NBSIR 88-3714

Mechanical and Physical Properties of Coquina Stone from the Castillo de San Marcos National Monument

L. I. Knab and J. R. Clifton

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Building Technology
Building Materials Division
Gaithersburg, MD 20899

January 1988

Sponsored by:

National Park Service
Historic Architecture Division
1980 Island Ford Parkway
Dunwoody, Georgia 30350

NBSIR 88-3714

MECHANICAL AND PHYSICAL PROPERTIES OF COQUINA STONE FROM THE CASTILLO DE SAN MARCOS NATIONAL MONUMENT

L. I. Knab and J. R. Clifton

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Building Technology
Building Materials Division
Gaithersburg, MD 20899

January 1988

Sponsored by:
National Park Service
Historic Architecture Division
1980 Island Ford Parkway
Dunwoody, Georgia 30350

U.S. DEPARTMENT OF COMMERCE, C. William Verity, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

Mechanical and Physical Properties of Coquina Stone from the Castillo de San Marcos National Monument

by Lawrence I. Knab and James R. Clifton
Center for Building Technology
National Bureau of Standards

1. Introduction

Castillo de San Marcos is located in St. Augustine, Florida, on the shore of Matanzas Bay, about a mile from the Atlantic Ocean. The Castillo is the oldest existing masonry fortress constructed with coquina stone. Its construction was started in 1672 and many modifications were made until its final deactivation as a fort in 1900. The outer walls of the structure were once covered with lime plaster[1*], most of which has been completely eroded. Gradually, the exposed surfaces of the exterior stone have weathered and some of the most severely deteriorated stone has been replaced. Several large vertical cracks have developed near the northwest and southwest corners which has caused concern regarding the possibility of structural problems.

The Castillo is exposed to seasonally heavy thunderstorms and seawater spray. Coquina is a porous stone which can be easily penetrated by water and, as a consequence, the walls of the Castillo are damp and in some areas efflorescence is observed. In addition, the terreplein (roof) has numerous cracks, and water appears to be able to penetrate the walls through the terreplein.

The National Park Service (NPS) has developed a preservation program for the Castillo which includes assessing the structural condition of the walls, identifying moisture migration patterns, and characterizing some of the important mechanical and physical properties of coquina stone. Knowledge of the mechanical and physical properties of coquina is needed to make decisions on the structural stability and integrity of the fort as well as its durability. Insufficient information, however, is available to make such decisions. The purpose of the work described in this report was to characterize some of the important mechanical and physical properties of coquina such as compressive and flexural strengths, dry density and water absorption.

2. Coquina Stone

Coquina stone was formed from cemented sea shells and shell fragments[2]. In the coquina stone samples investigated, the

* Raised numerals refer to references in section 6.

shells were incorporated into the stone in a fairly uniform bedding plane pattern (figure 1). This pattern resulted in the formation of a highly porous stone with high water absorption, low dry density, and low compressive strength (see Section 4).

3. Specimens, Preparation, and Testing Procedures

The coquina stone samples, which were air-freighted from Florida by the NPS to the National Bureau of Standards (NBS) in Gaithersburg, Maryland, consisted of (a) a nonhistoric piece not from the Castillo but from the vicinity of St. Augustine, Florida, which was roughly rectangular and measured 16x7x6 in; (b) several smaller nonhistoric fragments; and (c) a historic sample from the Castillo, which was an irregularly shaped piece with the longest dimension about 13 in. (In this report, "historic" refers to the coquina stone sample taken from the Castillo.) The exact location of the retrieval of the historic sample was described by the NPS as :

> "Castillo de San Marcos National Monument
> Southwest Bastion, north scarp (wall)
> Approximately 3 feet from corner and 4 feet from mean water line.
> Note: Water at this particular section of the moat is sea water which is subject to tidal effect; sample was retrieved from a structurally disturbed area where a crack runs north-south; one section of the stone cracked while in situ (which clearly suggests strong distresses prior to removal)."

