CHARACTERIZATION OF THE MORTARS OF EL CASTILLO DE SAN CRISTÓBAL

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ABSTRACT — This study characterizes the formulation of mortars used in the construction of Fort San Cristóbal located in the city of Old San Juan, Puerto Rico. Renders, horizontal surface mortars, and bedding mortars representing a period of time from the late 17th to the early 20th century were sampled from a variety of outworks on the site. Results of examination using optical microscopy/polarized light microscopy and x-ray diffraction show that mortar formulations were closely tied to their uses as well as their time periods. Evidence is presented that the Spanish were using hydraulic brick dust mortars during the second phase of construction at the fort in the late 18th century, in reaction to earlier failure of weak clay/lime mortars.

TITRE—La caractérisation des mortiers du *castillo* (fort) de San Cristóbal RÉSUMÉ—Cette étude caractérise la formulation des mortiers utilisés lors de la construction du fort de San Cristóbal situé dans le vieux San Juan, à Porto Rico. Des échantillons d'enduits, de mortier des surfaces horizontales et de lit de mortier, représentant une période de temps s'échelonnant du 17e jusqu'au début du 20e siècle, ont été prélevés sur une variété d'ouvrages extérieurs du site. Les résultats des examens au microscope optique, au microscope polarisant et par diffraction des rayons X démontrent que la formulation des mortiers était étroitement reliées à leur usage ainsi qu'à l'époque de leur utilisation. Il est démontré qu'au cours de la seconde phase de construction du fort à la fin du 18e siècle, en réaction à l'échec antérieur de l'usage d'un mortier fragile d'argile/chaux, les Espagnols ont utilisé un mortier hydraulique de poudre de briques.

TÍTULO—Título: Caracterização das argamassas do Castelo de San Cristóbal RESUMO—Este estudo caracteriza a formulação das argamassas utilizadas na construção do Forte San Cristóbal, localizado na cidade Viejo San Juan, em Porto Rico. Foram retiradas amostras de estuque, argamassa de superfície horizontal e argamassa de assentamento de blocos de várias fortificações do local, representativas do período entre o final do século XVII e o início do século XX. Resultados do exame a partir da microscopia ótica/microscopia de luz polarizada e difração de raio X revelam que as formulações da argamassa eram estritamente vinculadas aos seus usos, tanto quanto às épocas. É apresentada evidência de que os espanhóis utilizaram argamassa de pó de tijolo hidráulico durante a segunda fase de construção no forte no final do século XVIII, em resposta ao fracasso anterior da argamassa de argila/cal, que se mostrou fraca.

TITULO—Caracterización de los morteros del Castillo de San Cristóbal RESUMEN—Este estudio caracteriza la formulación de morteros utilizados en la construcción del Fuerte de San Cristóbal ubicado en la ciudad del Viejo San Juan, en Puerto Rico. Se tomaron muestras de enlucidos, mortero de superficies horizontales, y morteros de piso de piedra de una variedad de fortificaciones del período que va desde finales del Siglo XVII hasta comienzos del XX. Los resultados de los exámenes con microscopía óptica/microscopía de luz polarizada, y difracción de rayos X demostraron que las formulaciones de los morteros estaban fuertemente relacionadas con su tipo de uso, y con las épocas a que pertenecen. Se presenta evidencia de que durante la segunda fase de construcción del fuerte a finales del Siglo XVIII, los españoles utilizaban morteros hidráulicos de polvo de ladrillo, en respuesta a las fallas de morteros débiles de arcilla y cal que se utilizaban previamente.

1. INTRODUCTION

While historians have performed exhaustive research on the history of Spanish colonial forts and their architectural design, much less attention has been paid to the history and use of the materials of their construction, especially mortars (Tellez 1997). In particular, there is a paucity of published information on the materials of the fortifications of Old San Juan, Puerto Rico. Fort San Cristóbal, located in the northeast corner of Old San Juan, Puerto Rico (fig. 1), is the largest fortification built by the Spanish in the New World and has much potential to deliver

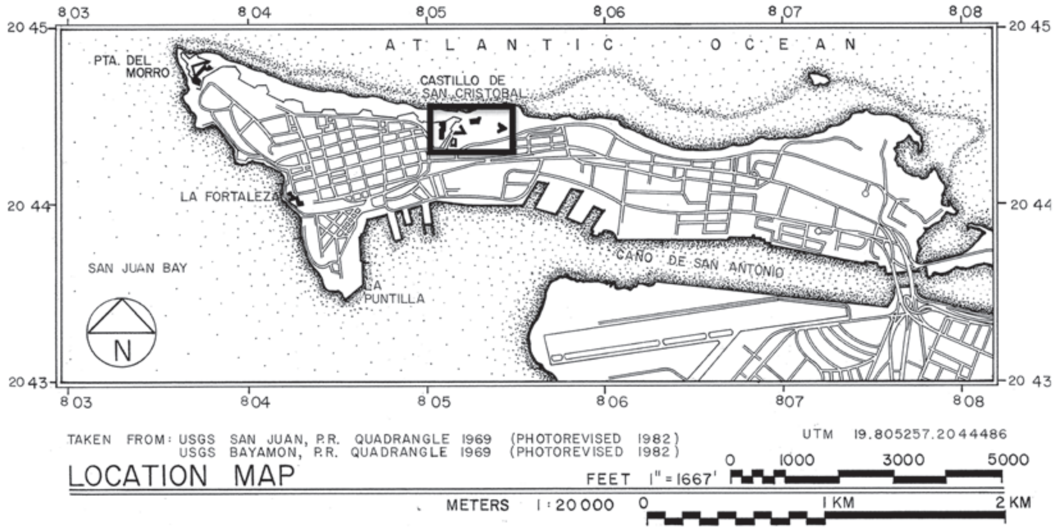

Fig. 1. Map of the location of Fort San Cristóbal on the island of San Juan (from HABS survey PR-91, call no. PR,7-SAJU,53)

significant details on Spanish building technology from the 16th to the 19th centuries. This fortification, one of several built by the Spanish during that time period in Puerto Rico, consists of extensive outworks that extend over 27 acres. To a large degree, it retains its late 18th century plan, and many of its original structures are relatively intact, especially on the eastern two-thirds of the site.

To date, published studies have focused on the mortars of San Felipe del Morro, an earlier fortification located opposite San Cristóbal on the far western side of Old San Juan (Jacob and Cavallo 1992; Crisson 1996). In an extensive literature search, no published studies were located on the mortars of San Cristóbal, although there is an unpublished historic structure report on the fortification (Berkowitz et al. 1991). To add to the general knowledge of construction materials used in the fortifications of Old San Juan, this study will characterize the three common types of mortars used in the fortifications of San Cristóbal: renders, horizontal surface (e.g., terreplein) mortars, and bedding mortars, with the goals of understanding the morphology and formulation of these mortars, and determining if these characteristics change based on location and construction period. It is hoped that this information will provide a comparison for the mortars used in other Spanish fortifications and will help inform the conservation of these structures.

The Spanish built San Cristóbal in the 17th century to guard the eastern side of the city of San Juan from pirate attack, and to complement the earlier fort of El Morro located at the opposite end of the city. San Cristóbal had two major construction phases. The first phase, based on a 1587 master plan by Bautista Antonelli, lasted from 1634 to 1650 (Manuncy and Torres-Reyes 1973). The second phase, based initially on plans from Alexander O'Reilly and later from Thomas O'Daly, lasted from 1766 to 1785, although some work continued into the 1790s. The engineer Juan Francisco Mestre headed up most of the work in the second phase (Torres-Reyes 1965; Manuncy and Torres-Reyes 1973).

