive Summary

Specimens of bricks and mortar from Castle Pinckney were characterized using modern analytical techniques and microscopy in a similar manner as used on masonry materials from Fort Sumter National Monument. The bricks were found to be of the "Charleston Grey" type of local manufacture used on many historic structures on the peninsula and at Fort Sumter. The bedding mortar was composed of oyster (burnt) lime, sand, and brick dust. Another mortar examined was lightly sanded and it was probably used in historic pointing of the walls. Additional studies should be considered if Portland cement based mortars, a potential threat to the historic bricks, are found on the scarp walls.

The author presents new theories of horizontal cracking observed on the South and East scarp walls and of the loss of brick in prominent areas on the South scarp wall (and to a lesser extent elsewhere). It is suggested that the weight of the infill of the structure not only is a root cause of settlement but also it is causing a bowing in the vertical direction of walls leading to tensile failures in the masonry bond – particularly near the elevation of the covered historic casemates on the Castle's interior. The infill also leads to a circumferential stress in the scarp walls leading to horizontal cracking.

Threats to Castle Pinckney were revealed in prior literature, and the author presents his opinion of issues that should be addressed in the near term to include: (a) at least partial removal of infill to relieve outward pressure on walls, (b) repair and fills behind rip-rap to prevent sea impingement and wave action from affecting the scarp walls, and (c) repair of missing bricks and pointing of the scarp walls. A structural assessment should be performed prior to any removal of infill or repairs to ensure safety of workers.

Castle Pinckney is a unique historical asset of particular importance to Charleston. It should be stabilized from decay as soon as possible. Eventual efforts to provide for public access and interpretation would only add to the many reasons that the City of Charleston is a "sacred" place to residents and a magnet for visitors.

Introduction

Castle Pinckney is a Second System brick masonry fortification on Schutes Folly Island one mile east of the lower peninsula of the City of Charleston, SC. It was built over the ruins of Fort Pinckney, a 1797 earthen fortification named in honor of Revolutionary War hero Charles Cotesworth Pinckney. The Fort served as a part of the "First System" of coastal defenses as a component of defense installations in the Charleston harbor that included Forts Johnson, Moultrie, and Mechanic. These forts protected Charleston against perceived naval threats – especially from France. Fort Pinckney was destroyed by a hurricane in 1804[1].

A fortification was rebuilt on the ruins of Fort Pinckney with construction beginning in 1809, and it was eventually called Castle Pinckney. Jonathan Williams, the first Superintendent of West Point, is credited with the design, and it reflected Williams' experience with European fortifications. The design was called a "casemated circular castle style" thought as particularly advantageous for a small island like Shutes Folly and one that could exhibit a wide field of fire when garrisoned by a relatively small contingent. It is important to consider the position of Castle Pinckney at one mile off the City's shoreline as an excellent deterrent from that day's naval ships having a maximum range of fire of about one mile.

The construction was through-wall masonry, similar to that of Castle Williams in New York harbor. Other Second System fortifications were either earthen and timber, brick masonry faced earth (with bricks to prevent erosion), or solid masonry (through wall). Of 32 Second System fortifications, only seven survive today.

The builder of Castle Pinckney was Alexander Macomb, a member of the 1st generation of West Point graduates. The original design included two tiers of casemated cannons with additional weapons en barbette on the terreplein. The design was reduced to a single tier of casemated cannons due to cost overruns for all period fortifications. No records were available to the author on sources of building materials or the identities of construction workers, although use of enslaved labor was likely. Construction was completed in 1810.

The history of the fortification and its use after construction is described by Ziegler[2]. The first archaeological assessment of Castle Pinckney was by Lewis and Langhorne[3]. A recent contribution by Weirick contains additional information and presents a thorough assessment of the Castle today[4].

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[1] Young, Rogers W., "Castle Pinckney, Silent Sentinel of Charleston Harbor" (1938), South Carolina Historical Society, 39 (1) 1-14 and 39 (2) 51-67.

[2] Christopher Ziegler, "The Origins and History of America's Forgotten Castle: Castle Pinckney", Thesis, University of South Carolina (2007).

[3] Lewis, Kenneth E. and Langhorne, William T. Jr., "Castle Pinckney: An Archeological Assessment with Recommendations" (1978), *Research Manuscript Series.* Book 145. http://scholarcommons.sc.edu/archanth_books/145.

[4] Weirick, David, "Castle Pinckney: Past, Present, Future", (2012) Thesis, Clemson University and the College of Charleston.

Notably, Confederate General G. P. T. Beauregard did not think Castle Pinckney would be important in Charleston's "first line" of Civil War harbor defenses, but as the attack on Ft. Sumter progressed the Castle became a "second line" of defense. One reason obvious to the Confederates was that naval cannon fire from the inner harbor could reach the docks and warehouses in Charleston without the deterrent of the Castle.

The Confederates covered the outside walls with protective materials and earth, and they in filled the interior at least partially with sand in building two batteries above the terreplein. The extra wall protection reflected the Confederate experiences at Battery Wagner and Fort Sumter. After the Civil War, General Quincy Adams Gilmore (USA) completed in filling of the Castle. The Castle was a part of the Lighthouse Corps (1880-1917) where a keeper's house and light tower were located over the fill. The Castle became a National Monument during the period of 1924-1956, but it was deactivated by the National Park Service due to potential costs for restoration. It was owned by the South Carolina State Ports Authority until recently when ownership transferred to a local (S.C.) chapter of the Sons of Confederate Veterans. A current web site reports oversight by the Castle Pinckney Historical Society[5].

Castle Pinckney was available for a field documentation activity on February 23, 2011, by students from the College of Charleston, and the author accompanied the students. Specimens of brick and mortar were obtained separately from Mr. Rick Dorrance of the National Park Service. Mr. Dorrance obtained these specimens from the East Bastion of the fortification at an elevation of about five feet above the existing exterior ground level – above a partially buried embrasure.

In early 2011, the condition of the fortification was residual fill against the gorge wall, in fill remaining within the fortification with tree cover, some added masonry elements on the North Wall – presumably present in the Confederate era, partial steel structures from the old lighthouse, evidence of foundations for later period structures on the Castle's in fill, and bricks in the marsh by the Parade presumably from original structures. There were no remaining buildings at the Castle. There was evidence of a light colored cementitious coating on the outer walls supporting the fact that the Castle was coated with a lime wash to reduce water infiltration into the casemates and magazines.

The purposes of the investigation were limited expressly to:

- Characterize brick and mortar specimens to determine their composition so as to aid in historic sourcing of materials and to be of use in any future restoration and repair efforts.

- Contribute to the body of knowledge of historic buildings and structures in Charleston, SC.

- Determine if evidence exists of diagenesis, i.e. alteration of materials by chemical species in the environment, as was observed in masonry materials at Fort Sumter and on structures on the Charleston peninsula.

[5] See www.castlepinckney.com. Incorporation in South Carolina reported on January 31, 2013.

Site Documentation

Historic and Modern Images

A watercolor in Bachman's sketch book shows the gorge wall and parade area in 1831 (Figure 1). Two tiers of embrasures are found on the bastions and gorge side, and these presumably served to allow small arms fire toward any land size combatants[6]. Only one level of embrasures is seen on the harbor side of the Castle.

The Castle is depicted as "cream colored" suggesting that a cementitious material was used over the brick masonry. This is consistent with findings of a residual coating on the bricks in 2011 (See Figure 7) where a white coating remains in places. The artist's rendition in Figure 1 may reflect a sunset lighting condition (gorge wall illuminated).

Figure 1: Watercolor of Castle Pinckney, Signed by George Lehman; In Mary Eliza Bachman's Sketchbook (1831)

A similar Castle orientation is shown in a Post-Civil War photograph (Figure 2). Notably, this photograph shows no Parade side fill. An interesting feature of this photograph is fill apparent at the West bastion from the Civil War protective wall system (Arrow in Figure 2, see also Figure 4). Areas of lighter colored pargeting on the gorge walls are noted in Figure 2.

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[6] Russell Horres, personal communication with D. A. Brosnan on June 5, 2013.

Figure 2: Post Civil War Photograph of Gorge Wall
(Reference 2, Attributed to Fort Sumter National Monument Flat Files)

The interior of the Castle is shown in 1861 when it was briefly used to house prisoners (Figure 3). The exposed walls appear white colored – with a notable exception of brick walls covering the casemates apparently constructed during the War forming prison cells.

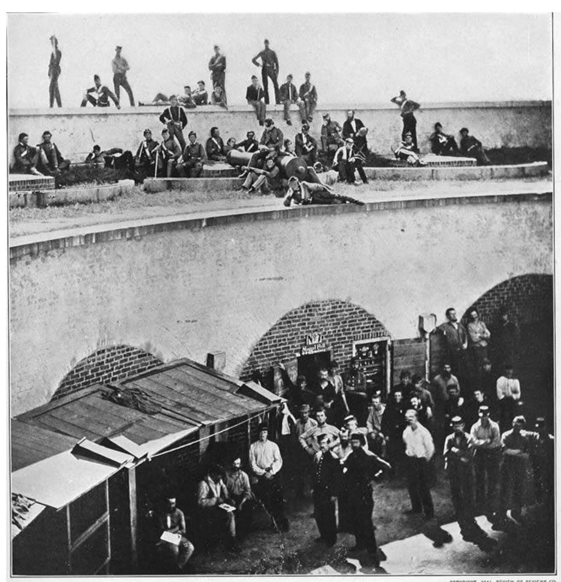

Figure 3: Interior Casemate View 1861
(Reference 2)

The Confederate earthen cover over the exterior walls is shown in Figure 4. This protective cover was added when Castle Pinckney became a second line of defense for Charleston. One feature of the photograph is particularly interesting (arrow). What appears as an opening in the earthen cover (lintel visible with masonry side supports) may be related to a masonry addition to the walls still visible today (Figure 5). This addition does not appear to be "tied in" to the original Castle Pinckney wall. The pilings visible in Figure 4 suggest that a dock for the Fort was located on this side prior to the Civil War (in addition to the stone dock/wharf on the Northeast face and the later wooden dock in the same location). The masonry addition appears to be a protective counter scarp wall in front of magazines (references 4 and 6). It is interesting that this protective wall is not mentioned in literature until 2012 by Weirick (reference 4). The massive nature of the counter scarp is shown in Figure 6.

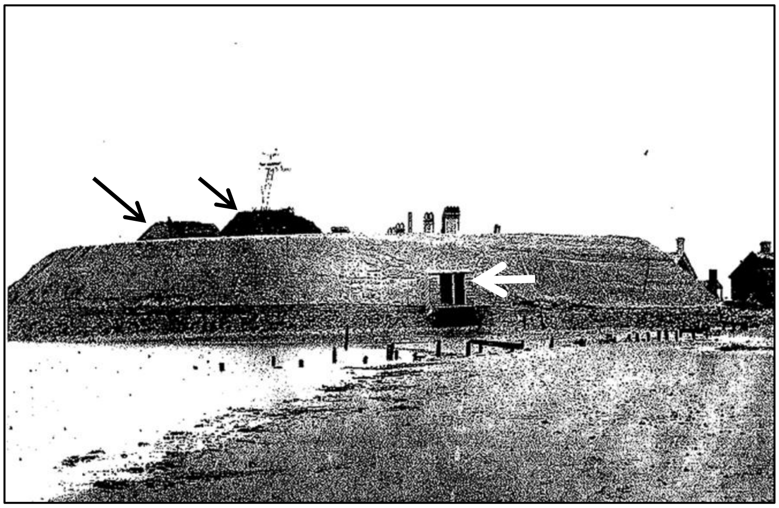

Figure 4: Exterior from North Side during Civil War
(Reference 2)

Images on 23 February 2011

Figure 5: Masonry Addition to North Wall

Figure 6: Counter Scarp Today (arrow)
(Image by U.S. Coast Guard, 2012)

The East bastion and parade are shown in Figure 7. There were no structures on the parade, but loose bricks were observed in the marsh. The partially buried sally port is barely visible in this photograph (arrow). The exterior walls show residuals from the white pargeting over the masonry (Figure 8). Weirick reports that the white coating was a "lime wash", and the implication is that it was applied to reduce water intrusion into the masonry as the Castle was repaired prior to the Civil War (reference 4). Water impingement on the masonry at high tide appears as likely in a clock wise direction from South to East. Contemporary sea level is about two feet higher today than that in 1860 (See the base of scarp in Figure 8 where the coating is removed by wave action).