From the large nonhistoric sample, 32 cubes were cut and tested in compression and 3 beams were cut and tested in flexure; from the historic sample, 24 cubes were cut and tested in compression and 2 beams were cut and tested in flexure. A diamond saw blade was used for cutting. The cubes were approximately 2 in on each side and the beams were approximately 2x2x6 in (beam span during testing was 4.68 in). The cubes were cut such that the bedding planes were approximately perpendicular to four of the cube faces and parallel to the other two faces (see Figure 1., ASTM C 170[3]). The beams were cut so that the bedding planes were approximately parallel to the top and bottom of the beam as tested - i.e. during flexural testing, the load was applied at the midspan of the beam and the direction of loading was perpendicular to the bedding planes. The cubes tested included two cubes cut from the two ends of each beam after the beam had been tested in flexure. (That is, there were 6 cubes taken from the 3 nonhistoric beams and 4 cubes taken from the 2 historic beams tested). Where possible[a], the compressive strengths were determined according to ASTM C 170[3]. Because of the friable and somewhat crumbly nature of the coquina stone, it was not possible to saw the opposite faces of cubes and beams to be parallel and flat - rather the cut faces were only approximately parallel and flat; the surfaces as sawn were used as bearing surfaces for compression testing - no sanding or grinding were performed. The cubes were selected at random from the historic and nonhistoric samples. For the compression cubes, the following test conditions were studied:

(a) Loaded perpendicular to the bedding planes - referred to as the "PER" loading direction; the PER loading direction was considered by the NPS to be the typical loading direction of the coquina stone at the Castillo de San Marcos National Monument

(b) Loaded parallel to the bedding planes - referred to as the "PAR" loading direction

(c) Dry (after drying at 105-108^{o}C for 22-24 h or, for a few cubes[b], drying at 48^{o}C to constant weight) - referred to as the "D" test condition (see below for a more detailed description of treatments performed on specimens)

(d) Wet (after immersing for 51-52 h in (i) distilled water at room temperature, or (ii) sea water, which was obtained from the vicinity of the Castillo, at room temperature) - referred to as the "WDIST" (distilled water immersion) or the "WSEA" (sea water immersion) test conditions.

All beams were tested dry at or near room temperature after they had been dried at 105-108^{o}C for 22-24 h.

Water absorption (percentage of dry weight) and bulk specific gravity[c] determinations were made on all cubes and beams prior to compression or flexural testing.

The absorption, bulk specific gravity, compression, and flexural tests were performed as follows. The beams and cubes were dried at 105[b]-108 degrees C for 24-26 h, soaked in distilled water for

---

[a] There were a number of variations. For example, in some cases the lateral dimension (distance between opposite vertical faces) was less than the required 2 in, but almost always exceeded 1.90 in; also in some cases, the ratio of the height to the lateral dimension was less than the required 1:1, but the ratio was almost always greater than or equal to 0.9:1 - see Section 6.1 of ASTM C 170[3].

[b] An exception was the drying of three cubes at 48^{o}C to constant weight - see table 2.

[c] Bulk specific gravity calculations were made according to Section 9 of ASTM C 97[4].

48-50 h at room temperature, then the absorption and bulk specific gravity values were measured according* to ASTM C 97[4]. The cubes and beams were further treated as follows: (a) cubes to be tested after immersion in distilled water were kept immersed in distilled water until just prior to testing in compression (the total immersion time was 51-52 h - just prior to compression testing, the cubes were removed from the water and their surface water removed); (b) cubes and beams to be tested dry were dried at 105-108°C for 22-24 h and tested in compression or flexure in their dry condition; (c) cubes to be tested after immersion in sea water were dried at 105-108°C for 22-24 h, immersed for 51 h in sea water at room temperature, then removed from the water and their surface water removed just prior to testing in compression; and (d) cubes which were cut from both ends of each beam after the beam was tested, were dried an additional 23-24h at 105-108°C prior to testing to remove any water absorbed during cutting the cubes from the beams.

All compression cubes were tested at or near room temperature using approximate load rates of either 1000-1200 lbf/min or 1600 lbf/min. Tables 1 and 2 give the loading and test conditions for the compression cubes. The beams were tested in flexure at or near room temperature using a deformation rate of 0.02 in/min (deformation applied by the testing machine to the beam at the beam centerline).

In addition to the bulk specific gravity measurements, approximate dry density determinations were made by dividing the oven dry weight of the cube by the approximate volume of the cube (based on the measured length x width x height of each cube).

4. Results and Data Analysis

Tables 1 and 2 give the compressive cube strength results for the historic and nonhistoric coquina stone samples respectively. Included are the absorption, bulk specific gravity, and dry density values for the respective compressive specimens. As shown in the tables, the data are divided into sets corresponding to the specific test conditions used in the compressive testing. For each set, the mean, standard deviation, and coefficient of variation ((standard deviation/mean) x 100) is given for the compressive strength. Table 3 presents the minimum and maximum values of the compressive strength (for the PER and PAR loading directions), absorption, bulk specific gravity, and dry density

---

* There were several variations, including weight measurements taken to the nearest 0.1 g rather than the required 0.02 g and absorption and bulk specific gravity measurements taken on the beams and the nonhistoric fragments, where the longest dimension (e.g. 6 in long beams) exceeded the required 3 in maximum dimension.

for the historic and nonhistoric samples. Also, the mean, standard deviation, and the coefficient of variation for the absorption, bulk specific gravity, and dry density data taken collectively for the historic (table 1) and nonhistoric (table 2) samples are given in table 3.