After the completion of San Cristóbal in the 1790s, most modifications were relatively minimal until the onset of the Spanish-American War when substantial portions of the fortifications in the south of the site were demolished, such as the Santiago Bastion and the Santiago Gate. From 1938 to 1940, the Army Corps of Engineers and the Works Progress Administration embarked on an extensive repair and renovation campaign, such as the installation of a stone and portland cement veneer to embrasures of the north bastion, curtain, and south bastion. The National Park Service became intimately involved

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Fig. 2. Main entrance to the fort through the North Gate

with the site in 1959, and over the years, restored much of the main fort including the north casemates, officers' quarters, and troops' quarters. The outworks were left relatively untouched except for the upper portion of El Abanico (Berkowitz et al. 1991).

2. SAMPLE COLLECTION

Fort San Cristóbal consists of dozens of large and small batteries, walls, revelins, and counterguards constructed from the middle of the 17th century to the late 19th century with a number of 20th century modifications on a site nearly a quarter mile long. Most of the modifications have been made to the western one-third of the site, while the eastern two-thirds of the site contains structures with remarkably few changes since their original construction. Establishing a sampling protocol for a site this large was a daunting task, but afforded the luxury of choosing structures with the fewest modifications after construction. The small number of samples obtained from each fortification is a recognized limitation of this study, but was necessary to avoid unacceptable damage and loss to areas being sampled. Pragmatic factors such as a finite amount of time to gather samples, available resources, and funding also influenced the total number of samples.

The essential criteria for choosing a particular structure, and a particular area of that structure for sampling was to obtain samples of mortars that represented, as closely as possible, the original construction materials. This selection was assisted through historical research that established the construction, modification dates, and specific changes for each structure, to allow careful sampling from areas that did not contain known or decipherable post-construction changes. Three different types of samples were taken to represent the major categories of mortars used in the fort: renders, horizontal surface mortars (typically used on terreplein surfaces), and bedding mortars.

The resulting structures that were selected that satisfied these criteria are the Fort of the Point, the lightning tower on the San Carlos Revelin, La Trinidad counterguard, El Abanico outwork, St. Teresa Battery, and an embrasure in the north casemates. Each sample was carefully removed with a small cold

Table 1. Mortar Samples

Sample ID	Location	Sample type	Rationale for selection
11M200	west side of east wall near the sentry box of the Fort of the Point	bedding	original mortar from construction; representative sample
11M201	inside the sentry box near the entrance of the Fort of the Point	render	representative mortar from WPA repairs in the 1930s
13M200	lightning tower on the San Carlos Revelin	render	representative render from early nineteenth century
13M201	lightning tower on the San Carlos Revelin	bedding	representative bedding mortar from early nineteenth century
14M200	upper level of the counterguard of La Trinidad	render	mortar from first phase of construction; representative sample
14M202	upper level of the counterguard of La Trinidad	horizontal surface	mortar from first phase of construction; representative sample
14M204	upper level of the counterguard of La Trinidad	bedding	mortar from first phase of construction; representative sample
16M200	south wall of the parade near the covered way of El Abanico	render	mortar from last phase of construction; representative sample
16M202	parade of El Abanico	horizontal surface	mortar from second phase of construction; representative sample
16M205	west wall of the parade near the moat of El Abanico	bedding	mortar from last phase of construction; representative sample
20M201	south wall of St. Teresa near the main entrance	render	representative render from late nineteenth century
20M203	top of east bunker of St. Teresa	horizontal surface	representative horizontal surface mortar from late nineteenth century
20M205	mid-way of the south wall of St. Teresa	bedding	representative bedding mortar from late nineteenth century
21M200	embrasure of casemate three from north casemates	render	mortar from second phase of construction; representative sample
21M203	embrasure of casemate three from north casemates	bedding	mortar from second phase of construction; representative sample

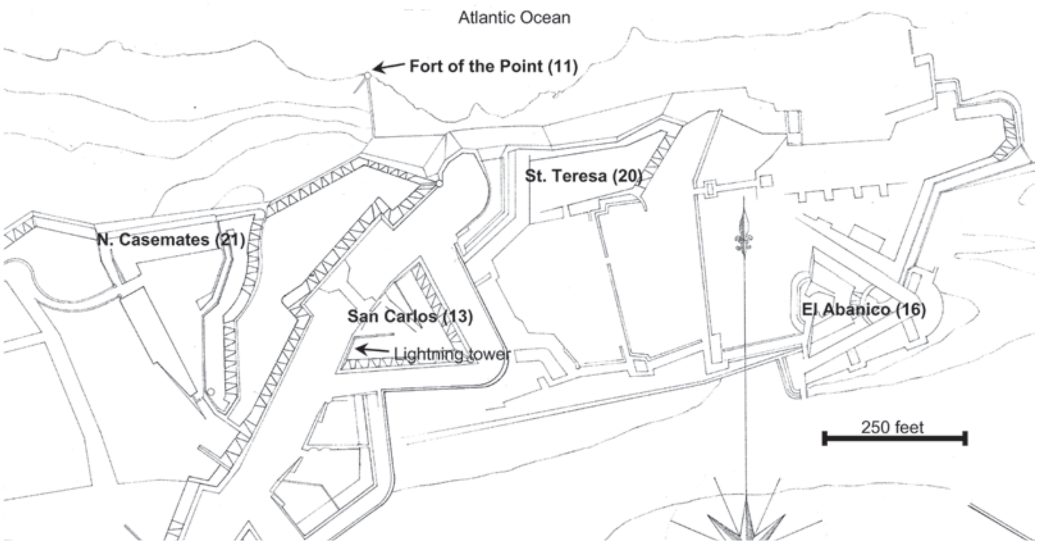


Fig. 3. Site plan of Fort San Cristóbal. Building IDs are in parentheses (adapted from 1899 map from HABS survey PR-94-C, call no. PR,7-SAJU,56C).

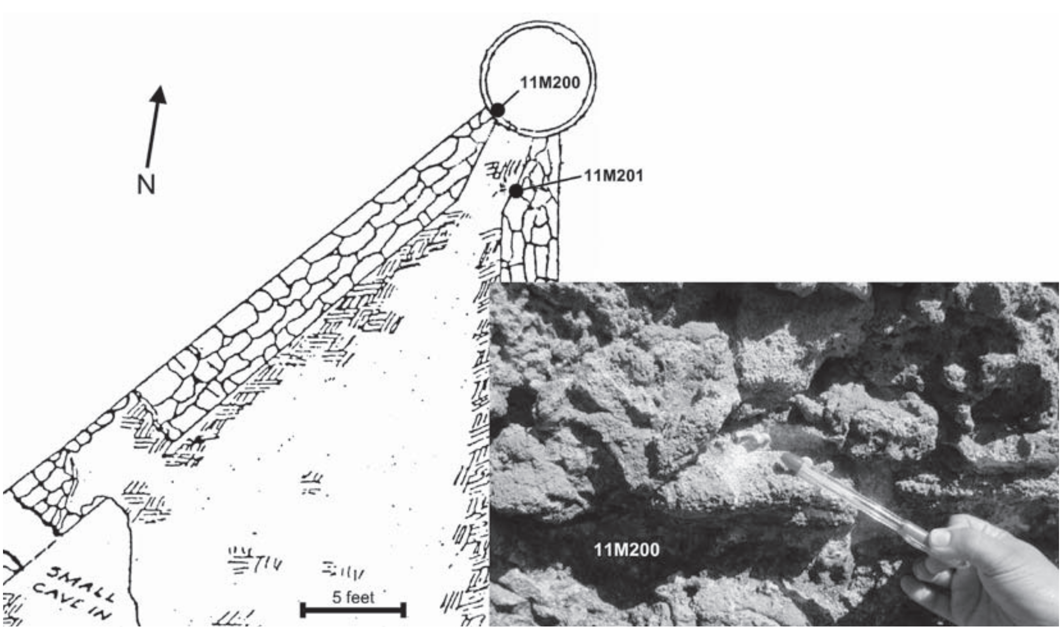


Fig. 4. Sample locations from Fort of the Point (11) (adapted from 1938–39 drawing by the United States Department of the Army, Engineers Office)

chisel and the area of its removal documented with photographs and noted on a map for future reference. Each sample was typically about 30 cm^3 in volume.