Figure 7: Right Flank and East Half-Round Bastion with Gorge Wall/Parade (right)

Figure 8: Harbor Face from Southwest

The remains of the 1900's era dock on the Southwest face are shown in Figure 9. This dock can be seen as leading to the top of the wall. The original dock structure is shown in Figure 10, and the suggestion is that the wooden dock is a post-Civil War addition. A stone structure in Figure 10 (arrow) is termed the "stone wharf" in literature, and it is likely part of the original construction of the Castle.

Figure 9: Remains of Dock on South West Side

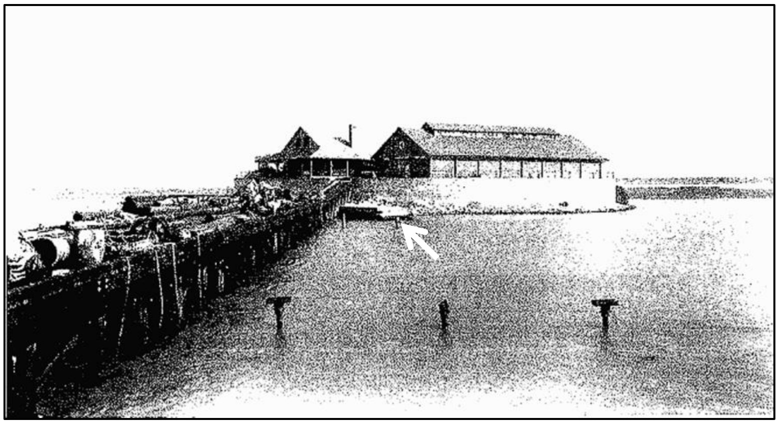

Figure 10: Dock Photograph in the 1930's (Reference 1)

The interior of the Castle is shown in Figures 11 and 12. Upper level embrasures are shown in Figure 11. Iron rods extend vertically as remains of a peripheral fence installed after the Civil War,

Figure 11: Upper Level Embrasures Facing Charleston

The interior earthen fill is obvious in Figure 12. It partially obscures the sally port which barely remains passable today due to the fill principally on the interior but also present on the exterior (Figure 7). There was apparently no obstruction of the exterior to the sally port in 1978 (Figure 13).

Figure 12: Sally Port from the Castle's Interior

Figure 13: Sally Port on Gorge Wall (1978, Lewis and Langhorn)

Lower level embrasures on the circular wall were closed with masonry (Figure 14) probably when the Confederates used the Castle as a prison. Lewis and Langhorn report that the casemates were disarmed in 1864 when the Confederates filled the interior with sand (reference 3). The base of the wall today is obviously damp due to sea water impingement.

Figure 14: Embrasure on East Exterior Wall Closed with Masonry

Specimens obtained for further study were from the East bastion midway in elevation between two embrasures (Figure 15). This was a location where two clay drainage pipes were installed after the Civil War and possibly during the days of lighthouse service. In the area of this repair (dashed box), the bricks are notably of a red color and the white coating is absent.

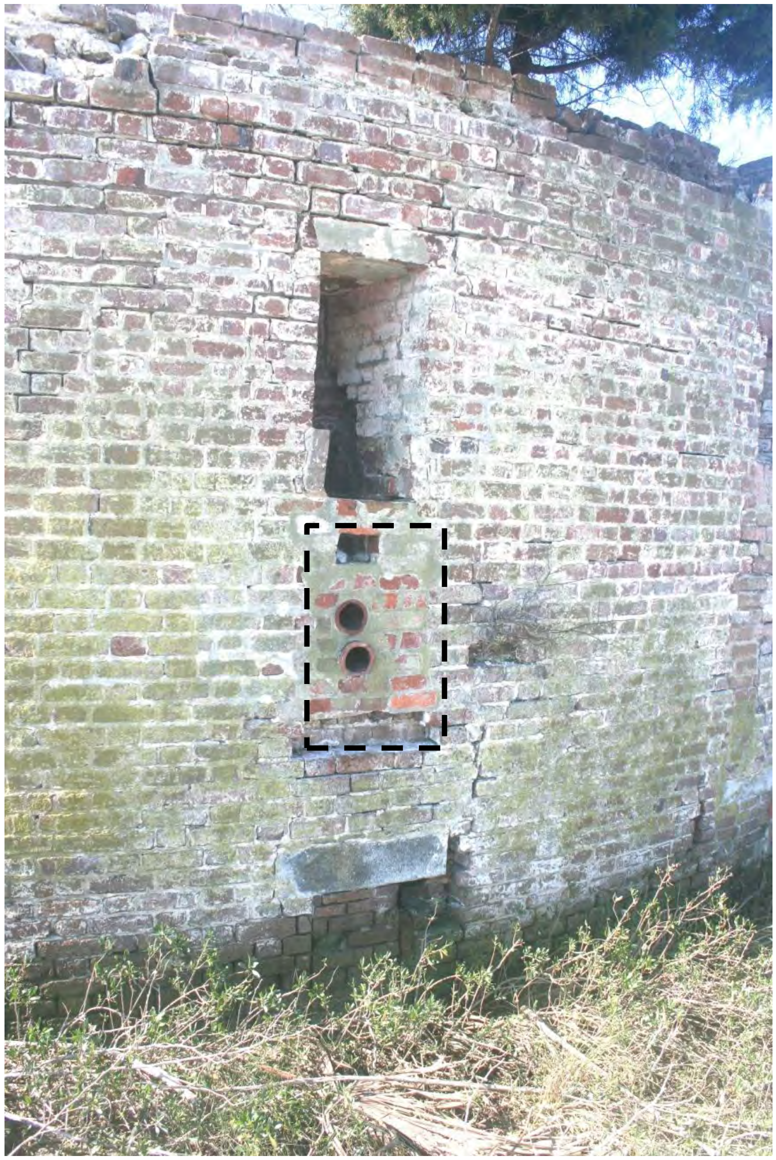

Figure 15: Specimen Location above Partially Buried Embrasure; East Bastion

Further detail of the sampling location is given in Figure 16. Two of the bricks in this study (designated East 82 and East 83) were taken from the lower course of darker bricks exhibiting iron spots (base of opening where bricks were removed). The other brick for this study (designated East 81) was of a light color and it was taken from the same area, although this brick was likely placed during installation of the clay pipes.

Darker colored bricks exhibiting iron spots are typical of bricks made near the immediate coast or along the Wando River. These dark bricks are found on many historic buildings on the peninsula and on Fort Sumter. By contrast, red bricks without iron spots are typical of those made inland near today's Dorchester County.

The loose mortar specimen was collected from this location. The mortar specimen designated as "83" was adherent to the brick labeled East 83 suggesting that it was original bedding mortar used in construction of the Castle.

Figure 16: Detail of Specimen Location with Original Masonry (Darker bricks, lower photograph) and Repair Masonry (Lighter bricks, upper photograph – possibly from installation of clay drainage pipes during lighthouse service, 1900's)

Considerations on Weirick's Assessment

Weirick reports, "The majority of original bricks, although marred by sloppy repointing, soiling, brick patches, and other superficial disfigurations, are in remarkably good condition" (reference 4, p. 78). Weirick states that the original bricks were handmade and lime mortar was used, with the mortar comments through his site observations and without support of analytical data or physical examinations.

Weirick presents numerous architectural drawings of the scarp walls noting vertical and horizontal cracks and what he terms "brick patches" (West and Southeast walls). Many of the vertical cracks are shown as "stair step" and/or vertical cracks as are typically found in brick masonry buildings that have undergone subsidence[7]. The horizontal cracks, however, are unusual in masonry, and they are typically absent in other masonry structures like Fort Sumter that have also exhibited subsidence. It is noted that Fort Sumter is a rectangular structure whose corners essentially stiffen the scarp walls.

It is suggested by this author that the horizontal cracks primarily result from bulging of the scarp walls caused by the lateral pressure of the fill. The buried casemates may be related to the elevations of some horizontal cracks, as Weirick shows horizontal cracks along the South scarp face near top of the embrasure elevations. In Fort Sumter, there was no masonry bond

[7] Franke, L. and Schumann, Damage Atlas: Classification and Analyses of Damage Patterns Found in Brick Masonry, Fronhofer IRB,Verlag (1998), See Section 3.6.2 "Settlement".

between casemates and the scarp wall – meaning the wall could move independently of the casemates[8]. Alternately, the casemates did nothing to stiffen the wall or restrain the wall from bowing. The weight of fill also created a tensile "hoop stress" on the walls leading to cracking that is primarily vertical (not in "stair steps"). The resulting bowing movement in places resulted in loosening of bricks in discrete areas – notably on the West façade (Figure 8) and the Southeastern façade (Shown in Weirick's Fig. 7.15). The "bulging" of the walls may be unique to the circular design of the fort lacking corners to stiffen the structure. A complete structural assessment could confirm the origin of horizontal cracks.

Weirick uses the term "brick patches" to presumably include the area of brick loss of Figure 8. This loss is more likely due to the structural phenomena discussed above where bricks simply fell out over time, as this phenomenon is seen on brick masonry buildings subject to a variety of stresses. Some actual "patches" were present to include lighthouse era repairs Figures 15 and 16).

Lewis and Langhorne express concern about structural stability of the scarp walls if fill is removed (reference 3). Weirick states, "The removal of the earth will not only require extensive archeological planning, but could have unintended structural effects on the masonry; such as soil rebound in reaction to removal of so much weight" (reference 4, page 83). Therefore, structural stability should be evaluated through a thorough engineering assessment to protect the historic asset and ensure safety prior to any restoration.

[8] Russell Horres, personal communication, June 26, 2013.

Experimental Methods

The characterization methods are briefly explained below (Table 1). The techniques are common in analysis of historic masonry units and mortar as well as with Portland cement and concrete. They are particularly useful in historic materials' characterizations. All analytical work was obtained at The National Brick Research Center, a component of Clemson University.

Table 1: Characterization Methods

Method	Abbreviation	Purpose	Brief Description
X-ray fluorescence	XRF	Determine the chemical analysis or assay of the material.	The specimen is prepared as a molten salt fusion to create a homogenous target for X-rays. This target is illuminated by monochromatic X-rays thereby, generating characteristic (new) X-rays emanating from the atomic species in the product. Analysis of these new X-rays allows a quantitative determination of the chemical species in the specimen.
X-ray diffraction	XRD	Determine the mineralogy of the material.	The powdered specimen is illuminated with a column of monochromatic X-rays producing characteristic reflections from crystal planes in the material. These reflections reveal the identity and quantity of constituent minerals in the specimen.
Thermal analysis	DSC-TG-FTIR	Determine the weight changes, reaction phenomena and evolved gases on heating of a specimen.	Determines the occurrence of chemical reactions by energy flow and weight change on heating, and observes gases evolved from the specimen. The information serves as a "fingerprint" of the constituent mineral and chemical species.
Water soluble salts by ion chromatography	IC	Determine the presence of salts that are present in the specimen.	The method involves extracting the water soluble salts in water at room temperature. The salt content is determined by ion chromatography (IC) and expressed in terms of the original specimen weight.
Petrographic microscopy	Petrography	Identify minerals in thin-section microscopy.	Thin sections are observed in a polarizing microscope using transmitted and/or reflected polarized light.
Scanning electron microscopy	SEM	Observe surface features using electrons reflected or generated by a specimen.	Identifies chemical species in artifacts on the specimen. The technique is particularly useful in observing decay mechanisms in concrete to include the well-known "alkali-silica reaction (ASR)".
Energy dispersive X-ray analysis	EDAX	Detect X-rays generated in the SEM to aid in mineral identification.	The technique is particularly useful in identifying constituents of concrete to include lime and cement type.