4.1 Compressive Strength and Flexural Strength

There was considerable variation (table 3) between the maximum and minimum compressive strength values for a given loading direction and stone sample (historic or nonhistoric) - for example, the value of the ratio of the maximum to minimum compressive strength was about 2 in the PER loading direction for the historic as well as the nonhistoric samples. Values of the coefficient of variation of the compressive strength data sets for the historic sample (table 1) ranged from 14.5 to 39.9 percent while the corresponding range for the nonhistoric sample (table 2) was from 4.6 to 21.8 percent.

Crushing and, in some cases, bulging was evident during compression testing of the cubes.

The strongest effect on the compressive strength for the test conditions studied was that of the direction of loading relative to the bedding planes ("PER" and "PAR"). Table 4 shows four comparisons of the PER and PAR loading directions, with each comparison consisting of two data sets taken from tables 1 and 2. Included in table 4 are values of the ratio of the mean compressive strength of the PAR loading direction to that of the PER loading direction. The range of the values of this ratio was 1.90 to 2.82. Values* of the "t" statistic and the corresponding cumulative distribution function (t_{cdf}) are shown[5,6]. In this report, only two-tailed "t" tests for comparing the means are provided (i.e., the null hypothesis was that the means of the two samples being tested were equal and the alternative hypothesis was that the two means were not equal). Values of t_{cdf} of 0.95 and greater for positive "t" values and 0.05 and less for negative "t" values were considered to be statistically significant in this report and correspond to a two-tailed test with a 0.10

---

* For unequal sample sizes, an "F" test (reference 5, page 4-8) of the equality of the variances was performed. If the calculated cumulative distribution function was equal to or greater than 0.95, then it was considered that the variances were not equal and the Behrens-Fisher test (reference 6, page 235) was used to compute the "t" and t_{cdf} values; otherwise the "t" test which assumes equal variances was used (reference 5, page 3-23) to compute the "t" and t_{cdf} values. For all cases of equal sample sizes, the "t" test which assumes equal variances was used to calculate "t" and t_{cdf} values. These procedures were used for all "t" and t_{cdf} calculations in this report.

level of significance. In this report, the "t" and t_{cdf} values based on small sample sizes (e.g., n = 3 to 6, as in tables 4 and 5) were considered approximate. The "t" and t_{cdf} values, however, were considered meaningful in analyzing the data. As the t_{cdf} values in table 4 show, the difference between the two loading directions was considered significant in three of the four comparisons and was fairly close to being significant (i.e., t_{cdf} = 0.089 instead of less than or equal to 0.05) in the remaining case. If it is assumed that there was no difference in compressive strength between immersion in distilled water and sea water (see below), then Sets H-2 and H-5 (table 1) provide additional support that there was an increase in compressive strength in the PAR as compared to the PER loading direction (ratio of the mean compressive strength of the PAR to that of the PER loading direction was 2.58; the "t" and t_{cdf} values for comparing the means were -3.78 and 0.032 respectively). The increase in compressive strength in the PAR as compared to the PER loading direction is evident in figure 2, where the various data sets in tables 1 and 2 are plotted. Thus, figure 2 and the comparisons in table 4 strongly suggest that substantial increases in compressive strength occurred when testing in the PAR direction as compared to the PER direction for both the historic and nonhistoric samples.

Using a format similar to that of table 4, the effects of the condition of wetness on compressive strength are shown in table 5. Values of the ratio of the mean compressive strength of the dry (D) test condition to the wet (WDIST and WSEA) conditions ranged from 0.858 to 1.31, with 5 of the 6 comparisons having ratio values of 1.13 to 1.31. The "t" and t_{cdf} values show that, in two of the comparisons where the ratio values exceed 1, the difference between the means could be considered to be statistically significant. In these two cases, there appears to be a small increase in the compressive strength of coquina cubes tested dry as compared to wet. The effects of the condition of wetness are also evident in figure 2.