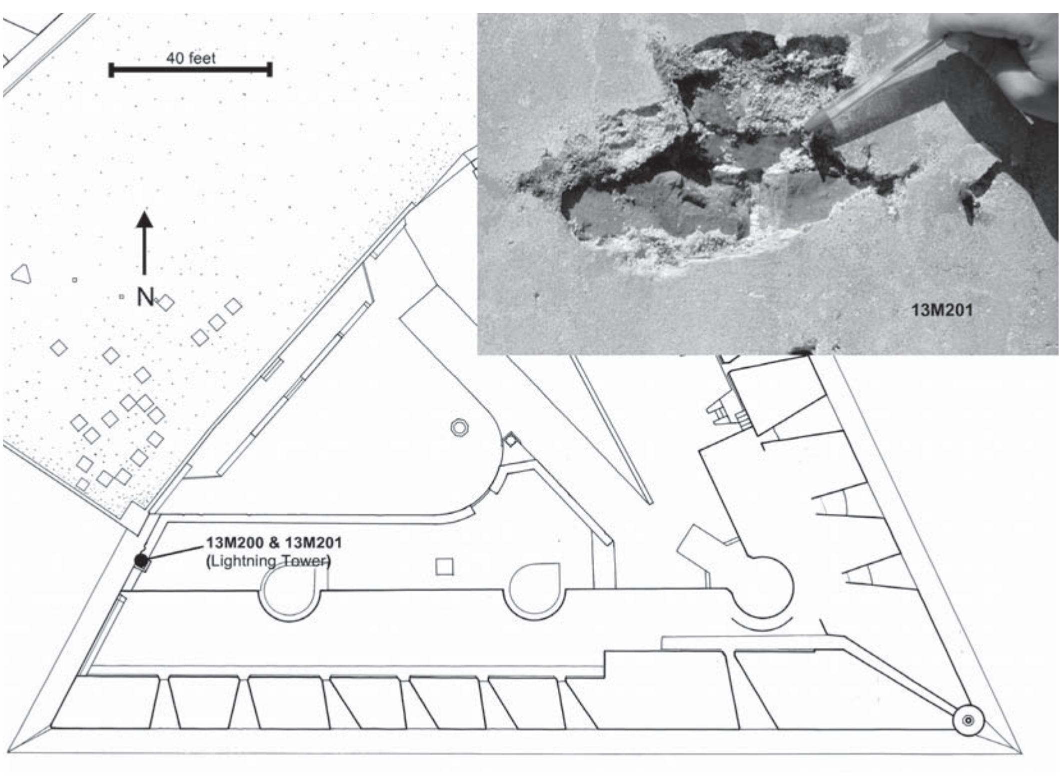
2.1 FORT OF THE POINT (ID NO. 11)

Fort of the Point or Fuerte del Espigón is more commonly known by the colloquial name La Garita del Diablo (the Garrison of the Devil) for its alleged propensity to make Spanish soldiers mysteriously disappear in the night. Located on the seashore directly in front of the North Bastion, it is the most northern and oldest of the fortifications at San Cristóbal. It consists of a *garita* (sentry box) and two short walls in a triangle shaped configuration. The walls are made of ashlar and stone rubble; the sentry box is a combination of these elements plus brick. A fortification existed at the present location of the Fort of the Point as early as 1634 to 1644, with indications that the existing structure dates to 1678. The *garita* was constructed sometime before the 1760s; in 1938, portions of the *garita* were repointed by the Works Progress Administration (Berkowitz et al. 1991).

2.2 SAN CARLOS REVELIN LIGHTNING TOWER (ID NO. 13)

The San Carlos Revelin is located directly to the east of the main moat between St. Teresa to the north and La Trinidad to the south. It is triangular in shape with a salient angle of sixty-five degrees. A *garita* is located at the origin of this angle and faces more or less southeastward. San Carlos is built of coursed ashlar, and rubble coated with stucco scored to look like ashlar. Sections of the parapets have had several coats of cement-based stucco applied. The interior of the structure is earth or *mampostería* (mixture of rubble stone, earth, and/or lime). San Carlos was constructed from 1766 to about 1770. In 1818, plans were drawn up for the masonry lightning tower that

Fig. 5. Sample location from San Carlos (13) (adapted from HABS survey PR-93, call no. PR,7-SAJU,44)



was constructed on the edge of the south terreplein facing the South Bastion (Berkowitz et al. 1991).

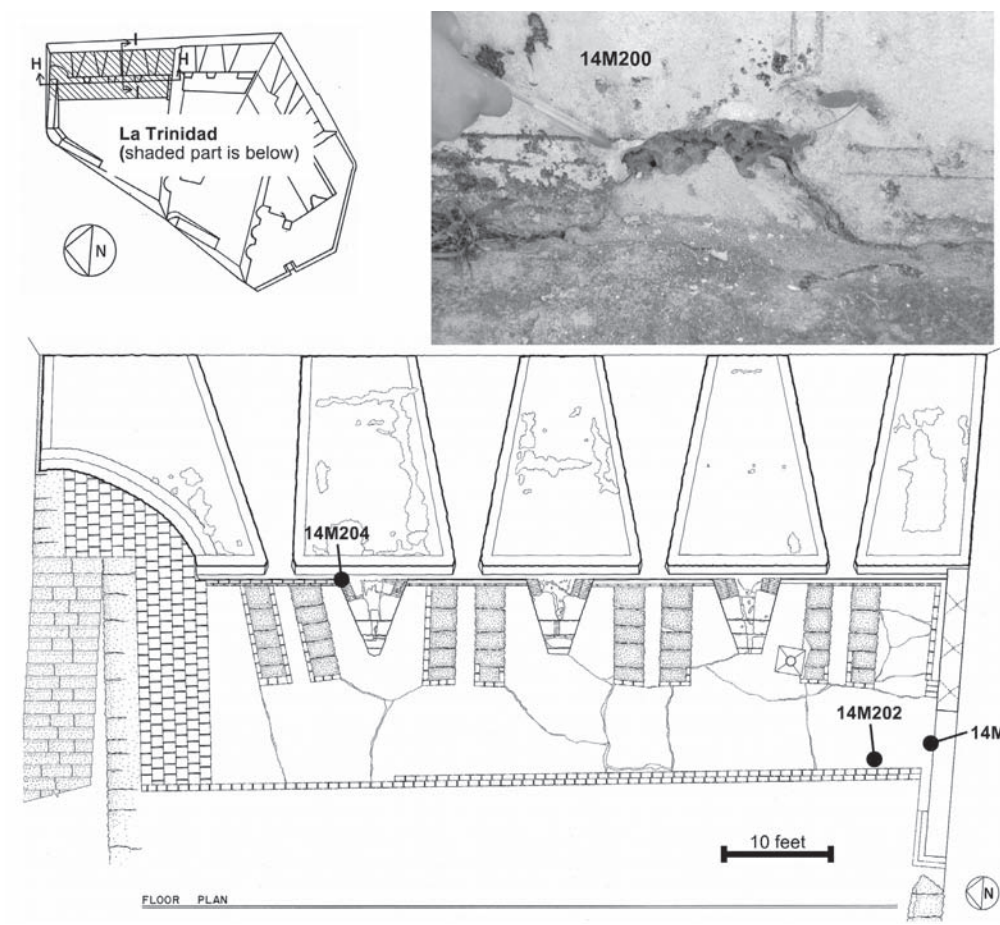
2.3 LA TRINIDAD (ID NO. 14)

La Trinidad counterguard is located directly to the south of San Carlos on the east side across the main moat from the South Bastion. It was constructed in four levels to accommodate the terrain and is irregular in plan. Two stucco campaigns are evident: one that used raised joints, and another that used scored and penciled joints to create faux ashlar. As with the other fortifications, La Trinidad is constructed of a combination of coursed ashlar, brick, and *mampostería* covered in stucco. Construction of La Trinidad occurred between 1766 and 1783; the majority of the work appears to have occurred before 1774. A fourth embrasure on the top level was added between 1792 and 1861 (Berkowitz et al. 1991).