Results

Analytical results are presented in this section with the intent of characterizing the masonry materials and discovering information pertinent to repair and restoration. For the reader only interested in the consequences of the results, each section is followed by "Summary Comments".

Key Results, Mortars

The as-received mortars are shown in Figures 17-18. The loose mortar consisted of granules, and it was obtained by collecting the fragments from the sampling location on top of a ledge of bricks (Figure 14). The other mortar specimen labeled as "83" was adherent to a brick specimen confirming that it was an original bedding mortar used when that brick was laid.

Figure 17: Loose Mortar Particles As-Received

Figure 18: Mortar 83 Adherent to Brick East 83

Chemical Analysis and Mineralogy, Mortars

The chemical analyses for mortars are given in Table 2 with mineralogy results provided in Table 3. Cementitious mortars typically contain large quantities of lime (CaO) and silica (SiO_2), the latter primarily from the sand component of the mortar. The difference in silica content is immediately obvious suggesting the loose mortar might be a lightly sanded material such as a pointing mortar or coating. It is also possible that this "loose" mortar specimen was not representative of the original product where the mortar was used.

Table 2: Chemical Analyses of Mortars (Oxidized Basis, Weight %)

Constituents	Loose Mortar	83 Mortar
Al_2O_3	2.36	1.85
SiO_2	39.63	78.38
Na_2O	<0.5	<0.5
K_2O	0.35	0.09
MgO	0.76	5.01
CaO	54.42	12.83
TiO_2	0.21	0.12
MnO	0.02	0.08
Fe_2O_3	0.62	0.81
P_2O_5	0.07	<0.05
S	0.94	0.33
Sum of Major Constituents	99.38	99.50
Additional Data		
Loss on Ignition, % by weight	30.26	11.84
Insoluble Residue, % by weight (ASTM C 1324)	24.87	68.45

The loss on ignition (LOI) represents the weight loss due to any species released from heating a dried material to 1000°C, a temperature sufficient to decompose hydrated phases and carbonates within the mortar specimens. The loss on ignitions and insoluble residues (quantity after acid digestion) exhibit major difference when comparing the two mortars reflecting their differences in composition.

The LOI suggests a greater quantity of cementitious phases in the loose mortar supporting the idea that its composition is significantly different than the "83" bedding mortar. The insoluble residue data suggests that the silica sand content of the mortars is dramatically different (Note that shell components are likely dissolved in the insoluble residue test).

The mineralogy results show both mortars to contain silica (as quartz) and calcium carbonate, the latter originating from atmospheric carbonation of the mortar and from shell components in the mortar (Table 3). It is interesting that the XRD identified hematite (Fe_2O_3) as a component of mortar 83. While this was a "weak" XRD peak, the identification raises the possibility of an iron source such as brick dust as a component of the 83 mortar.

The insoluble residue and XRF results are not in agreement with respect to the sand content of the 83 mortar, i.e. the insoluble residue of 68% and the XRD result of 85.2% are unexpectedly different (Table 3). This is likely due to the inhomogeneous nature of the specimen.

Table 3: Mineralogy of Mortars (XRD)

Loose Mortar Phases	83 Mortar Phases	Quantitative Mineralogy 83 Mortar
Quartz (sand)	Quartz (sand)	Quartz – 85.2%
Calcite ($CaCO_3$)	Calcite ($CaCO_3$)	Calcite – 13.8%
	Hematite (Fe_2O_3)	Other – 1.0%

Physical data on the mortars is provided in Tables 4 and 5 where results in Table 4 were obtained by mercury porosimetry (MIP). The MIP technique very useful for small specimens obtained from historic masonry. The data in Table 4 is consistent with the idea that the loose mortar is a lightly sanded mixture while the 83 bedding mortar has a sand content expected for laying bricks, i.e. the 83 mortar has higher density and lower porosity than the loose mortar. Both mortar specimens exhibit a "high" fraction of porosity smaller than one micron suggesting leaching of the binder phase by sea water. By way of explanation, chemical attack on ceramic materials usually results in an elevation of the fraction of fine porosity.

Table 4: Physical Data by MIP - Mortars

Property	Loose Mortar	83 Mortar
Bulk density, g/cm^3	1.51	1.83
Apparent porosity, %	38.64	20.95
Pores <1 micron	42.03	48.09

The porosimetry results can be compared to other historic mortars from Charleston. In analyses of natural cement based mortars at Fort Sumter National Monument, bedding mortars not exposed to constant with sea water or ground salts exhibited about 24-29% of pores less than one micron, while mortars exposed to sea water exhibited 74-83% of pores less than one micron[9]. The increase in the fraction of fine pores for constant sea water contact was attributed to corrosion (loss of lime by solution in sea water).

The oyster lime-sand mortar 1680 Fortified Wall in Charleston (exposure to ground salts) exhibited 59.3% of porosity less than one micron[10]. By contrast an 1800's era lime mortars (little

[9] [9] D. Brosnan, Characterization and Forensic Studies of Construction Materials from Fort Sumter National Monument, January 11, 2010 (A Report for the National Park Service).

[10] Denis A. Brosnan, Forensic Evaluation of Bricks and Mortar 17th Century Charleston Fortified Wall, Submitted to the Charleston Museum, August 16, 2011

exposure to ground salts) from Columbia, SC, exhibited 30.5% of porosity less than one micron[11].

The particle size distribution of the sand (insoluble residue) of the 83 mortar is given in Table 5. This size distribution is typical for contemporary masonry sand and approximates the current specifications for sand for masonry mortar[12].

Table 5: Particle Size Distribution of Insoluble Residue Particles (Sand), East 83 Mortar

Screen #	Opening [mm]	% Retained
4	4.76	0.00
8	2.38	0.00
16	1.19	6.03
30	0.59	27.30
50	0.297	39.37
100	0.149	16.83
200	0.074	6.98
Pan	0	3.17
Total		99.68

Thermal Analysis - Mortars

The thermal analysis results for the mortars are presented in Figures 19 and 20. By way of explanation, the graphs show the following features:

- Green trace – the weight loss on heating versus temperature, also called the thermogravimetric (TG) curve.

- Blue trace – the energy flow into (endothermic) or out of (exothermic or "exo") the specimen while heating due to chemical reactions and/or phase changes in the specimen. This is called the differential scanning calorimetry (DSC) trace.

- Black trace – the evolution of water vapor from the specimen while heating. This trace was obtained by analysis of evolved gases by FTIR,

- Red trace – the evolution of carbon dioxide (CO_2) from the specimen while heating. This trace was obtained by analysis of evolved gases by FTIR,

[11] Denis A. Brosnan, Unpublished work, the "Confederate Wall", University of South Carolina, Columbia, SC, Analysis of January 20, 2011.
[12] ASTM C144, Standard Specification for Aggregate for Masonry Mortar.

The various events on heating can be compared to known phenomena when heating minerals and cementitious materials. In some cases, mineral reactions can be detected with greater precision than is possible with other techniques. The results of the thermal analysis are after comparison with known data is provided in Table 6.

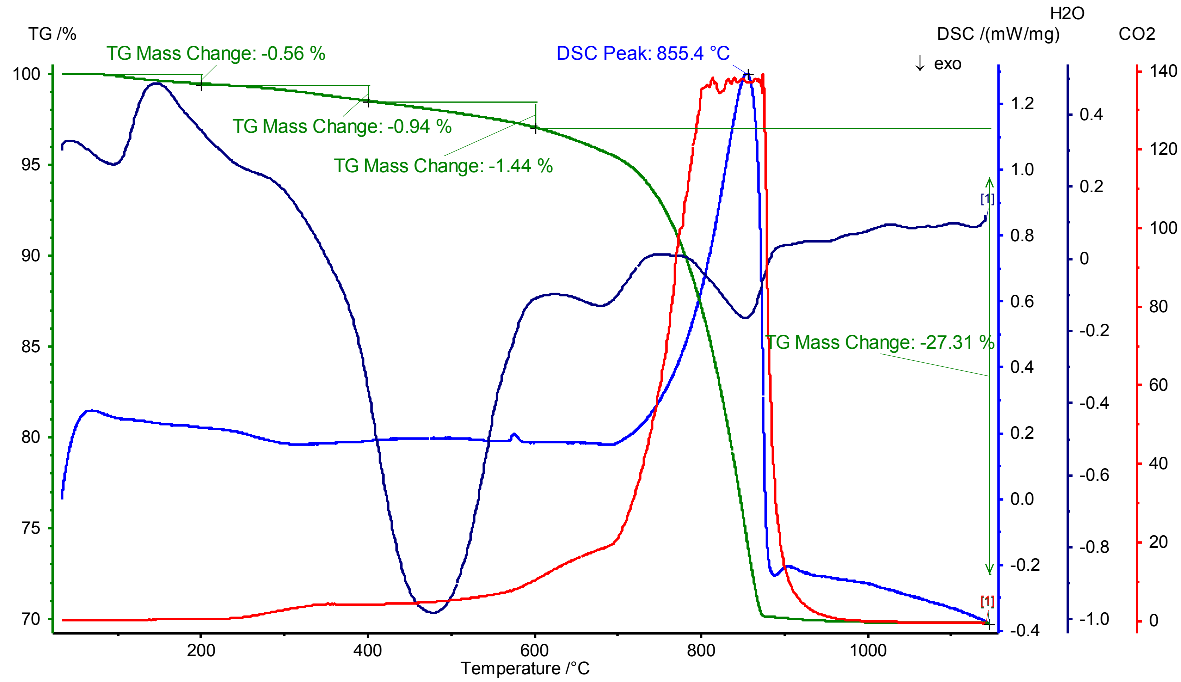

Figure 19: Simultaneous Thermal Analysis of Loose Mortar

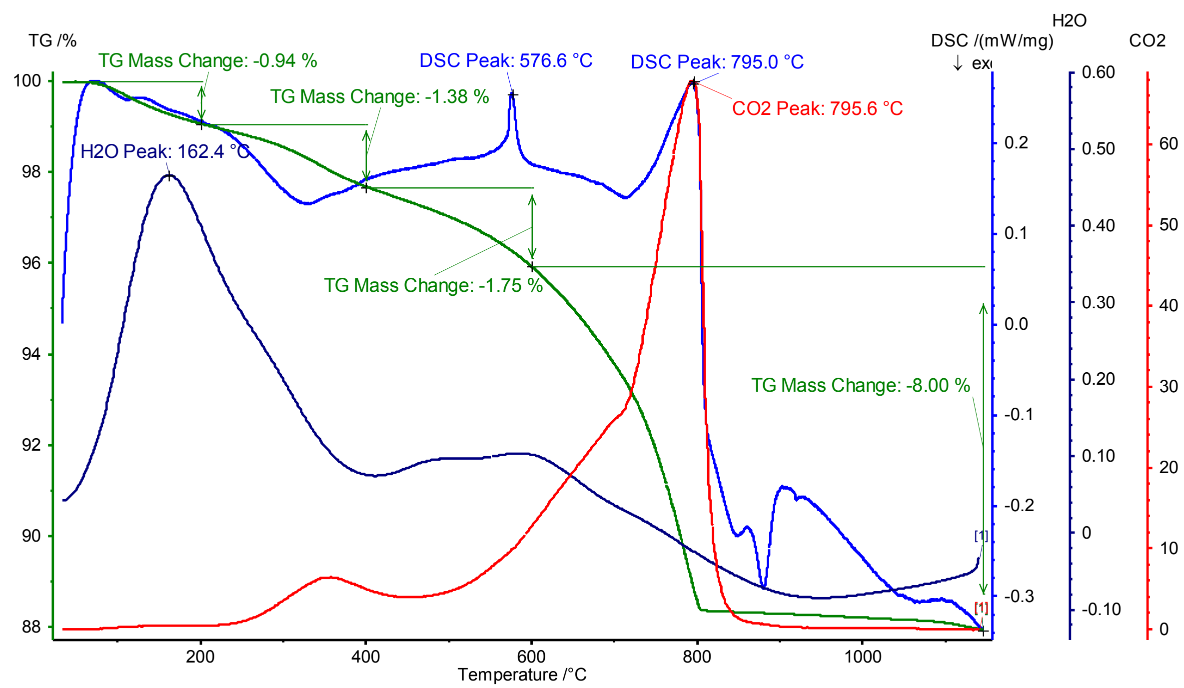

Figure 20: Simultaneous Thermal Analysis of Mortar 83

The thermal analysis results in Table 6 confirm the presence of the carbonate binder and quartz sand (also seen in the XRD mineralogy – Table 3), and it indicates that organic matter has permeated the mortar. Not surprisingly, ettringite[13] (calcium sulfo-aluminate) is seen decomposing at low temperature. The results suggest the presence of magnesium hydroxide (also known as brucite, a phase found in mortars containing magnesium and/or those exposed to salt water).