One comparison could be made with regard to the effect of immersion in distilled water (WDIST) as compared to sea water (WSEA): Set H-2 versus H-3 (table 1). The means (and the standard deviations) of the compressive strength for the two sets were almost the same, indicating that there was essentially no difference in compressive strength between immersion in distilled water as compared to sea water.

A comparison can be made with regard to the effect of loading rate by comparing sets NH-2a and NH-2b (table 2). The value of the ratio of the means of the compressive strength of the higher (1600 lbf/min) to lower (1000-1200 lbf/min) load rates was 1.16 and the "t" and t_{cdf} values were -1.50 and 0.083 respectively, indicating that the higher load rate may not have caused a change (increase) in the compressive strength. (It is noted that the cubes in Set NH-2b had three cycles of 22-26 h drying at 105-108°C prior to testing as compared to Set NH-2a, which had two cycles of drying - this extra drying cycle is not considered to have caused a substantial change in the compressive strength values in Set NH-2b*.) If it is assumed that there is no difference in compressive strength between immersion in distilled water and sea water (see previous paragraph), then the difference in mean compressive strengths between sets NH-3 and NH-4 is probably attributable to the effect of load rate. The value of the ratio of the mean compressive strength of the higher (1600 lbf/min) to lower (1000-1200 lbf/min) load rates was 1.18 and the "t" and t_{cdf} values were -1.98 and 0.040 respectively, suggesting that the increased load rate caused a small increase in the compressive strength. An increase in compressive strength with increasing rate of load application was not unexpected - for example, a similar trend has been documented for concrete[7,8]. It is also noted that the sea water immersion required an extra cycle of drying at 105-108°C as compared to immersion in distilled water - the extra drying is not considered to have substantially affected the compressive strength.

A comparison can be made with regard to the temperature used to dry the cubes. In Set NH-1 (table 2), the cubes had two cycles of drying to constant weight at 48°C as compared to set NH-2a which had two cycles of drying for 22-26 h at 105-108°C. The value of the ratio of the mean compressive strength of the lower temperature (48°C) drying to that of the higher temperature (105-108°C) drying was 1.19 and the "t" and t_{cdf} values were -1.43 and 0.098 respectively, indicating that drying temperature did not appear to have caused a significant change in compressive strength.

The variability of the coquina stone investigated was assessed by comparing the differences in compressive strength between the historic and nonhistoric samples: Set H-1 versus Set NH-2b and Set H-2 versus Set NH-4. The values of the ratio of the mean compressive strength of the historic to that of the nonhistoric samples were 1.47 and 1.44. Based on the corresponding "t" (-5.9, -3.1) and t_{cdf} (0.000049, 0.0075) values, the compressive strength of the historic sample was considered to be different (larger) than that of the nonhistoric sample. The differences in compressive strength between the historic and nonhistoric samples for the comparisons discussed are shown in figure 2.

---

* Similarly, there did not appear to be a substantial difference in compressive strength for the cubes in set H-1 (table 1) which had three drying cycles as compared to the cubes in set H-1 which had only two drying cycles.

Compressive strength did not appear to be strongly correllated with absorption or bulk specific gravity.

To give a preliminary indication of flexural strength, two beams were tested from the historic sample and two* from the nonhistoric sample - the beams and compression cubes were cut from the same samples. The flexural strengths (extreme fiber stress) for the historic sample were 153 and 182 psi (mean = 168 psi) and for the nonhistoric sample were 116 and 125 psi (mean = 120 psi). These flexural strengths correspond to subjecting the bottom beam "fibers" to tension and the top beam "fibers" to compression in directions parallel to the bedding planes. The value of the ratio of the mean flexural strength of the historic sample to that of the nonhistoric sample was 1.39, which was roughly similar to the corresponding values of 1.44 and 1.47 (see above) for the ratio of the mean compressive strength of the historic sample to that of the nonhistoric sample.

4.2 Absorption, Bulk Specific Gravity, and Dry Density

The percent absorption values ranged from 14.3 to 18.9 for the historic sample and from 16.0 to 20.9 for the nonhistoric sample (table 3). The difference between the maximum and minimum absorption values was about 5 percent for both the historic and nonhistoric samples.

The bulk specific gravity values ranged from 1.58 to 1.68 for the historic sample and from 1.54 to 1.64 for the nonhistoric sample (table 3). The difference between the maximum and minimum bulk specific gravity values was 0.10 for both the historic and nonhistoric samples. The dry density values ranged from 1.36 to 1.55 g/cm^3 for the historic sample and from 1.32 to 1.50 g/cm^3 for the nonhistoric sample.