2.4 EL ABANICO (ID NO. 16)

El Abanico ("the fan"), an outwork located on the far east of the site south of La Princesa, was constructed between 1779 and 1783. It is an equilateral triangle in overall plan with one point facing directly east. It is surrounded by a moat; access is via a bridge from the west. The northeast and southeast facing walls form a

Fig. 6. At top: overall plan of sample location from La Trinidad (14) (in shaded area). At bottom: detail plan of sample location from upper level of La Trinidad (14) (adapted from HABS survey PR-121, call no. PR,7-SAJU,59).



parapet and terreplein. The terreplein of the fortification is accessed by one of two ramps found in a middle indent in the west side of the structure. El Abanico is made of coursed ashlar, brick, and *mampostería* covered with stucco (Berkowitz et al. 1991).

2.5 BUNKER AND GUN EMPLACEMENT FROM ST. TERESA (ID NO. 20)

The St. Teresa Battery is located directly to the east of the North Bastion and northeast from San Carlos. It is on the north edge of the glacis. St. Teresa has existed in various forms since the 18th century; the majority of what remains today was built in 1897. The vaulted bunker is a small, short structure with an arched roof and a single doorway. The vaulted bunker is constructed of concrete coated with stucco, but the gun emplacement appears to have used rubble stone construction similar to that used in older parts of the fort; the same beige-colored mortar is used for bedding material. Stucco has been applied on the surface. Few, if any, changes appear to have been made to these two structures from the time of their construction to the present (Berkowitz et al. 1991).

2.6 EMBRASURE OF CASEMATE THREE FROM N. CASEMATES (ID NO. 21)

The North Casemates consist of a structure one room deep and one to two stories high, located directly to the north of the *Plaza de Armas*. Its north side faces the ocean. A one-story loggia fronts the plaza side of the casemates. Each casemate has been assigned a number by the National Park Service starting at the far west side (casemate one) and proceeding to the far east side (casemate eleven). The casemates consist of large vaulted rooms with window embrasures facing north. The entire structure is load-bearing masonry. Work on the North Casemates began with the construction of the powder magazines (casemates ten and eleven) from 1768 to 1771. Construction of casemates one to nine occurred between 1774 and 1785 (Berkowitz et al. 1991).

3. ANALYTICAL TECHNIQUES

The analyses performed on the mortar samples consisted of optical and polarized light microscopy (PLM) followed by x-ray diffraction (XRD). XRD is commonly used to identify major phases of the binder (Lewin 1982; Charola et al. 1986; Anderson et al. 2000; Callebaut et al. 2000); optical and polarized light microscopy is useful for characterizing the aggregate for grading, shape, and size, and for identifying various mineral species (Barnett 1991; Reedy 1994; Doebley and Spitzer 1996; Van Balen et al. 2000). Digital image processing provided binder to aggregate ratio data. These techniques were primarily chosen because of support for them in the literature, and because they yield useful information at relatively low cost in time and money.

3.1 OPTICAL AND POLARIZED LIGHT MICROSCOPY

All samples were initially examined under a low-power stereo microscope to begin basic characterization analyses and to help identify samples for petrographic thin sections. Thin sections (30μm), vacuum-impregnated with blue epoxy, were made of each sample. Half of each thin section was stained with Alizarin-S to identify the presence of calcite. A particle dispersion was made from a sample of brick from an 18th century building in Old San Juan to provide a control to help determine the presence of brick dust in the thin sections.

Each thin section was observed at approximately 100x to 1000x using a polarized light microscope. Samples were examined under ordinary transmitted light and with crossed polars to identify various mineral phases using interference colors and figures. Characterizations made with PLM included general color under transmitted and reflected light, pleochroism, refractive index, prominence, isotropy/anisotropy, interference colors, birefringence, twinning, and extinction; these were recorded and matched to reference samples in the *Particle Atlas* (McCrone Research Institute 1992).

Aggregates were characterized for color, size, morphology, distribution, and mineralogy. Color was determined using Munsell color chips under natural light from a northern source. Binders were characterized for calcite stain, porosity, binder to aggregate ratio, and color. Quantitative microscopy was employed to measure particle size, porosity, binder to aggregate ratios, and frequency counts of various mineral phases within the mortars.

Comparison of the binder to aggregate ratio was performed via digital image analysis of thin sections

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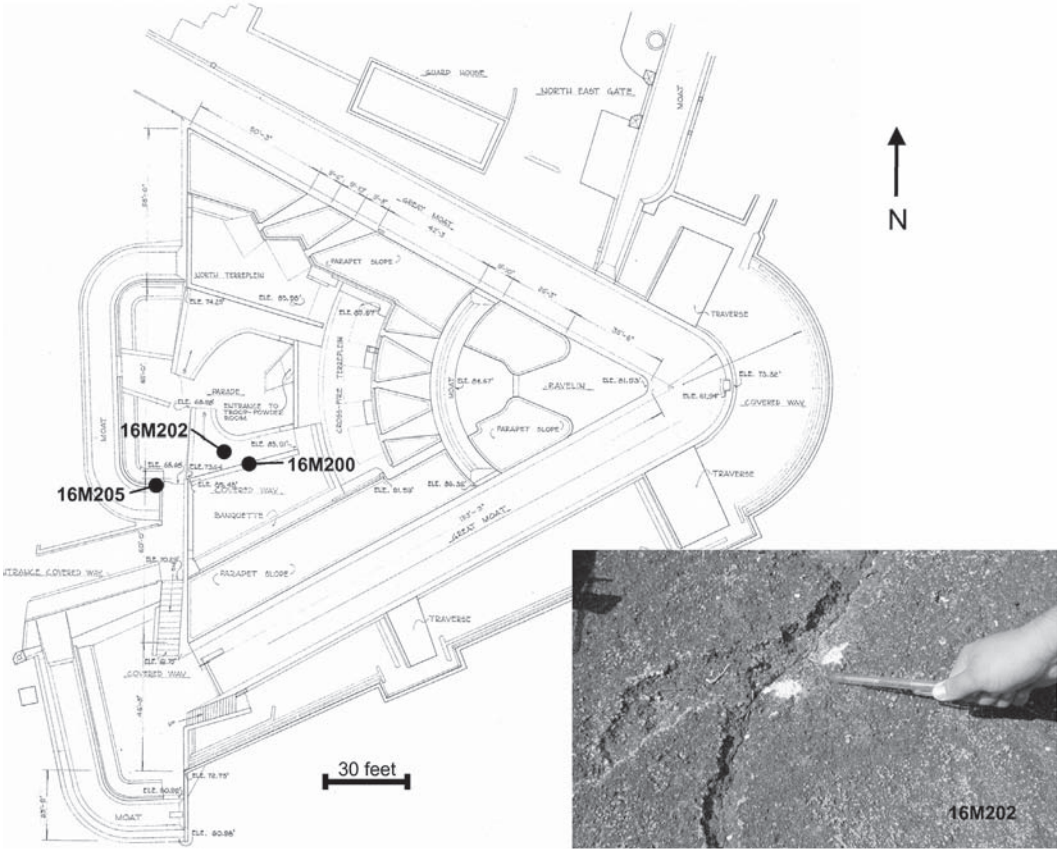