Table 6: Thermal Analysis Observations – Mortars

Event Temperature, ^{o}C	Loose Mortar	83 Mortar	Event description
180	Observed	Observed	Decomposition of ettringite.
20-220+	Observed	Observed	Oxidation of organics indicating permeation by organic bearing liquids or presence of plant residuals.
≈350	Observed	Observed (slight)	Decomposition of $Mg(OH)_2$ indicating permeating by sea water.
400-500	Observed	Observed (slight)	Dehydroxylation indicating the presence of clay or brick dust.
577	Observed (slight)	Observed	Quartz inversion due to the presence of sand.
795-855	Observed	Observed	Decomposition of $CaCO_3$ (binder).

Water Soluble Salts - Mortars

Water soluble salts are presented in Table 7 with data reported as a weight quantity per weight of dry mortar specimen. The designation parts per million (ppm) indicates a weight quantity. As an example, 1000 ppm of a species in a mortar indicates that the soluble content of that species is 0.1% of the original specimen dry weight.

[13] Ettringite is commonly found in hardened masonry mortars.

Table 7: Water Soluble Salts in Mortars

Species	Loose Mortar	Mortar 83
Cations	ppm	ppm
Lithium	ND	11.22
Sodium	434.34	276.17
Ammonium	20.14	182.31
Potassium	567.43	455.39
Magnesium	168.46	184.30
Calcium	2685.72	1192.34
Anions	ppm	ppm
Fluoride	26.34	63.84
Chloride	550.24	537.61
Nitrite		5.90
Nitrate	5782.33	1584.36
Sulfate	352.23	255.49

The major soluble cation (positive ion) is calcium, a species expected as soluble in cementitious mortars. The soluble magnesium may reflect sea water impingement over years of exposure, and the sodium is likewise from sea water contact. The potassium levels are surprising, and they suggest presence of brick dust in the mortar (confirmed by microscopy below). The ammonium content of the mortars is very surprising and could reflect acid rain and/or past surface cleaning.

The soluble anions (negative ions) include chloride and sulfate – both attributable to sea water contact. The fluorite and nitrate ions may be due to rain water impingement and surface water absorption.

Microscopy - Loose Mortar

Optical microscopy, frequently called petrography, is used in the analysis of cementitious materials such as mortars and bricks to further identify binder materials and minerals. Reviews of petrography for natural and manufactured building materials are available[14]. The technique frequently uses thin sections of the specimens viewed under either transmitted or reflected light in a polarizing microscope.

An image of the loose mortar is shown in Figure 21. Notably, the mortar contains oyster shell relics (labeled "<u>SH</u>") and lime agglomerates (labeled "<u>L</u>"). The other minerals include sand (in various stages of light extinction) and particles suspected as "brick dust". Brick dust has been used in lime mortars since the Roman Era to strengthen mortars and impart chemical durability.

[14] Ingham, Jeremy, Geomaterials Under the Microscope, Manson Publishing, ISBN 978-1-84076-132-0 (2011).

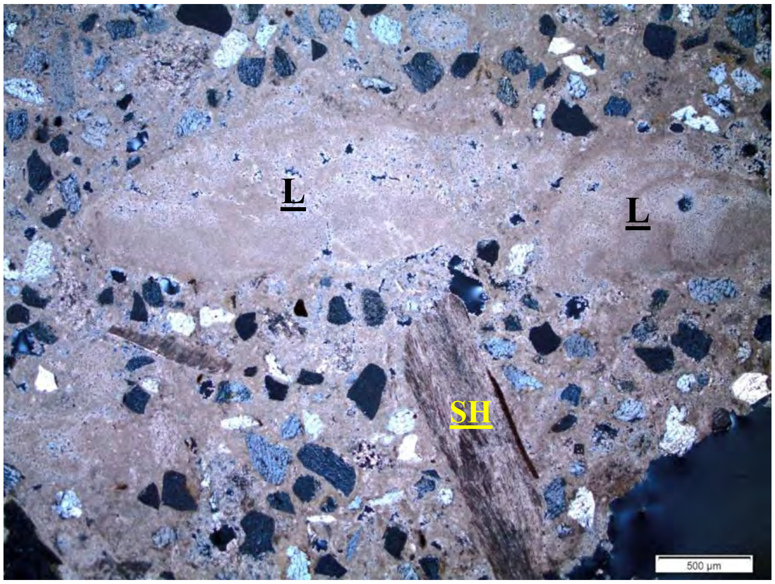

Figure 21: Microscopic Image of Loose Mortar

Microscopy - Mortar 83

A low magnification image of mortar 83 is shown in Figure 22. The quartz sand comprises the angular particles in various degrees of brightness (stages of extinction). The continuous phase around sand grains is comprised of calcium carbonate binder and opaque particles suspected as brick dust.

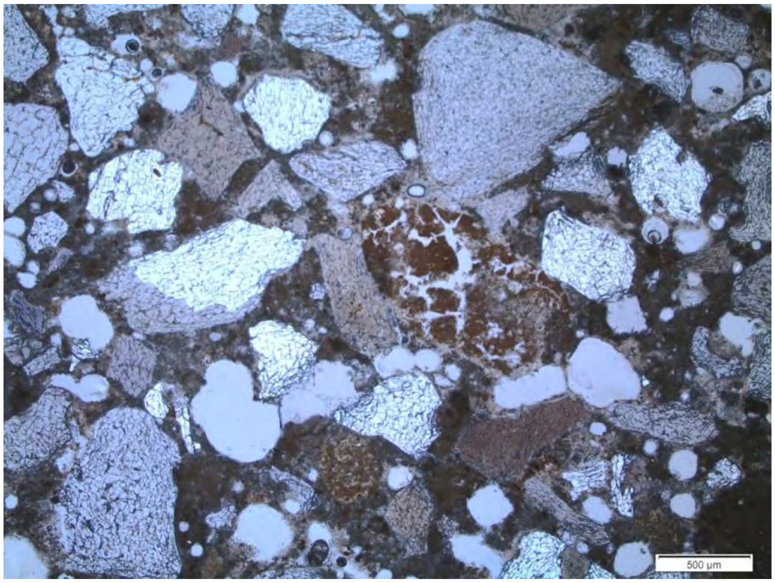

Figure 22: Petrographic Image of Mortar 83

The phases in the mortar 83 matrix are observed at higher magnification in Figure 23. The sand grains (labeled "S") are located around an agglomerate of opaque particles suspected as brick dust (labeled "Br"). The calcium carbonate binder phase ("Bi") is light colored. Continuous blue areas are porosity ("P").

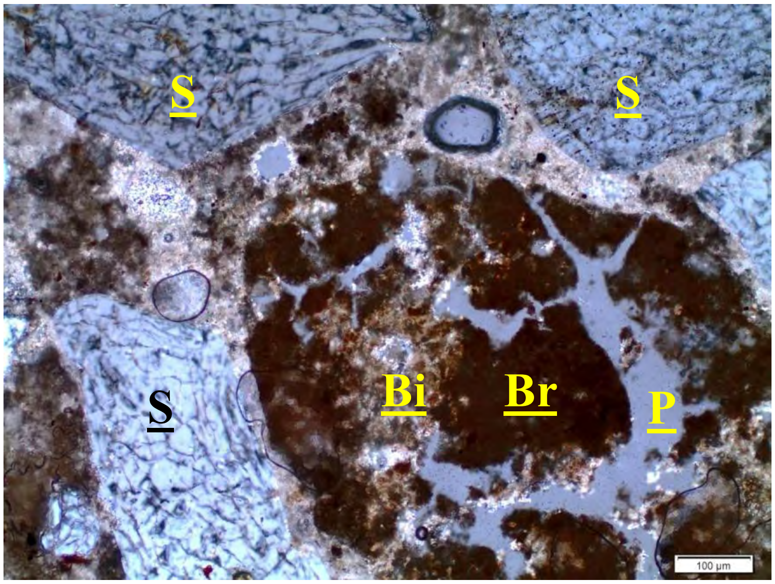

Figure 23: Petrographic Image of Mortar 83 at High Magnification

Scanning Electron Microscopy – Loose Mortar

Scanning electron microscopy provides an image of a surface (Figure 24) under investigation and a chemical analysis of selected artifacts. The analysis of artifacts is reported as oxide constituents following cement chemistry notation (Table 8).

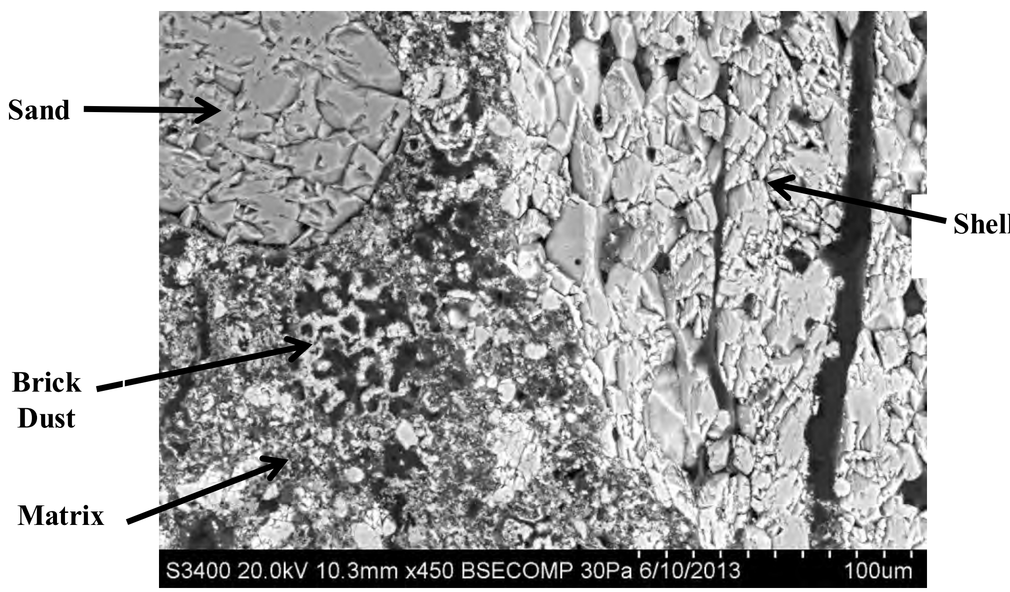

Figure 24 – SEM Image of the Loose Mortar

The identification of artifacts in the loose mortar's microstructure is based on the appearance of the artifacts, also called their morphology, and on their chemical analysis (Table 8). Comments on individual mortar constituents are as follows:

- The quartz sand particles exhibit at least 96% SiO_2, a value seen in quartz sands in mortar in other historic properties in Charleston.
- The shell chemistry on an oxidized basis contains 91.5% CaO. Oyster shells are composed of calcium carbonate in the form of the mineral aragonite. When analyses of shell are expressed on an oxidized/ignited weight basis, the species reported is CaO. The MgO content of the shell reflects the magnesium content of sea water.
- The brick dust is recognized by its ratio of Al_2O_3 to SiO_2, its K_2O content, and its morphology.
- The white relics in the matrix (continuum) are shell fragments based on their analogous chemistry to the larger intact shell visible in the microstructure.
- The darker phases (grey shades) in the matrix contain largely CaO and SiO_2 reflecting the carbonated lime binder and fine sand.