The variability of the coquina stone with respect to its absorption, bulk specific gravity, and dry density properties was assessed as follows. The value of the ratio of the mean absorption value (table 3) of the historic sample to that of the nonhistoric sample was 1.10. Based on the corresponding "t" and t_{cdf} values (-5.6 and 4.1×10^{-7} respectively), the absorption of the historic

---

* Actually three nonhistoric beams were tested - due to testing machine difficulties the results of one beam could not be used.

sample was considered to be different than that of the nonhistoric sample. The value of the ratio of the mean bulk specific gravity value of the historic to that of the nonhistoric sample was 1.03. Based on the "t" and t_{cdf} values (-6.4 and 1 x 10^{-7} respectively), the bulk specific gravity of the historic sample was considered to be different than that of the nonhistoric sample. Similarly, the value of the ratio of the mean dry density of the historic sample to that of the nonhistoric sample was 1.05 and the dry density of the historic sample was considered to be different than that of the nonhistoric sample ("t" and t_{cdf} values of -6.1 and 1 x 10^{-7} respectively). In addition to the large nonhistoric sample (16x7x6 in), three smaller nonhistoric fragments were obtained from several nonhistoric coquina pieces. Preliminary absorption and bulk specific gravity determinations for the three fragments resulted in absorption values ranging from 10.6 to 12.2(percentage of dry weight) and bulk specific gravity values ranging from 1.91 to 1.96-substantially different from the corresponding values given in table 3. These preliminary data, combined with the differences discussed above in the absorption and bulk specific gravity values of the historic as compared to the nonhistoric samples given in table 3, demonstrate the large degree of variability found in the absorption and bulk specific gravity values for the coquina stone samples investigated. Additional evidence indicating variability in the different samples was the difference in the dry density between the historic and nonhistoric samples and the difference in compressive strength (and flexural strength) between the historic and nonhistoric stone samples.

5. Discussion and Significance of Results

The values of absorption (14-21, percentage of dry weight, table 3) of the coquina stone were extremely high relative to absorption values for concrete aggregates (about 0.2 to 4.5, percentage of dry weight[9]). Similarly, the dry density values (1.32 to 1.55 g/cm^3, table 3, values include voids) of the coquina samples were extremely low relative to density values for common building and monument stone (density in g/cm^3 of about 1.8 to 3.1, see reference 10). The high absorption and low dry density values of the coquina stone are consistent with its visibly evident porous structure. Relative to compressive strengths of common building and monument stone (minimum compressive strength of about 1000-2000 psi - based[10] on "0.1" kilobars uniaxial compressive strength), the values of the coquina compressive strengths were extremely low (72-413 psi, table 3). The compressive strength values of the coquina stone in the typical loading direction (PER - load directed perpendicular to the bedding planes) were the lowest, with many values below 100 psi (tables 1 and 2). The extremely low compressive strength values of the coquina stone are believed to be caused, at least in part, by the porous and friable nature of the coquina stone. The compressive strength values (tables 1,2,and 3) are preliminary because they are based on only two samples and only one of the samples was from the Castillo. Additional coquina stone samples need to be taken at the Castillo to better estimate the compressive strength of the coquina stone.

The extremely low coquina compressive strength values are reason for concern because of the very large difference in the compressive strength of the coquina stone relative to common building stone. The extremely low coquina compressive strength values need to be taken into account when analyzing the load bearing and structural capacity and the corresponding factor of safety of existing structural elements (walls, etc.) comprised of coquina stone. For example, assuming a dry density value (including voids, table 3) of 1.55 g/cm^3, the component of compressive stress due to the dead load of the coquina stone alone (effect of mortar between coquina blocks neglected) would be 0.67 psi per foot of height*. At the bottom of a 32 ft high wall (average height of exterior wall of the Castillo de San Marcos National Monument assumed to be 30 to 32 ft), the component of compressive stress due to the dead load of the coquina stone would be 32 x 0.67 psi = 22 psi. A similar calculation assuming that the coquina stone absorbs 20 percent water (based on its dry weight, table 3) results in a density value of 1.86 g/cm^3 (= 1.55 + (0.2 x 1.55)); the corresponding component of compressive stress due to the dead load of the coquina stone for a 32 ft high wall would be (1.86/1.55) x 22 psi = 26 psi. These dead load calculations are preliminary because : (a) they are based on only one sample of coquina stone from one location at the Castillo, and (b) as the results of this report have shown (see below), there was considerable variability in the physical properties of the coquina stone, including its absorption and density. Hence, additional coquina stone samples need to be taken (also see previous paragraph) at the Castillo to better estimate the actual absorption, density, and corresponding dead load of the coquina stone. The calculations, however, illustrate that the computed dead load stresses (22 to 26 psi) are substantial when compared to the compressive strength values for the typical loading direction (72 to 175 psi, table 3). Any additional loads (other dead load, live load, wind load, buoyancy, etc.) and other factors (mortar joints, taper or tilt of wall, etc.) would also need to be taken into account in the structural analysis and in establishing the actual stress levels.