Fig. 7. Sample location from El Abanico (16) (adapted from HABS survey PR-94, call no. PR,7-SAJU,56)

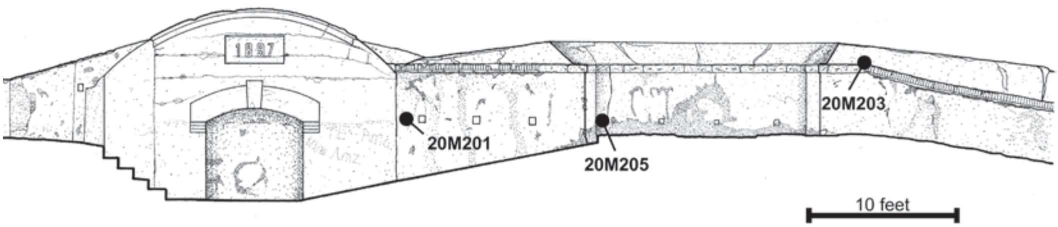

Fig. 8. Sample location from St. Teresa (20), looking north (adapted from HABS survey PR-91, call no. PR,7-SAJU,53)

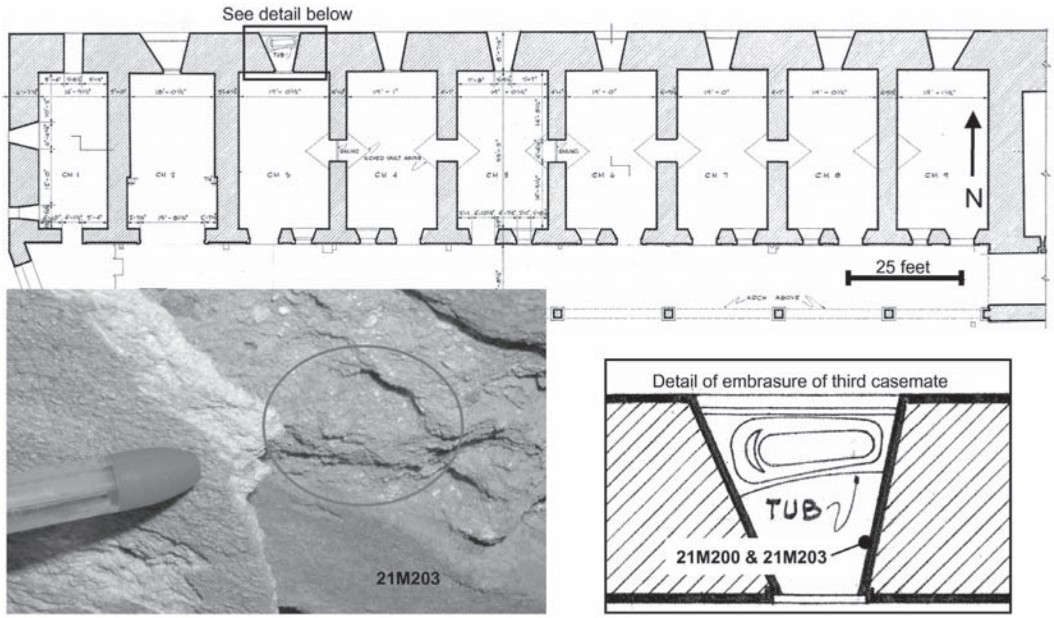

Fig. 9. Sample locations for the third casement of the North Casemates (21) (adapted from HABS survey PR-101, call no. PR,7-SAJU,45)

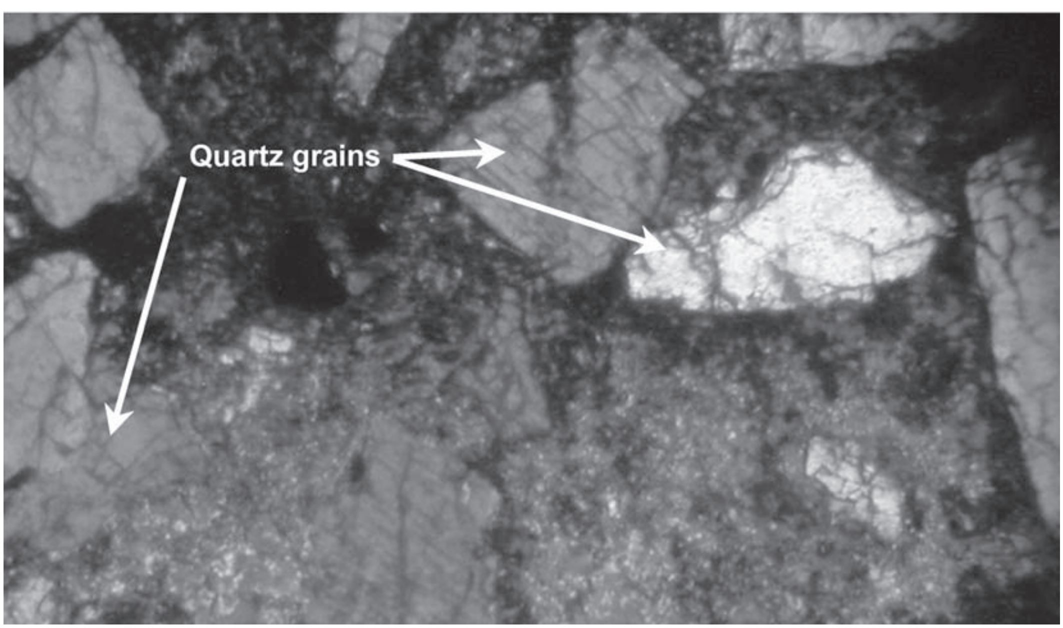

Fig. 10. A thin section of 16M205 in transmitted light, crossed polars and full wave compensator (gypsum plate) inserted. This beige-colored mortar sample contains brick powder which is evident from the appearance of the binder under crossed polars.

of the mortars (see Crabtree et al. 1984; RILEM TC 167-COM 2001; Casadio et al. 2005; Reedy 2006). High-resolution images were captured using transmitted light via an 8-megapixel digital camera. Histograms and adjustment of hue, saturation, and intensity in Adobe Photoshop segmented the binder from the aggregate. An analysis of the area of each phase provided an estimate of the binder to aggregate ratio. Thin sections of known binder to aggregate ratios provided calibration controls to ensure correct interpretation of the areal analysis.

The characterization of aggregates is based on well-established soil micromorphology methods (see FitzPatrick 1984) from which aggregate classifications have been derived, including classification of roundness (angular, subangular, subrounded, rounded, well rounded) and sphericity (tabular, ovoid, subspherical, spherical). "Sharp" sands are those whose roundness classification is angular or subangular, while "rounded" sands are subrounded to well rounded. "Well-graded" aggregates have a wide and very even distribution of particle sizes between approximately 75-μm and 0.5 mm; "medium-graded" aggregates have one or more particle sizes predominating, but still exhibit a particle size distribution between approximately 75-μm and 0.5 mm; while "poorly-graded" aggregates consist of particles in which one or more sizes predominate in context with the near or complete absence of representative particle sizes in the range of approximately 75-μm to 0.5 mm. Aggregate size is classified as large (greater than 2 mm), medium (200–2000μm), and small (60–200μm). Bioclasts (carbonates of biological origin) were identified by their calcite stain and morphology (e.g., appearance of shells, marine life).