Table 8: Summary of EDAX Analysis of Spectra of Loose Mortar (Wt. %. Oxidized Basis)

Species	Sand Range Several Areas	Shell	Brick Dust Agglomerate	Matrix White Relics	Matrix Dark Background Range Several Areas
Na_2O	0.27 - 0.37	0.37	ND	0.45	0 - 1.06
MgO	0 - 0.20	0.56	1.61	1.56	1.61 - 2.10
Al_2O_3	ND	0.45	3.01	0.51	2.92 - 3.01
SiO_2	96.62 - 97.36	4.81	23.64	5.56	23.64 - 30.71
Cl	ND	ND	2.03	ND	1.51 - 2.03
K_2O	ND	ND	1.06	ND	0.12 - 0.82
CaO	2.37 - 2.81	91.50	68.64	91.50	60.04 - 68.64
Fe_2O_3	ND	ND	ND	0.42	0 - 0.84

ND = Not Detected

The constituents of this loose mortar suggest that the specimen is a pointing mortar. The evidence includes a significantly lower SiO_2 content than in the 83 mortar (Table 2) suggesting the light sanding (low sand content) of pointing mixes. Further, the bulk density and the porosity of the loose mortar are different than that of the 83 mortar (Table 4) in such a manner as to imply the loose mortar was used for pointing.

Scanning Electron Microscopy – 83 Mortar

The microstructure of the 83 mortar by SEM is shown in Figure 25. One interesting observation is that large shell relics are not found in the mortar (confirming the observations by petrography in Figures 22 and 23). The chemical analyses of artifacts are reported in Table 9 allowing the following observations:

- The analysis of the sand is slightly different in the East 83 mortar than the loose mortar suggesting a different source (East 83 at 98.6-99.3% SiO_2 compared to the loose mortar at 96.6-97.4% SiO_2). This implies that the mortars could have been made at different time periods using a different source for the sands, i.e. the bedding mortar may be original construction and the loose mortar from a repair.

- The ratio of Al_2O_3 to SiO_2 in brick dust in the East 83 mortar at 0.12 compares favorably to the value for brick dust in the loose mortar of 0.13. This simply says that similar brick dust as from local bricks was used in both specimens.

- The white relics represent the matrix/continuum of the mortar and represent the carbonate binder with small shell fragments and fine sand.

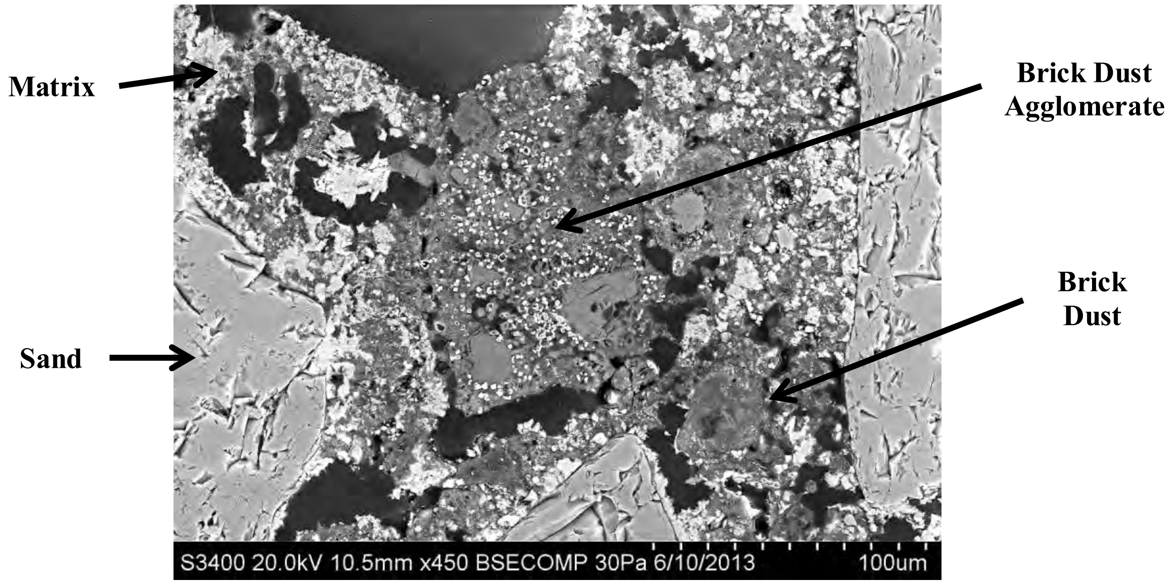

Figure 25: SEM Image of the 83 Mortar

Table 9: Summary of EDAX Analysis of Spectra of 83 Mortar
(Wt. %. Oxidized Basis)

Species	Sand Range	Brick Dust	Brick Dust, Lime & Sand Agglomerate	Matrix White Relics Range	Matrix Dark Background Range
Na_2O	0.21 - 0.22	0.49	0.43	0.45 - 0.52	0 - 0.48
MgO	0.44 - 0.58	28.36	27.33	3.91 - 17.5	16.37 - 34.73
Al_2O_3	ND	1.11	11.21	0.78 - 4.88	5.32 - 6.91
SiO_2	98.59 - 99.34	9.25	50.14	13.45 - 17.35	35.05 - 45.55
Cl	0 - 0.16	0.88	0.30	0.13 - 0.28	0.44 - 0.91
K_2O	ND	0.41	0.45	0 - 0.31	0.47 - 0.51
CaO	0 - 0.45	6.32	4.81	27.12 - 41.35	9.26 - 38.29
Fe_2O_3	ND	4.87	4.87	0.48 - 2.33	2.59 - 3.45

ND = Not Detected

The constituents of mortar 83 are typical for a bedding mortar based on lime derived from oyster shells. There is no evidence of other cements used in the mortars – such as imported Roman cement. The original construction was before the era of Portland cement (1st use of imported Portland cement at Forts Moultrie and Sumter in 1873) and before the era of domestic natural cement used at Fort Sumter after about 1840.

Summary Comments – Mortars

- The mortar compositions of the loose mortar and the 83 bedding mortar were significantly different. The constituents in the loose mortar suggest it was a pointing mortar while the constituents of mortar 83 (and the source from the bed face of a brick) confirm it was a bedding mortar. Both mortars contain a binder phase originating from burnt oyster lime.

- The chemical data suggests the use of sands from different sources in the mortars raising the possibility that the 83 mortar was an original bedding mortar while the loose mortar was a pointing mortar used on the Castle in improvements prior to 1860.

- Both mortars contain brick dust as an additive to improve strength and durability. Brick dust was a common addition to mortars in Charleston in the 1800's.

Key Results, Bricks

The as-received bricks are shown in Figures 26-28. The East 82 and East 83 bricks are hand molded bricks of a coloration expected for peninsula sources such as the Wando River or Daniel Island. The East 81 brick is pressed bearing a manufacturer's imprint, and it is of a coloration suggesting it was a refractory or fireplace brick. The East 81 brick is labeled as "Excelsior" (brand) and "Williams, SC", the latter a possible location of manufacture (Figure 28). Williams, SC, is located on the kaolin clay belt crossing South Carolina (near Aiken), and kaolin was the raw material used in refractory or fireplace bricks. It is possibly rubble from the hot shot furnace or fireplaces in the original structures at the Castle, and it was reused in wall repairs.

Figure 26: Brick East 82

Figure 27: Brick East 83

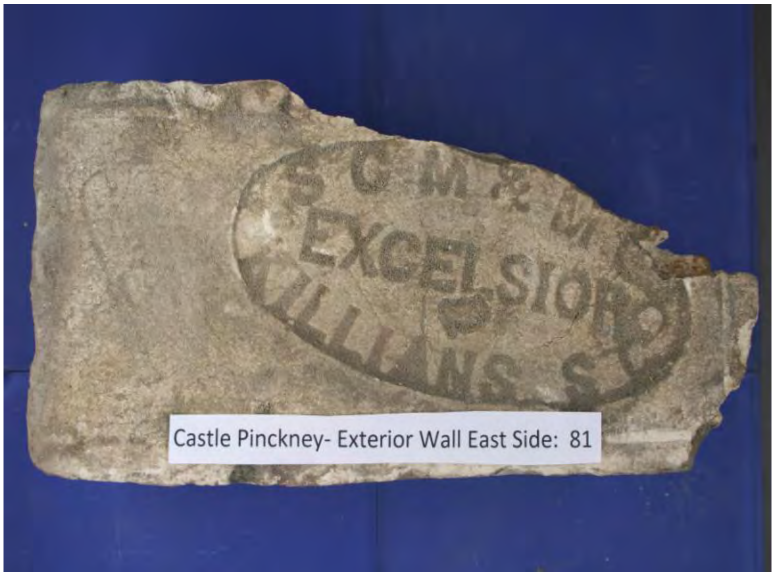

Figure 28: Brick East 81

Chemical Analysis and Mineralogy, Bricks

The chemical analyses for bricks are given in Table 10 with mineralogy results in Table 11. The East 82 and East 83 bricks are very similar in composition. The major difference in these two bricks is in CaO content, with the East 82 brick possibly impregnated with soluble lime from the mortar while in service. The chemical analyses for these bricks are also very similar to the values for bricks in "Families 1-4" (bricks in scarp walls) at Fort Sumter National Monument built in the period 1840-1860[15].

The East 81 brick exhibits much higher alumina (Al_2O_3) reflecting its manufacture as a refractory brick. The Al_2O_3/SiO_2 ratio of the East 81 brick is in the area expected for a kaolin based clay product.

Table 10: Chemical Analyses of Bricks (Oxidized Basis, Weight %)

Constituents	East 82	East 83	East 81	Typical Charleston Bricks FSNM (reference 15)
Al_2O_3	10.90	10.44	22.33	7.2-10.6
SiO_2	77.64	82.00	72.77	78.7-82.4
Na_2O	<0.5	<0.5	0.55	<0.50
K_2O	1.05	0.66	0.90	0.57-1.55
MgO	0.46	0.31	<0.2	0.57-0.86
CaO	3.59	0.44	0.01	0.49-1.17
TiO_2	1.24	1.04	1.41	1.01-1.41
MnO	0.03	0.02	0.01	NA
Fe_2O_3	4.46	4.54	1.73	3.49-6.07
P_2O_5	0.05	0.05	0.05	NA
S	0.13	0.07	<0.05	NA
Sum of Major Constituents	99.54	99.57	99.75	NA
Additional Data				
Al_2O_3/ SiO_2	0.14	0.13	0.31	0.09-0.13
Loss on Ignition, % by weight	7.56	1.20	0.53	NA

NA = Not available

The mineralogy of the bricks is reported in Table 11. These results confirm the manufacture of the East 81 brick as a refractory, i.e. the mullite peaks and the prominence of the cristobalite peak implies a higher firing temperature than the construction bricks East 82 and

[15] Denis A. Brosnan, Characterization and Forensic Studies of Construction Materials from Fort Sumter National Monument, A Report to the National Park Service, November 13, 2009.

East 83. By way of explanation, the mineral quartz in clays is transformed progressively to tridymite and cristobalite as firing temperatures and firing duration increase[16]. The lack of hematite (FeO) in the East 81 brick is consistent with its manufacture using a kaolin raw material.

The crystalline silica content, as quartz, is provided in Table 12. The quartz content of the East 81 brick is consistent with its manufacture using a kaolin raw material. The quartz content of the East 82 and East 83 bricks is consistent with their manufacture near the Charleston peninsula.

Table 11: Mineralogy of Bricks (XRD)

East 82	East 83	East 81
Quartz	Quartz	Quartz
Tridymite	Tridymite	Cristobalite
Cristobalite	Cristobalite	Mullite
Calcite	Mullite	Hematite
Mullite	Hematite	
Hematite		

Table 12: Crystalline Silica (Sand) Content of Bricks

Brick	Quartz, %
East 82	7.35
East 83	5.21
East 81	37.79

Physical data for bricks regarding density, porosity, and pore structure is provided in Table 13, and graphs of the pore size distribution are given in Figures 29-31. Measurements are either by mercury porosimetry (labeled MIP) or by water displacement (labeled displacement)[17]. Some observations are:

- The densities and porosities of the East 82 and East 83 bricks are similar to those of local manufacture used on Fort Sumter. The pore structure of these bricks is also similar.