The wide range in the absorption and bulk specific gravity values in the three samples of coquina investigated (table 1, historic; table 2, nonhistoric; and additional nonhistoric fragments) clearly indicate the large variability in the coquina stone investigated. Additional evidence indicating variability in the different samples was the difference in the dry density between the historic and nonhistoric samples, and also the difference in compressive strength (and flexural strength) between the historic and nonhistoric stone samples.

---

* That is, (1.55 x 62.4 lb/ft^3) x 1 ft = 96.7 lb/ft^2 which is equivalent to 0.67 lb/in^2 per foot of height.

For both the historic and nonhistoric coquina stone samples, the compressive strength appeared to be substantially higher when the stone was loaded parallel (176-413 psi - table 3 and figure 2) to its bedding planes as compared to when the stone was loaded perpendicular (72-175 psi -table 3 and figure 2) to its bedding planes. The reason for this difference in strength due to loading direction is not known.

The creep characteristics of coquina stone, which could result in substantial and unwanted deformations, need to be investigated. Creep should be measured at anticipated stress levels, moisture conditions, temperatures, and at the anticipated loading direction relative to the bedding planes. The unusally low compressive strength of coquina stone may intensify the potential problem of creep.

The effects of long term water immersion on the strength of coquina stone also need to be investigated. Similarly, the effects of wetting and drying cycles on the strength of coquina stone need to be investigated. The conditions used in the immersion and wetting-drying tests should simulate the Castillo environment (e.g., temperature, water type (rain water, sea water, ground water, etc.) as well as tidal action); reference 11, for example, provides information on factors affecting the dissolution of calcium carbonate.

Acknowledgements

This work was funded by the National Park Service, Southeast Region, Historic Architecture Division. The authors appreciate the statistical consultation provided by Dr. James J. Filliben of the NBS Center for Applied Mathematics. They also acknowledge the assistance of Mr. David Savage in the water absorption and bulk specific gravity determinations and Mr. Nat Waters in the preparation and testing of the test specimens.

6. References

1. Rands, D.G., Davis, S.D., and Arana, L.R., "Chemical and Biological Processes in Coquina of Castillo de San Marcos National Monument," Schweiz. Z. Hydrol. 46/1, 109-116, 1984.

2. Schmidt, W. et.al., "Report of Investigation NO.88, The Limestone, Dolomite and Coquina Resources of Florida," Bureau of Geology, Florida Department of Natural Resources, Tallahassee FL, 1979.

3. ASTM "Standard Test Method for Compressive Strength of Natural Building Stone," ASTM C 170 - 85, Annual Book of ASTM Standards, Volume 04.08, Philadelphia PA, 1986.

4. ASTM "Standard Test Methods for Absorption and Bulk Specific Gravity of Natural Building Stone," ASTM C 97 - 83, Annual Book of ASTM Standards, Volume 04.08, Philadelphia, PA, 1986.

5. Natrella, M.G., "Experimental Statistics," National Bureau of Standards Handbook 91, National Bureau of Standards, Gaithersburg, MD, 1963.

6. Brownlee,K.A., Statistical Theory and Methodolgy in Science and Engineering, John Wiley and Sons, Inc., New York,NY, 1960.

7. Neville,A.M., ACI, Hardened Concrete: Physical and Mechanical Aspects, Monograph No. 6, American Concrete Institute, Detroit, MI, and The Iowa State University Press, Ames,IA, ch. 4, pp. 33-35.

8. Mindess, S. and Young, J.F., Concrete, Prentice-Hall Inc., Englewood Cliffs, NJ, 1981,pp.421-422.

9. Neville,A.M., Properties of Concrete, John Wiley and Sons, Inc.,New York, NY, Second Edition, 1973, Table 3-11, p. 126.

10. Robertson, E.C., "Physical Properties of Building Stone," Conservation of Historic Stone Buildings and Monuments, National Academy Press, Washington D.C., 1982, pp.62-86.