3.2 X-RAY DIFFRACTION

Powder XRD analyses were performed on all samples and on the fines (< 62μm) remaining from acid digestion of mortar samples 14M204 and 16M205. Samples were prepared by gently hand grinding in a mortar and pestle to avoid pulverizing the aggregate, and then sieving the resulting powder to separate the fraction less than 38μm in diameter for analysis. This was done to help separate the siliceous aggregate from the sample in order to increase the relative fraction of the binder in the sample. The powdered sample was scattered on a clean glass slide and spread using a small amount of acetone. X-ray diffraction patterns were collected in the range of 2 and 70 degrees 2θ using $CuK\alpha$ radiation source at 45 kV and 30 mA from a DMAX-B diffractometer (Rigaku Co., Tokyo, Japan). The fPDSM software assisted pattern matching for phases in the sample.

Samples 14M204 and 16M205, which contained a large amount of beige-colored, non-calcareous binder, were subjected to acid digestion before the analysis in order to increase the relative concentration of non-carbonate minerals and improve the detection capability of the XRD analysis. Both samples were ground with a mortar and pestle and then subjected to acid digestion with 4M hydrochloric acid for twenty-four hours and then dried in a 60ºC oven for 24 hours.

4. RESULTS

4.1 BEDDING MORTARS

Two primary types of bedding mortars were found to have been used in the construction of Fort San Cristóbal. Bedding mortars located near the oldest and lowest portions of structures, such as foundations, are beige in color (14M204, 16M205, 20M205, 21M203) while bedding mortars located at higher elevations—especially on merlons and parapets—are white (e.g., 13M201). These mortars are referred to by their general color for ease in identification.

All thin sections were viewed under high magnification (400x and 1000x) and polarized light to identify the presence of brick powder or clay. As a reference, PLM was performed on a dispersion of very finely ground brick particles (see section 3.1). Very small brownish-red particles, less than ten microns in size, were found with embedded quartz grains in sample 16M205 (fig. 10), consistent with the brick reference. These embedded quartz grains were quite easy to see under a rotated stage with crossed polars and the full-wave compensator (gypsum plate) inserted. Similar particles were found in 14M204, but they did not have embedded quartz grains and as such, are more consistent with clay. In addition, reaction borders (rim-like structures surrounding silicate grains that are indicative of the formation calcium silicates), were found around a number of particles consistent with brick dust (Charola and Henriques 2000).

Based on the preliminary PLM characterization results, a representative sample containing probable clays (14M204) and a representative sample containing probable brick powder (16M205) were

Table 2. Provenance and characteristics of the binder and aggregate of mortar samples

Use	bedding						render						horizontal surface		
Sample ID	11M200	14M204	21M203	16M205	13M201	20M205	14M200	21M200	16M200	13M200	20M201	11M201	14M202	16M202	20M203
Attributed date	1650-1700	1766-1770	1774-1780	ca. 1780	1818	1897	1770-1820	1774-1787	1780-1820	1818	1897	1930s	1770s	ca. 1780	1897
Color[a]	white (10Y 9/2)	beige (5YR 6/6)	beige (5YR 7/8)	beige (5YR 7/6)	white (10Y 9/2)	beige (7.5YR 6/6)	white (10Y 9/1)	white (10Y 9/1)	white (10Y 9/1)	white (10Y 9/1)	white (10Y 9/1)	gray (7.5Y 9/2)	beige (7.5YR 8/6)	white (10Y 9/2)	gray (7.5Y 9/2)
Binder:aggregate[b]	1:1	1:9	1:1	1:3	1:3	1:2	1:2	1:2	1:3	1:2	1:2	1:2	1:2	1:2	1:4
BINDER															
Calcium carbonate[c]	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Gismondine zeolite[d] (pozzolana evidence)				X											X
Reaction rims[e] (pozzolana evidence)				X											
Clays[d]		X	X			X									
AGGREGATE															
Grading[e, f]	med	med	med	poor	med	med	med	med	med	med	poor	well	poor	med	well
Large aggregate[e] (> 2 mm)															X
Medium aggregate[e] (200-2000 microns)	X		X	X	X	X	X	X	X	X	X	X	X	X	X
Very small aggregate[e] (2-60 microns)		X	X												
Spherical/ rounded sand[e]	X				X		X	X	X	X	X		X		X
Sharp sand[e]		X	X	X		X						X		X	
No bioclasts present[e]											X	X			
Quartz[c]	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Larger brick particles[e] (as aggregate)														X	X

[a] Munsell chip color match using natural light (northern exposure)
[b] Assessed via digital image analysis
[c] Determined by x-ray diffraction and polarized light microscopy (calcite stain).
[d] Determined by x-ray diffraction only
[e] Determined by polarized light microscopy/optical microscopy

[f] well = having a wide and very even distribution of particle sizes between approximately 75µm and 0.5 mm
medium = having one or more particle sizes predominating, but still exhibiting a particle size distribution between approximately 75µm and 0.5 mm
poor = having one or more sizes predominate in context, with the near or complete absence of representative particle sizes in the range approximately 75µm to 0.5 mm.

selected for XRD analysis. The suspected brick powder sample (16M205) was very hard and brittle while the suspected clay sample (14M204) was quite friable. During acid digestion, the aqueous mixture from sample 14M204 was bubbly and chocolate-brown in color, while that from sample 16M205 was dark red in color, without the bubble formation found in 14M204. [1]

X-ray diffraction was then performed on the dried fines from the acid-digested samples. The suspected clay sample (14M204) contains a significant amount of kaolinite (a clay) along with orthoclase, quartz, and potassium and sodium feldspars. The suspected brick powder sample (16M205) contains potassium feldspars, gismondine (a zeolitic calcium aluminum silicate hydrate), and quartz. The presence of gismondine, a zeolite, is particularly important as it forms when hydraulic components, such as brick powder, chemically react with calcium carbonate and water. Zeolites, such as gismondine, are commonly created as part of the process of hydration of cementitious binders (Grutzeck et al. 1997, Grutzeck et al. 1999). More specifically, gismondine is a known reaction product that results from the addition of pozzolans such as fly ash (Antiohos et al. 2006) and metakaolin (Silva and Glasser 1993) to calcium hydroxide pastes. Gismondine can therefore be considered an indicator of the presence of pozzolans in the mortar, which in this case are most likely to be finely ground brick particles. As the Spanish were lacking in the technology to produce well-fired brick during the construction of San Cristóbal, the lack of fired-clay indicators, such as crystobalite and mullite, is not unexpected as these compounds only form in quantities that reach the detection threshold of XRD analyses at temperatures exceeding 1000°C (Pavía 2006).

The beige-colored bedding mortars (14M204, 16M205, 20M205, 21M203) were analyzed via PLM. All of these mortars used sharp sands. 14M204, 16M205, and 21M203 had a low bioclast content in comparison to the rest of the samples. 14M204 and 21M203 used aggregates that were smaller than the other samples. Based on digital image analysis (see section 3.1), 14M204 and 16M205 had high binder to aggregate ratios. Calcite staining and subsequent XRD analysis confirmed that the binder is predominantly calcite.

The result of the binder to aggregate ratio digital image analysis for sample 14M204 (1:9) is unusual. No mortar would have sufficient cohesiveness to function properly with so little binder. It is not surprising, therefore, that this sample was particularly friable compared to the other bedding mortar samples. It seems unlikely that sample 14M204 is representative of the bedding mortar for the La Trinidad fortification. A more plausible explanation is that this sample represents an isolated portion of the bedding mortar that was improperly mixed during construction.