[16] Quartz, tridymite, and cristobalite are forms of crystalline SiO_2 exhibiting different crystal structures. The form cristobalite is rarely found in the Earth's crust. The presence of cristobalite is usually interpreted as firing temperatures of clay products exceeding about 1250°C. More intense firing (as in longer firing cycles) above the threshold temperature for conversion elevates cristobalite content.

[17] See ASTM C20-00(2010) Standard Test Methods for Apparent Porosity, Water Absorption, Apparent Specific Gravity, and Bulk Density of Burned Refractory Brick and Shapes by Boiling Water.

- The East 82 and East 83 bricks are rated as "Frost Resistant" by the index proposed by Maage[18]. This implies that the bricks are also resistant to salt crystallization phenomena, and it is noted that salt scaling (spalling) is not visible on the scarp bricks.

- The density and porosity of the East 81 brick (the suspected refractory brick) is dissimilar to the other structural bricks. Refractory bricks typically exhibit a preponderance of pores less than one micron in size, and this is the case for the East 81 brick. The difference is easily visualized using the pore size distributions in Figures 29-31.

- The East 81 brick would likely be classed as a "Low Heat Duty" brick in contemporary refractory standards[19]. As is typical for refractory bricks, the durability rating for the East 81 brick according to the Maage index is "Not Frost Resistant" (rating ≤55).

Table 13: Physical Data for Bricks

	East 82	**East 83**	**East 81**	**Typical Charleston Bricks FSNM (reference 15)**
Method	MIP	MIP	MIP & Displacement (D)	MIP & Displacement (D)
Total Intrusion Volume	0.161	0.158	0.214	NA
Median Pore Diameter	25.140	39.300	0.753	NA
Bulk Density, g/cm^3	1.71	1.67	1.68 (D)	1.59-1.65
Apparent Density, g/cm^3	2.27	2.15	2.09 (D)	NA
Porosity, %	27.49	26.41	37.40 (D)	34.18-38.01
Pores >3 Microns, %	97.97	92.03	10.08	NA
Maage Index (reference 16)	255.04	241.12	39.15	NA
Pores >10 Microns, %	95.18	87.82	6.11	NA
Pores 10-1 Microns, %	3.51	7.54	29.34	NA
Pores <1 Microns, %	1.31	4.64	64.55	1.9-9.4

NA = Not available

[18] Manfred Maage, *Frost Resistance and Pore Size Distribution of Bricks*, Ziegelindustrie International, 9 (1990) 472-481. Frost resistant bricks exhibit an index ≥70.
[19] ASTM C27 − 98, Standard Classification of Fireclay and High-Alumina Refractory Brick.

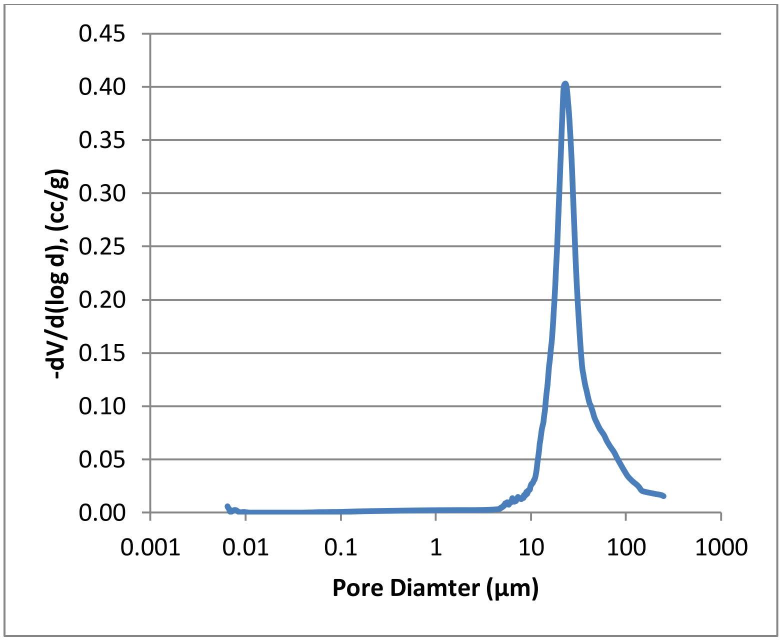

Figure 29: Pore Size Distribution of Brick 82

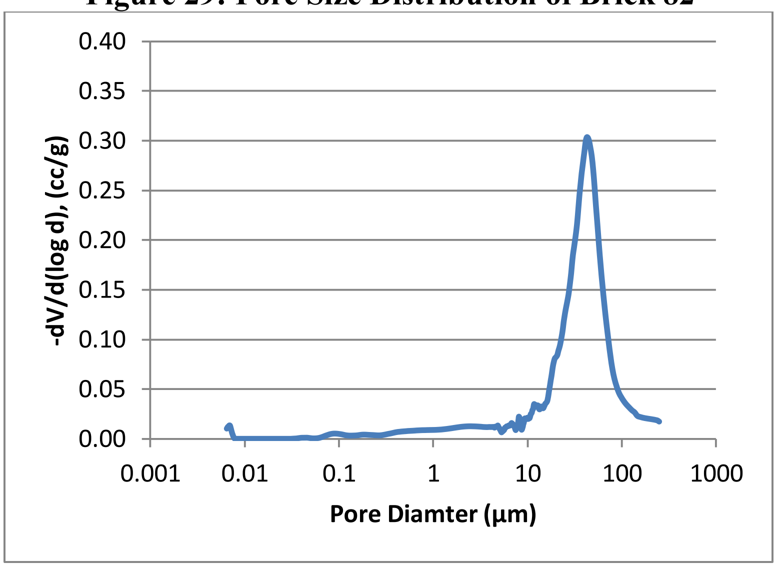

Figure 30: Pore Size Distribution of Brick 83

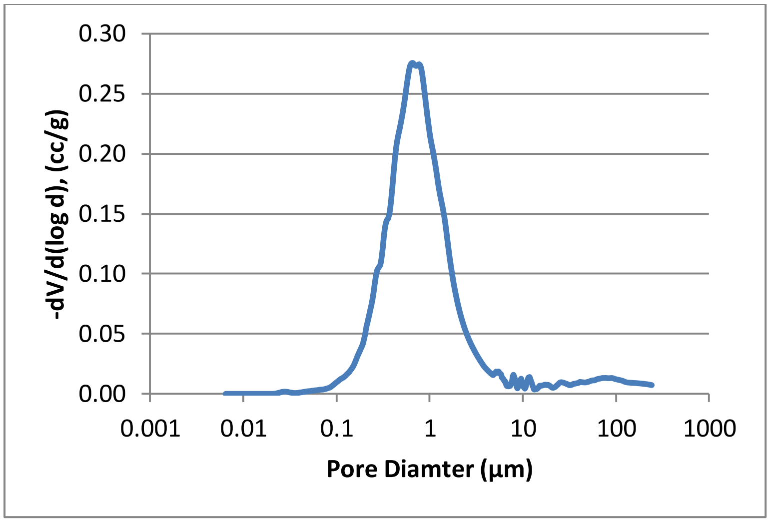

Figure 31: Pore Size Distribution of Brick 81

Thermal Analysis, Bricks

The thermal analysis graphs for the bricks are given in Figures 32-34 with results summarized in Table 14. These observations pertain to the thermal analyses:

- All bricks exhibit low temperature oxidation of organic matter that permeated the bricks over time.
- Brick East 81 exhibits an absence of some phenomena observed in East 82 and East 83 bricks reflecting the difference in composition between the East 81 brick and the other bricks.
- The data suggests the presence of iowaite in the East 83 brick. This phase is associated with diagenesis (mineral alteration in service) by environmental chemicals[20].

[20] Brosnan, D., Sanders, J., and Stroble, R., Application of Thermal Analysis in Preservation and Restoration of Historic Masonry Materials, Part B – Degradation of Materials, Journal of Thermal Analysis and Calorimetry, Published May 12, 2013 (available on-line).