11. Friedman, G.M. and Sanders, J.E., Principles of Sedimentology, John Wiley and Sons, Inc., New York, NY, 1978.

Table 1. Compressive Strength, Absorption, Bulk Specific Gravity, and Dry Density Values for the Historic Coquina Stone Cubes

Set	Compressive Strength						Absorption (%)	Bulk[e] Specific Gravity	Dry[e] Density (g/cm^3)
	Test Conditions[a]		Cube Data (psi)	Mean (psi)	s.d.[b] (psi)	cov[b] (%)			
H-1	D,PER	1.1	149				18.7	1.59	1.44
		1.1	130				15.4	1.65	1.42
		1.1	148				15.2	1.67	1.51
		1.1	103				18.9	1.58	1.37
		1.1	165				17.2	1.63	1.49
		1.1	170[c]				16.9	1.63	1.53
		1.1	141[c]				17.4	1.61	1.46
		1.1	169[c]				17.4	1.61	1.46
		1.1	146[c]	147	21.2	14.5	16.9	1.63	1.53
H-2	WSEA,PER	1.1	146				16.3	1.65	1.47
		1.1	89				16.6	1.64	1.36
		1.1	132				16.9	1.63	1.51
		1.1	138	126	25.5	20.2	16.0	1.64	1.50
H-3	WDIST,PER	1.1	175				14.3	1.68	1.55
		1.1	120				17.8	1.60	1.37
		1.1	120				15.9	1.66	1.44
		1.1	109				17.5	1.62	1.47
		1.1	118	128	26.4	20.6	17.1	1.62	1.44
H-4	D,PAR	1.1	397				17.6	1.64	1.46
		1.1	176				16.7	1.63	1.44
		1.1	264	279	111	39.9	16.6	1.62	1.49
H-5	WDIST,PAR	1.1	236				16.0	1.65	1.47
		1.1	413				17.3	1.64	1.50
		1.1	327[d]	325	88.5	27.2	16.1	1.64	1.49

[a] D = tested after drying; PER = loaded perpendicular to bedding planes; PAR = loaded parallel to bedding planes; 1.1 = 1000-1200 lbf/min, approximate load rate; WDIST = tested wet after immersion in distilled water; WSEA = tested wet after immersion in sea water.

[b] s.d. = standard deviation; cov = (standard deviation/mean)x100

[c] Cubes cut from beam ends after beams were tested in flexure.

[d] The load rate was approximately 1100 lbf/min up to about 80 percent of the failure load, then the load rate was increased to approximately 11000 lbf/min and maintained at that rate to failure.

[e] Bulk specific gravity determined according to ASTM C 97(there were several variations - see text); dry density determined by dividing the oven dry weight of a cube by its measured (length x width x height) approximate volume.

Table 2. Compressive Strength, Absorption, Bulk Specific Gravity and Dry Density Values for the Nonhistoric Coquina Stone Cubes

Set	Compressive Strength: Test Conditions[a]		Cube Data (psi)	Mean (psi)	s.d.[b] (psi)	cov[b] (%)	Absorption (%)	Bulk[e] Specific Gravity	Dry[e] Density (g/cm^3)
NH-1	D,PER	1.6	131[c]				16.0	1.64	1.38
		1.6	136[c]				18.2	1.60	1.40
		1.6	148[c]	138	8.7	6.3	17.6	1.60	1.36
NH-2a	D,PER	1.6	82				20.1	1.56	1.37
		1.6	90				18.3	1.58	1.32
		1.6	119				17.5	1.62	1.41
		1.6	129				18.0	1.61	1.38
		1.6	129				17.5	1.62	1.39
		1.6	148	116	25.3	21.8	18.4	1.61	1.40
NH-2b	D,PER	1.1	89[d]				18.0	1.60	1.43
		1.1	105[d]				19.9	1.59	1.43
		1.1	90[d]				20.9	1.54	1.36
		1.1	108[d]				18.0	1.60	1.43
		1.1	108[d]				19.9	1.59	1.43
		1.1	99[d]	100	8.7	8.7	20.9	1.54	1.36
NH-3	WDIST,PER	1.6	111				18.9	1.55	1.40
		1.6	90				18.5	1.61	1.37
		1.6	116				18.7	1.60	1.42
		1.6	99				18.1	1.61	1.35
		1.6	99	103	10.4	10.1	Values missing		1.37
NH-4	WSEA,PER	1.1	107				Values missing		1.42
		1.1	72				18.0	1.60	1.41
		1.1	102				17.9	1.58	1.38
		1.1	89				18.5	1.60	1.40
		1.1	82				20.4	1.55	1.32
		1.1	72	87.3	14.9	17.0	18.2	1.57	1.37
NH-5	D,PAR	1.6	301				20.1	1.59	1.39
		1.6	388				17.5	1.62	1.45
		1.6	293	327	52.7	16.1	18.7	1.59	1.36
NH-6	WDIST,PAR	1.6	243				16.2	1.58	1.50
		1.6	263				17.8	1.59	1.42
		1.6	243	250	11.5	4.6	19.6	1.58	1.42