4.2 RENDERS

All sampled renders have white-colored binders. Of these samples, only 13M200, 14M200, 16M200, and 20M201 have colored surface finishes. This surface finish is quite consistent across samples and manifests itself as a very thin transparent orange layer that does not penetrate very far into the substrate. Samples 13M200, 14M200, and 16M200 have a very smooth polished surface.

The renders were also analyzed via PLM. All of the sands were spherical and rounded. 13M200 and 21M200 had a large amount of bioclasts while 14M200 and 16M200 had a moderate amount. With the exception of 20M201, which was poorly graded, the sands had a medium degree of grading consistent with the use of beach sand for aggregates. Calcite staining and subsequent XRD analysis confirmed that the binder is predominantly calcite.

Unlike the bedding mortars, there was no evidence of any hydraulicity in the mortars or added clays based on an XRD analysis. With the exception of 11M201, which dates from the 1930s, these mortars were very white in appearance (fig. 11), which is consistent with the aesthetic qualities that are typically desirable in a material that is meant to be visible.

4.3 HORIZONTAL SURFACES

The horizontal surface samples were taken from terreplein, merlin, and embrasure surfaces of the fortifications. There is a wide degree of variation between samples. 14M015 and 14M202 were similar to the clay/lime bedding mortars, while 16M202 clearly had brick added to it due to the presence of large (> 1 mm) chunks of brick that were easily observable under zero to low magnification. Sample 20M203, dating from 1897, is an even gray color, quite hard and non-friable, with very large aggregates.

Samples 14M202, 16M202, and 20M203 were

Fig. 11. Interior surface of mortar sample 14M200 under low magnification. The binder is very white, which is aesthetically consistent with a render that is meant to be seen.

analyzed using PLM. The sands from 14M202 and 16M202 both contained a large amount of bioclasts, but 14M202 had poorly graded spherical/rounded sand while 16M202 had medium-graded sharp sand. Larger brick particles were clearly evident in 16M202 to the unaided eye and under low magnification, but there was no brick powder evident under high magnification under crossed polars. Calcite staining and XRD analysis indicate that calcite is a major component of the binder for all these mortars.

Sample 20M203 from St. Teresa dates to 1897 and had the most unique composition of all the samples. Its aggregate was quite large (> 2 mm) and complex, consisting of quartz grains, brick, and a variety of other mineral species, based on PLM analysis. The matrix was gray in color, and it was extremely hard compared to all other samples analyzed. XRD analysis revealed a significant amount of gismondine. The extreme hardness of the mortar coupled with the presence of large amounts of a zeolite indicate that the binder has hydraulic components.

5. DISCUSSION

In general, the results of this study are consistent with the limited examples of other analyses of mortars in Puerto Rico, such as the analysis of mortars from San Felipe del Morro by Jacob and Cavallo (1992) and Crisson (1996). These authors found similar binder to aggregate ratios and mortar constituents, such as clay, which Spanish masons added to mortars in an effort to extend limited supplies of lime. The most salient aspect of this study is that the Spanish masons may have changed the formulation of bedding mortars as a result of a catastrophic collapse of a wall under construction at the fort in 1769. At the time, the failure was blamed on the addition of clay to the lime bedding mortars (Manuncy and Torres-Reyes 1973). Based on the analysis of samples that date after 1769, bedding mortars no longer contained clay, but rather contained powdered brick and its associated hydraulic properties. For instance, the beige bedding mortars used for foundation work in the first phase of Fort San Cristóbal's construction in the 18th century (14M204 and 21M203) have significant amounts of clay—either added or naturally occurring in the sand selected for the aggregate. Sample 16M205 from El Abanico is formulated with brick powder and dates to the second phase of construction in the late 18th century. Samples 14M204 and 21M203 were likely already in place by the time this wall collapsed occurred. Sample 16M205, however, clearly dates to after the wall collapse.

While it is relatively easy to look for markers of highly-fired clays, such as mullite, using a technique such as XRD, such readily available markers have not been identified for poorly-fired clays where a combination of indicators must be used, such as been done with this study. More research in this area would be valuable, such as relatively simple methods that a conservator, in the absence of highly specialized, expensive and difficult to obtain equipment, could use to determine the presence of brick pozzolans in mortar. Many areas of the world that contain Spanish mortar technology are also correspondingly poor in both material scientists as well as analytical equipment, and are positioned to greatly benefit from such research.

An important limitation of the study of mortars, such as the one that is presented here, results from the difficulty of obtaining a statistically relevant probability sample from a specific construction phase of a building or structure. While the author went to great lengths to research the history of the fort in order to establish where representative mortars could be obtained from specific construction phases of the site, errors could have occurred in selecting a sample. Sample 14M204 is representative, for instance, of a mortar whose formulation would certainly have resulted in failure had its use been widespread, which is unlikely. With valuable monuments, such as Fort San Cristóbal, it is not feasible to introduce a three-dimensional grid into a structure and obtain a sample per every cubic half-meter or less in order to obtain a probability sample. Such a program would present extremely rigorous data with a low probability of error, but would result in the unacceptable destruction of the monument and a prohibitively massive number of samples. Careful examination of the structure being sampled, however, will help to ensure that representative mortar samples are acquired. The use of a loupe to examine a region where a mortar sample is taken can ensure that the sample is consistent within a larger area and not an aberration in regard to formulations. Other factors include avoiding weathered samples or samples from regions of the building with an unknown provenance.

Lastly, while this study partially addresses the lack of published research on the materials of Caribbean fortifications, many questions remain. For instance, the results provide evidence that the Spanish switched from non-hydraulic bedding mortars containing clay to hydraulic mortars in response to the collapse of a wall during the construction of the fort. More data, from research in historical archives and material analyses, is needed to give weight to this theory. It would be useful to see if a similar switch occurred to other fortifications in Old San Juan, including the city wall, that were under construction shortly after the collapse of the wall at San Cristóbal. Indeed, further studies could help determine the source of the clay in the bedding mortars sampled for this study. Was the clay added or was it naturally present in the aggregate that was chosen? Other questions pertain to additional mortar additives that the analytical techniques used for this study could not identify—chiefly organic materials. The Spanish were known to use certain plants, such as prickly pear cactus in Arizona, as mortar additives in some applications; such additives may be present in the mortars used in San Cristóbal, as well as in other fortifications in the Caribbean. If these additives do exist, then the next logical step would be to ask why they might have been added.

While much has been published on the architectural history of the Caribbean, very little has been written on the building materials of the Caribbean and their relevance to architectural history, cultural studies, and site preservation and restoration. The results of this study, therefore, may be compared with existing and future analysis of mortars from Spanish colonial fortifications in order to identify broad trends that would represent masonry practice of the period. A future investigation might compare these results with historical architectural treatises in order to obtain a better understanding of historical construction techniques in the Spanish New World. For instance, the results presented here are consistent with historical recommendations that renders should be binder-enriched with rounded aggregates while bedding mortars should use "sharp" aggregates (e.g., Vitruvius [ca. 25 BC] 1960; Alberti [1755] 1987).

6. CONCLUSION

Fort San Cristóbal represents an important opportunity to learn about traditional Spanish masonry practices of the 17th through 19th centuries. The majority of the results are consistent with what one would expect of masonry technology from these time periods. The majority of bedding mortar samples exhibited a 1:3 binder to aggregate ratio compared to renders and horizontal surfaces, which had a 1:2 binder to aggregate ratio. Sharp sands were predominantly associated with bedding mortars, while rounded sands were associated with renders and horizontal finishes. Conversely, bedding mortars were formulated with sharp sands with less binder. An important finding is that Spanish masons were adding brick dust to bedding mortars to enhance performance under conditions of high moisture. This study's results, in conjunction with information contained in historical records, provide support for a theory that Spanish masons began to use hydraulic mortars with little to no clay, in place of non-hydraulic clay/lime bedding mortars, after a wall collapsed in 1769 during Fort San Cristóbal's construction.