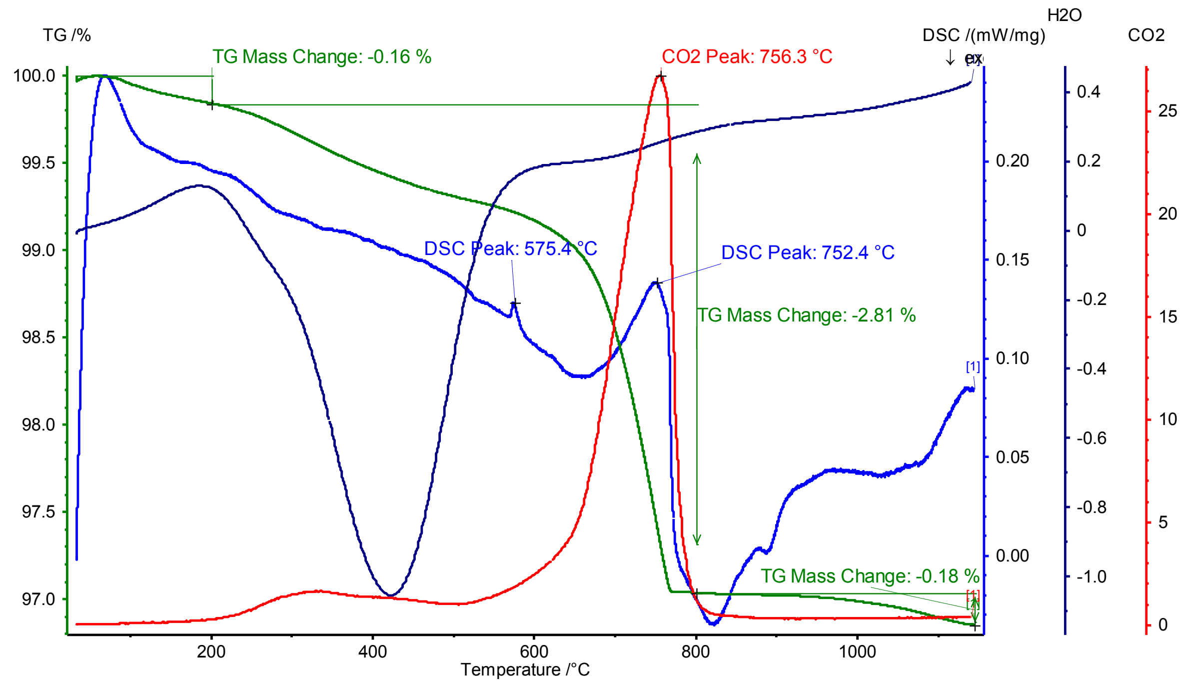

Figure 32: Simultaneous Thermal Analysis of Brick 82

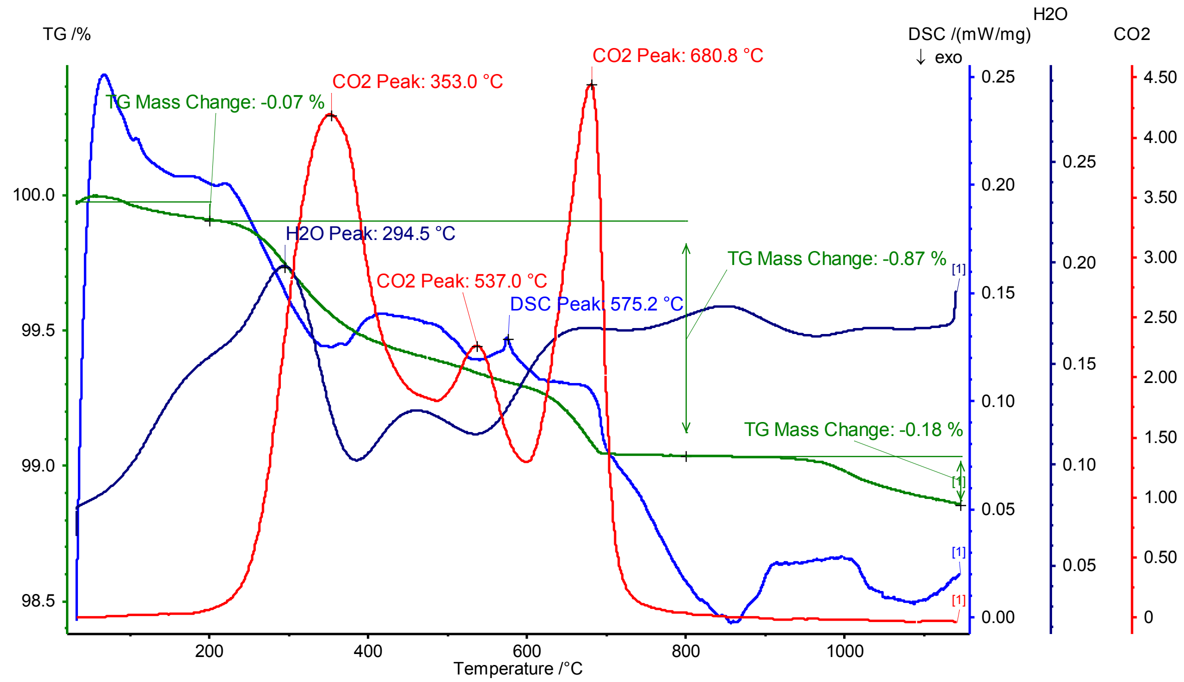

Figure 33: Simultaneous Thermal Analysis of Brick 83

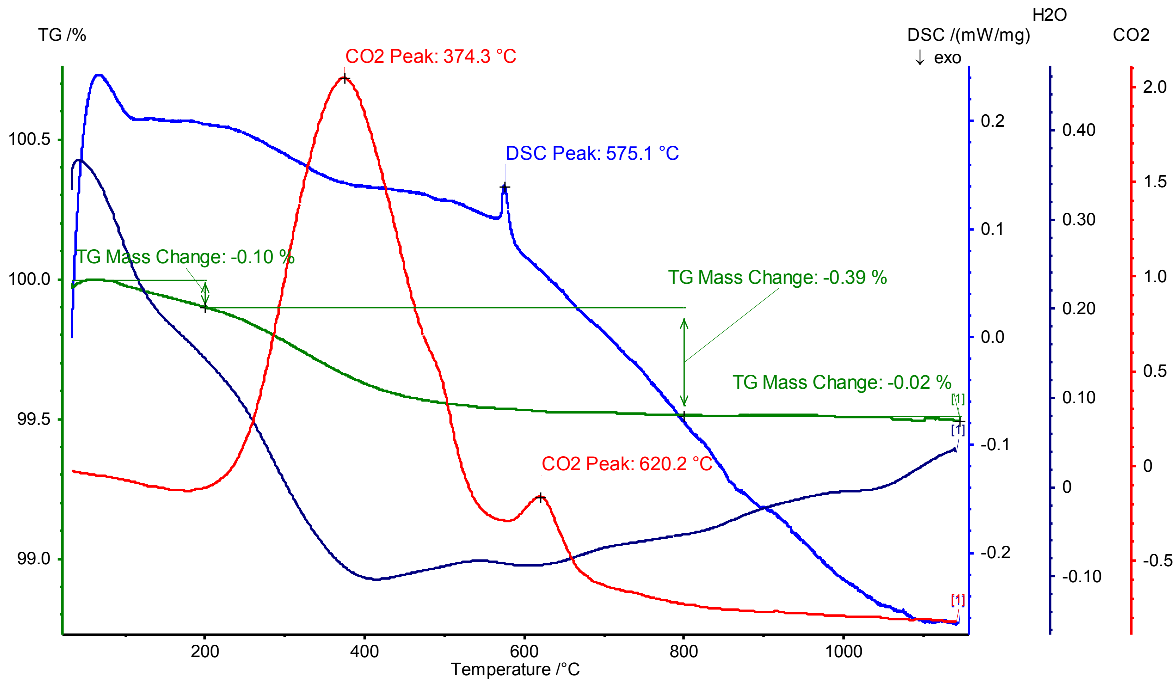

Figure 34: Simultaneous Thermal Analysis of Brick 83

Table 14: Thermal Analysis Observations – Bricks

Event Temperature, °C	Brick East 82	Brick East 83	Brick East 81	Event description
20-220+	Observed	Observed	Observed	Oxidation of organics
~300	Observed	Observed		Decomposition of $Mg(OH)_2$
~400	Observed	Observed		Decomposition of $Ca(OH)_2$
~500	Observed	Observed		Dehydroxylation (rehydration)
537		Observed		Decomposition of iowaite
575	Observed	Observed	Observed	Quartz inversion
620-756	Observed	Observed	Observed	Decomposition of $CaCO_3$

Thermal Expansion, Bricks

Thermal expansion of bricks was determined by dilatometry as shown in Figures 35-37 with the results summarized in Table 15. For restoration purposes, the thermal expansion behavior near ambient temperature is important. The measurements were continued to elevated temperatures so that the firing temperature could be estimated by the temperature of initial deformation[21].

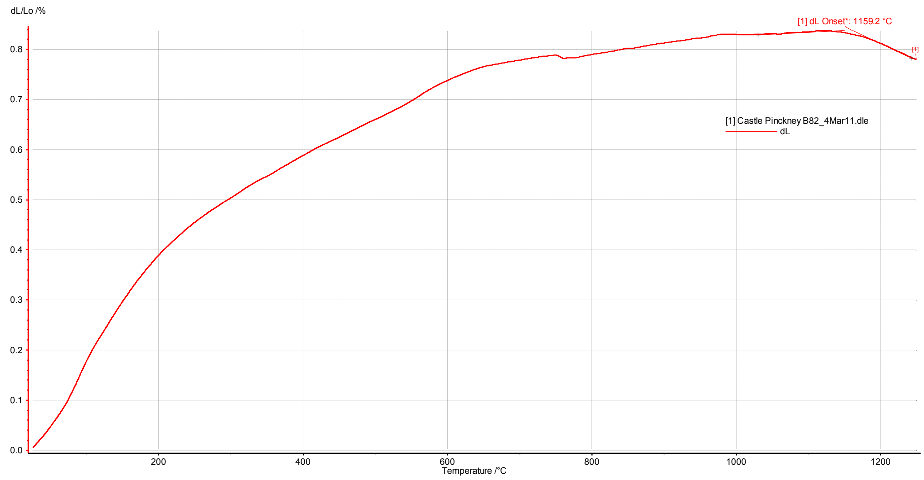

Figure 35: Thermal Expansion of Brick 82

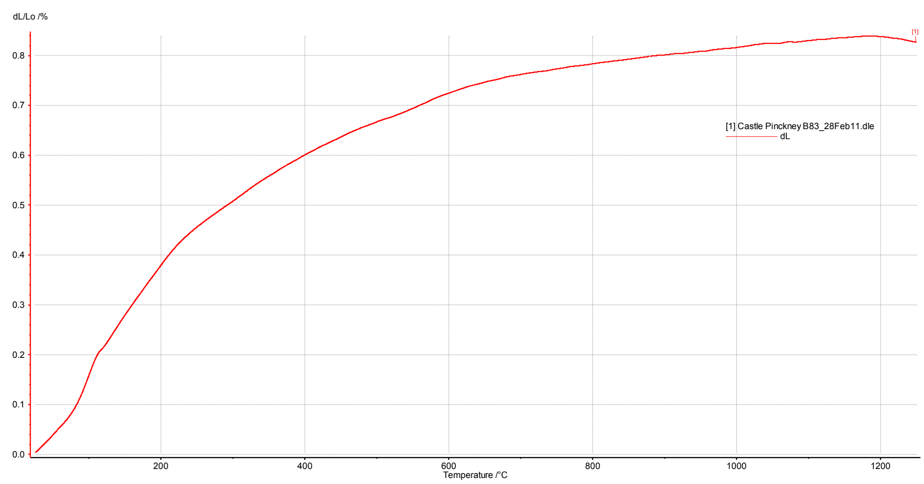

Figure 36: Thermal Expansion of Brick 83

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[21] Franke, L. and Schumann, I., Subsequent Determination of the Firing Temperature of Historic Bricks, in Conservation of Historic Brick Structures, (1998) Donhead Publishing Company.

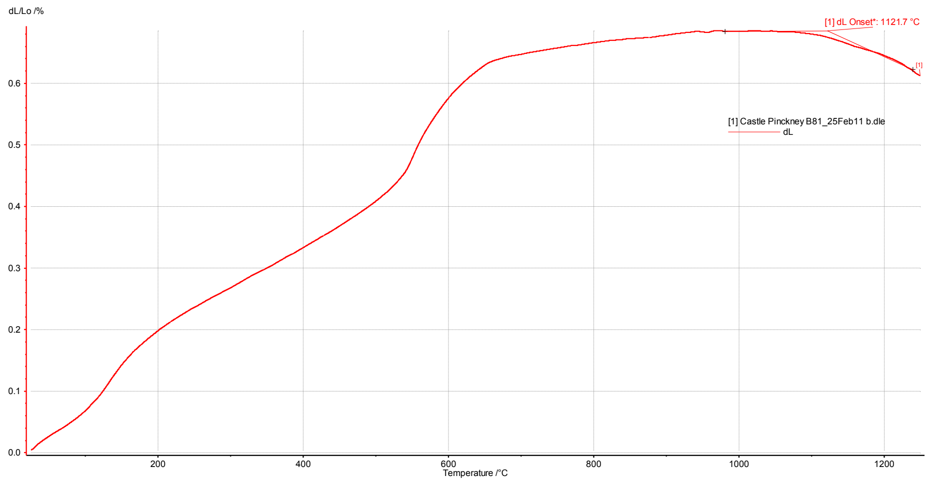

Figure 37: Thermal Expansion of Brick 81

The thermal expansions in the low temperature region of interest (for repairs) are extremely high reflecting the crystalline silica content of the bricks. The high values of the thermal expansion coefficient are particularly affected by the cristobalite content due to its polymorphic inversion at about 180°C. Values this high are exhibited by silica refractories produced from nearly 100% quartzite (ganister).

Bricks East 82 and East 83 appear to be fired to similar peak temperatures based on their deformation temperatures. The kaolin brick (East 81) is apparently fired to a higher temperature supporting the idea that it was manufactured as a refractory.

Table 15: Thermal Expansion Summary

Brick	CTE/°C 20-200°C	CTE/°C 20-500°C	Deformation Temperature, °C
East 82	≈18.0	13.5	1159
East 83	16.7	13.3	1180
East 81	15.0	9.0	1217

Color Measurements of Bricks

The color of the as-received bricks was measured with a Minolta Colorimeter with the results expressed in the L*a*b* color space (illustrated in Figure 38). This color space contains a “lightness” axis as “L” (white to black), a red-green axis as “a”, and a blue-yellow axis as “b”. The color is expressed as a number determined on each axis.

The results in Table 16 show that Brick East 81 (the refractory) is of a much lighter shade with a yellowish tint. Bricks East 82 and East 83 are of a similar color. Repair bricks for the scarp wall should match the color characteristics of East 82 and East 83 as closely as possible.

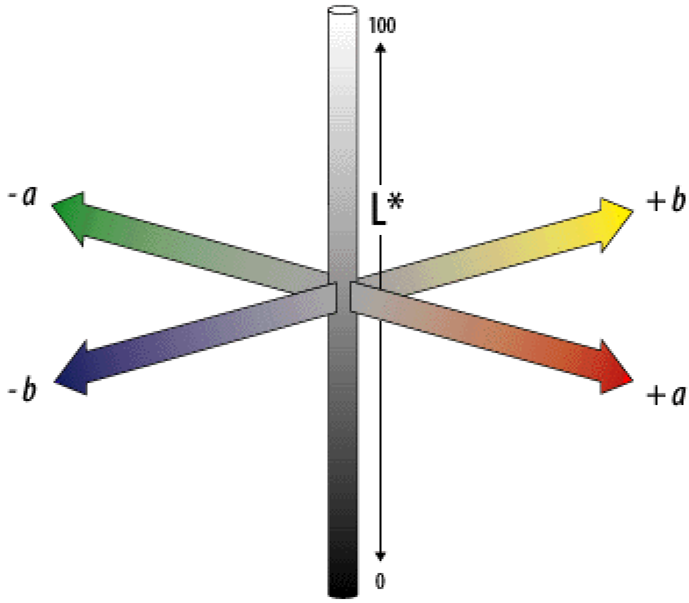

Figure 38: L*a*b* Color Space

Table 16: L*a*b* Color Measurements of Bricks

	East 82	East 83	East 81
L*	48.58	45.30	81.62
a*	5.11	5.01	1.8
b*	9.02	8.67	11.97

Soluble Salts – Bricks

Water soluble salts were determined by extraction in deionized water at room temperature with analysis of the leachate by ion chromatography (as with mortars reported above). The results are provided in Table 17. The following observations are made:

- All of the Castle Pinckney bricks exhibit similar soluble salt content with the exception of higher sodium and chloride in the East 81 refractory brick. This may be related to the capillary suction of this brick (higher than East 82 and East 83 based on pore sizes). Solvated ions of low ionic radius, such as sodium and chloride, have been found to permeate ceramics with small pore sizes faster or more completely than larger solvated ions like calcium.

- The nitrate contents of the East 82 and East 83 bricks are unusually high.

- In comparison to bricks from Fort Sumter, the soluble salts indicate that these Castle Pinckney specimens did not have constant sea water contact.

Table 17: Water Soluble Salts in Bricks

Species	East 82	East 83	East 81	Fort Sumter No constant sea water contact (Reference 15, Brick 1)	Fort Sumter Constant sea water contact (Reference 15, Brick 2)
Cations, ppm					
Sodium	26.91	55.23	103.09	24.2	2171
Ammonium	8.13		6.31	8.2	126
Potassium	38.13	68.46	31.50	14.1	860
Magnesium	20.87	23.66	27.74	22.5	94.2
Calcium	163.38	398.23	107.60	69.5	684
Anions, ppm					
Fluoride	8.39	1.60	5.41	9.7	359
Chloride	61.05	37.53	188.24	47.9	3178
Nitrate	570.53	392.36	22.19	4.9	56
Sulfate	20.21	45.96	100.17	20.9	306
Phosphate	14.24	0.00	46.36	14.7	94.8

Physical Data Related to Contemporary Specifications for Bricks

Physical property data for the Castle Pinckney bricks is presented in Table 18 with a comparison to bricks from Fort Sumter. The cold water absorption (CWA), boiling water absorption (BWA), and saturation coefficient (C/B) were obtained according to the methods in ASTM C 67, while the densities and porosities were obtained using the methods in ASTM C 20 (reference 17).

The purpose of testing for specified properties is to provide guidance for any future repairs where modern bricks might be obtained to repair damage or losses in the Castle Pinckney scarp walls. Any repair bricks should generally match these properties and the thermal expansion coefficient of the bricks as provided above.

The absorption properties of the Castle Pinckney bricks are similar to those for the Fort Sumter bricks. The East 81 refractory brick exhibits a very high saturation coefficient due to its fine pore structure – a result expected for refractory bricks. Modern refractory bricks should not be used in repairs in any masonry exposed to water saturation due to potential freeze-thaw or salt expansion deterioration.

Table 18: Water Absorptions, Density, and Porosity – Bricks

Sample	CWA (%)	BWA (%)	C/B	Bulk Density	Apparent Density	% Apparent Porosity
ASTM C67 Grade SW	NS	≤ 17.0	≤ 0.78	NS	NS	NS
ASTM C67 Grade MW	NS	≤ 22.0	≤ 0.88	NS	NS	NS
East 81	19.52	22.21	0.88	1.68	2.69	37.36
East 82	12.81	19.62	0.65	1.67	2.48	32.75
East 83	18.42	23.80	0.77	1.55	2.45	36.80
Fort Sumter Brick 1 (Reference 15)	15.26	21.05	0.72	1.62	2.47	34.18
Fort Sumter Brick 31 (Reference 15)	19.59	24.95	0.79	1.65	2.46	38.01

NS = Not specified in ASTM C 216.

Petrographic Microscopy – Bricks

Similar optical microscopy/petrography techniques were used with bricks East 82 and East 83 as with the mortars (reported above). A low magnification photomicrograph of brick East 82 is shown in Figure 39. The most interesting feature is the chert nodule (labeled "C"), an artifact found frequently in Charleston historic bricks.

The chert nodule originates in marine sediments, and nodular forms are common in layers of limestone or chalk, i.e. marl sediments, as found in the once-submerged land masses of the Southeastern coast[22]. Polymetallic nodules may be hollow like geodes according to one source[23]. On firing of the bricks when local clays contain chert nodules, the chert is transformed into a black colored hard mass situated in and surrounded by the lighter colored clay continuum. The black masses are commonly called "iron spots" in contemporary language. Bricks containing these iron spots are common on historic buildings on the Charleston peninsula giving rise to the term "Charleston Grey Bricks".

The East 82 brick of Figure 39 also shows large pores and a void in the chert nodule (labeled "P"). The matrix or continuous phase (labeled "M") is composed of clay, fine silica crystals, pores, and other minerals. The East 83 brick of Figure 40 exhibits a similar microstructure, although no chert nodules are seen in the field shown. There was no microscopic characterization of the East 81 brick.

[22] Tucker, M., Sedimentary Petrology (2009), Blackwell Publishing, See pp. 212-218.
[23] http://en.wikipedia.org/wiki/Nodule_(geology).

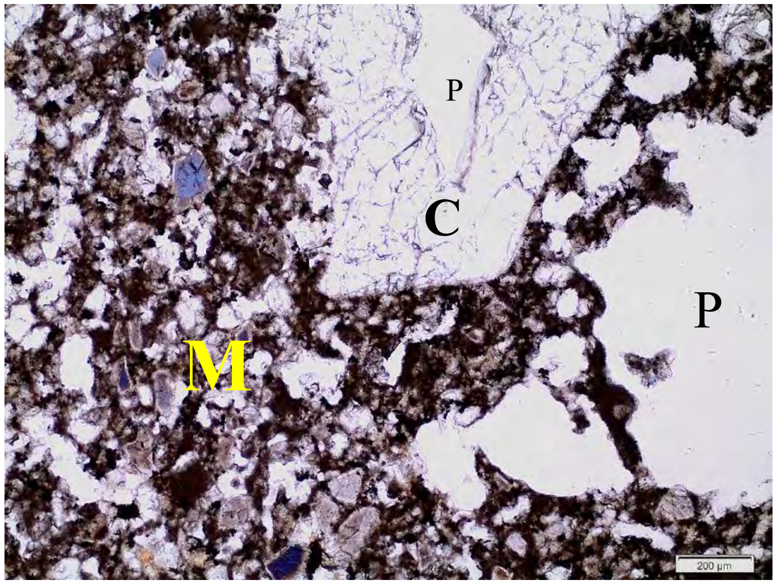

Figure 39: Brick East 82 (See chert "C")

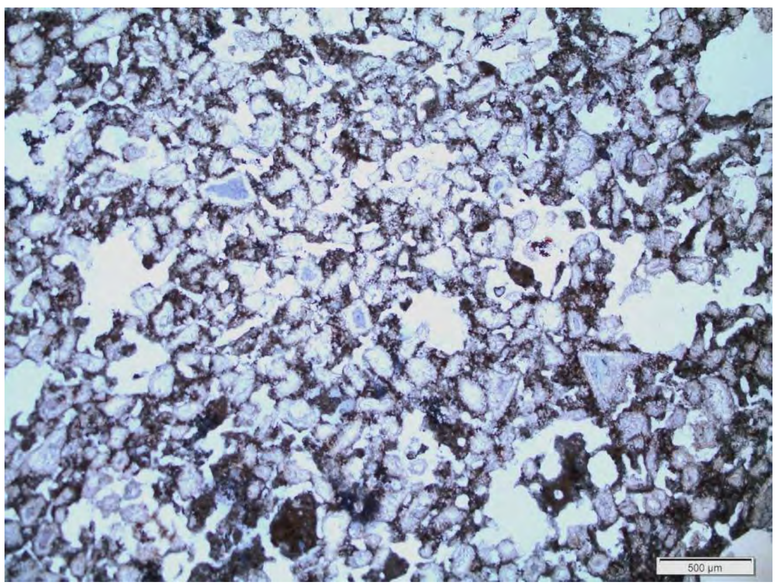

Figure 40: Brick East 83

<u>Summary Comments – Bricks</u>

- The East 82 and East 83 bricks are hand molded fired clay bricks of local Charleston peninsula origin. The East 81 specimen was a fireclay refractory brick probably obtained from deconstruction rubble and used in a 1900's era repair to the wall when clay sewer pipe were added.

- The physical properties and thermal expansion coefficients of the historic bricks were determined for use as a guide in any repairs using contemporary bricks. Any manufacturer of repair bricks will have to adjust the brick composition, especially the sand content, and the firing temperature so that the brick properties and color will match the historic bricks. Failure to match thermal expansion coefficient can result in long-tern degradation of the historic masonry.

- Mineral alteration through diagenesis is suggested, but this is a secondary threat to the structure as the consequence of diagenesis in bricks is unknown today.

Materials Issues in Conservation and Restoration of Castle Pinckney

Issues identified by Lewis and Langhorne (reference 3) and Wierick's thesis (reference 4) should be carefully considered providing a "blueprint" for restoration. Both references identify safety concerns with respect to wall stability if infill is removed. Yet, it is the weight of infill influencing continued settlement and the outward bowing that is primarily threatening the structure. Another important threat is sea water impingement on the base of the Castle.

Approaches taken at Fort Sumter National Monument over years provide a pathway for the repair process. These near-term repairs should include at least partial removal of infill, addition of rip-rap and fill on the Eastern and Southern boundaries of the Castle, and pointing of the masonry with a compatible material while filling voids in the masonry with replacement bricks. The use of natural hydraulic lime mortars should be considered since the original bedding mortar contained brick dust (natural hydraulic limes offer a similar mineralogical influence on durability as brick dust and oyster lime).

Wierick reports on Portland cement in repair mortars near the top of walls and in other locations (presumably used after about 1900). Additional inspections and analytical work should be considered to confirm the presence of Portland cement use on scarp walls, as Portland cement is considered to accelerate masonry decay in historic brick structures.

Therefore, the immediate threats to the structure are:

- Settlement and outward bowing of walls due to infill creating walls of unknown stability if fill is partially or completely removed. The bowing may be responsible for loss of brick in "patches" (identified by Weirick as "prior repairs"). Structural assessments should be made to ensure public safety.

- Sea water impingement along the base of the Castle in Eastern and Southern areas.

- Missing brick areas on the scarp walls and the need to point mortar joints to minimize continuing mortar loss.

Summary Conclusions

- Bricks in the scarp walls are Charleston Grey bricks of local origin. These bricks have unique properties that must be considered for modern repairs. Repairs to some areas with brick loss on the scarp walls should be considered on a priority basis.

- Bedding mortar was based on oyster lime and local sand with addition of brick dust to increase longevity. Natural hydraulic limes mimic the mineralogical processes in the original bedding mortars.

- A number of threats to the structure have been identified in prior investigations. The author provides recommendations for repairs and his concerns over safety based on his education and masonry experience.

Acknowledgement

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Dedication

This report is dedicated to the memory of Alan E. Ferguson, a Clemson University Ceramic Engineering graduate, who passed away in 2011. Mr. Ferguson's daughter, Katie (Katherine M. Ferguson), was with the group of College of Charleston students performing a site documentation of Castle Pinckney on February 23, 2011, when the author was permitted to visit the site. The author still recalls his conversation with Alan when we discussed this visit, and Mr. Ferguson's love for his daughter was very evident in the discussions.