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NOTE

1. Additional tests that could have identified the presence of organic material and clays were not performed; however, such bubbles are often associated with the presence of soluble and insoluble organic compounds, such as albumin found in the foam of ocean waves (Sharkov 2007). Furthermore, clay particles in water form a colloidal solution, reducing surface tension (Schwartz 1952), and thereby promote the formation of bubbles. The presence of bubbles during acid digestion of the sample is thus strongly suggestive of the presence of clay. In the process of firing clays, organic material is oxidized, and the size of particles increases through sintering and vitrification, reducing the potential to form colloidal solutions in water. Although not conclusive evidence, the lack of bubbles and the dark red color of the solution during acid digestion of sample 16M205 (suggesting the presence of iron and organic compounds which were oxidized upon heating) are associated with fired clays.

REFERENCES

Alberti, L. B. [1755] 1987. *The ten books of architecture: The 1755 Leoni Edition*. New York: Dover Publications.

Anderson, H. D., H. D. Zimmerman, H. Friis, and U. Schnell. 2000. Examination of hydraulic lime mortars of medieval churches in Denmark. In Bartos, Groot, and Hughes 2000, 37-42.

Antiohos, S., A. Papageorgiou, and S. Tsimasa. 2006. Activation of fly ash cementitious systems in the presence of quicklime. *Cement and Concrete Research* 36(12): 2123–31.

Barnett, W. K. 1991. Optical petrography as a tool for examining gypsum and lime plaster pyrotechnology. *Journal of Field Archeology* 8:253–56.

Bartos, P., C. Groot, and J. J. Hughes, eds. 2000. *International RILEM workshop on historic mortars: Characteristics and Tests.* Proceedings of the International RILEM Workshop, Paisley, Scotland, May 12–14, 1999. Paisley: RILEM Publications.

Berkowitz, J., E. B. Cliver, J. Jacob, F. Matero, and B. Yocum. 1991. *The fortifications of San Juan National Historic Site; Historic structure report, vol. 2: El Fuerte de San Cristóbal.* Atlanta, Ga.: Southeast Regional Office, National Park Service.

Callebaut, K., W. Viaene, K. Van Balen, and R. Ottenburgs. 2000. Petrographical, mineralogical and chemical characterisation of lime mortars in the Saint Michael's Church (Leuven, Belgium). In Bartos, Groot, and Hughes 2000, 113–24.

Casadio, F., G. Chiari, and S. Simon. 2005. Evaluation of binder/aggregate ratios in archaeological lime mortars with carbonate aggregate: A comparative assessment of chemical, mechanical and microscopic approaches. *Archaeometry* 47(4): 671–89.

Charola, A. E., M. Dupas, R. P. Sheryll, and G. G. Freund. 1986. Characterization of ancient mortars: Chemical and instrumental methods. In *Scientific methodologies applied to works of art: Proceedings of the symposium, Florence, Italy 2-5 May 1984*, ed. P. Parrini. Milan: Montedison Progetto Cultura, 28–33.

Charola, A., and M.A. Henriques. 2000. Hydraulicity in lime mortars revisited. In Bartos, Groot, and Hughes 2000, 95–104.

Crabtree, S. J., R. Ehrlich, and C. Prince. 1984. Evaluation of strategies for segmentation of blue-dyed pores in thin sections of reservoir rocks. *Computer Vision, Graphics and Image Processing* 28:1–18.

Crisson, R. C. 1996. San Juan historic structure report stucco project. In *Third international symposium of historic preservation on Puerto Rico and the Caribbean*, ed. M. F. Román. Puerto Rico: National Park Service, 87–102.

Doebley, C. E., and D. S. Spitzer. 1996. Guidelines and standards for testing historic mortars. *In Standards for preservation and rehabilitation* (STP 1258), ed. S. J. Kelley. West Conshohocken, Penn.: ASTM. 285–93.

FitzPatrick, E. A. 1984. *Micromorphology of soils*. London: Chapman and Hall.

Grutzeck, M. W., J. L. Thompson, and S. Kwan. 1997. Characteristics of C-S-H gels. In *Proceedings of the 10th international congress on the chemistry of cement, Gothenburg, Sweden*, ed. H. Justnes. Göteborg, Sweden: Amarkai AB and Congrex. 2–67.

Grutzeck, M. W., S. Kwan, J. L. Thompson, and A. A. Benesi. 1999. A sorosilicate model for calcium silicate hydrate. *Journal of Material Science Letters* 18:217–20.

Jacob, J. and G. J. Cavallo. 1992. Masonry mortars in the Castillo de San Felipe del Morro, San Juan, Puerto Rico: A method for categorization. In *Conservation of the Iberian and Latin American cultural heritage: Preprints of the contributions to the Madrid Congress, 9-12 September 1992*, ed. H. W. M. Hodges, J. S. Mills, and P. Smith. London: The International Institute for Conservation of Historic and Artistic Works. 72–75.

Lewin, S. Z. 1982. X-ray diffraction and scanning electron microscope analysis of conventional mortars. In *Mortars, cements and grouts used in the conservation of historic buildings, symposium* 3-6.11.1981. Rome: ICCROM. 102–31.

Manuncy, A. C. and R. Torres-Reyes. 1973. *Puerto Rico and the forts of Old San Juan*. Riverside, Conn.: The Chatham Press, Inc.

McCrone Research Institute. 1992. Particle atlas: Electronic edition. Hayward, Calif.: Micro-Dataware. Print editions by W. C. McCrone and J. G. Delly, 1974–1980.

Pavía, S. 2006. The determination of brick provenance and technology using analytical techniques from the physical sciences. *Archaeometry* 48(2): 201–18.

Reedy, C. L. 1994. Thin-section petrography in studies of cultural materials. *Journal of the American Institute for Conservation* 33(2): 115–29.

Reedy, C. L. 2006. Review of digital image analysis of petrographic thin sections in conservation research. *Journal of the American Institute for Conservation for Historic and Artistic Works* 45(2): 127–46.

RILEM TC 167-COM. 2001. Characterization of old mortars; recommendations COM-C1: Assessment of mix proportions in historical mortars using quantitative optical microscopy. *Materials and Structures* 34:387–88.

Schwartz, B. 1952. Fundamental study of clay: XII, a note on the effect of the surface tension of water on the plasticity of clay. *Journal of the American Ceramic Society* 35(2): 41–43.

Sharkov, E. A. 2007. *Breaking ocean waves: Geometry, structure and remote sensing.* Chichester, U.K.: Praxis Publishing Ltd.

Silva, P. S. and F. P. Glasser. 1993. Phase relations in the system CaO---Al2O3---SiO2---H2O relevant to metakaolin - calcium hydroxide hydration. *Cement and Concrete Research* 23(3): 627–39.

Tellez, G. 1997. Caribbean fortification design and technology, comments. In *Fortificaciones del Caribe; Memorias de la reunion de expertos, 31 de Julio, 1 y 2 de Agosto de 1992, Cartagena de Indias, Colombia*. Colombia: Colcultura. 75–81.

Torres-Reyes, R. 1965. *Construction history of San Cristobal*. Puerto Rico: National Park Service.

Van Balen, K., E.-E. Toumbakari, M.-T. Blanco-Varela, J. Aguilera, F. Puertas, C. Sabbioni, G. Zappia, C. Riontino, and G. Gobbi. 2000. Procedure for mortar type identification: A proposal. In Bartos, Groot, and Hughes 2000, 61–70.

Vitruvius, M. [ca. 25 BC] 1960. T*he ten books on architecture.* Transl. by M. H. Morgan. New York: Dover. First published 1914 by Harvard University Press.

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