[a] D = tested after drying; PER = loaded perpendicular to bedding planes; PAR = loaded parallel to bedding planes; 1.1 = 1000-1200 lbf/min and 1.6 = 1600 lbf/min, approximate load rates; WDIST = tested wet after immersion in distilled water; WSEA = tested wet after immersion in sea water.

[b] s.d. = standard deviation; cov = (standard deviation/mean)x100

[c] Prior to absorption and bulk specific gravity determinations, cubes were dried at 48 °C to constant weight and soaked in distilled water at room temperature for 48-50 h. Prior to compression testing, the cubes were again dried at 48 °C to constant weight. This is in contrast to the 105-108 °C drying temperature used for all other cubes (see text for further details).

[d] Cubes cut from beam ends after beams were tested in flexure.

[e] Bulk specific gravity determined according to ASTM C 97(there were several variations - see text); dry density determined by dividing the oven dry weight of a cube by its measured (length x width x height) approximate volume.

Table 3. Summary Statistics for Compressive Strength, Absorption, Bulk Specific Gravity, and Dry Density for Historic and Nonhistoric Samples - Based on All Values in Tables 1 and 2.

	Compressive Strength (psi) PER[a]		Compressive Strength (psi) PAR[a]		Absorption (%)					Bulk Specific Gravity[c] (Dry Density[c] g/cm^3)				
	Min	Max	Min	Max	Min	Max	Mean	s.d.[b]	cov[b] (%)	Min	Max	Mean	s.d.[b]	cov[b]
Historic Sample (table 1)	89	175	176	413	14.3	18.9	16.8	1.03	6.2	1.58 (1.36)	1.68 (1.55)	1.63 (1.47)	0.023 (0.050)	1.4 (3.4)
Nonhistoric Sample (table 2)	72	148	243	388	16.0	20.9	18.5	1.22	6.6	1.54 (1.32)	1.64 (1.50)	1.59 (1.39)	0.024 (0.037)	1.5 (2.7)

[a] PER = loaded perpendicular to bedding planes; PAR = loaded parallel to bedding planes. See tables 1 and 2 for definitions of other related test conditions.

[b] s.d. = standard deviation, cov = coefficient of variation = (standard deviation/mean) x 100.

[c] Bulk specific gravity determined according to ASTM C 97(there were several variations- see text); dry density determined by dividing the oven dry cube weight by its measured (length x width x height) approximate volume.

Table 4. Comparisons of the Effect of Direction of Applied Load on Compressive Strength: Load Applied Perpendicular ("PER") as Compared to Parallel ("PAR") to Bedding Planes.

Set No.*	Compressive Strength** n	mean (psi)	s.d. (psi)	Test Conditions	mean of "PAR" strength / mean of "PER" strength	t***	t_{cdf}***
H-4	3	279	111.	D,PAR,1.1			
H-1	9	147	21.2	D,PER,1.1	1.90	-2.0	8.9×10^{-2}
H-5	3	325	88.5	WDIST,PAR,1.1			
H-3	5	128	26.4	WDIST,PER,1.1	2.54	-3.8	3.2×10^{-2}
NH-5	3	327	52.7	D,PAR,1.6			
NH-2a	6	116	25.3	D,PER,1.6	2.82	-8.4	3.2×10^{-5}
NH-6	3	250	11.5	WDIST,PAR,1.6			
NH-3	5	103	10.4	WDIST,PER,1.6	2.43	-18.6	8.0×10^{-7}

* H = historic stone sample; NH = nonhistoric stone sample - see tables 1 and 2

** n = number of replicates; s.d. = standard deviation; D = tested after drying; PER = loaded perpendicular to bedding planes; PAR = loaded parallel to bedding planes; 1.1 = 1000-1200 lbf/min and 1.6 = 1600 lbf/min, approximate load rates; WDIST = tested wet after immersion in distilled water; WSEA = tested wet after immersion in sea water.

*** t and t_{cdf} are the "t" statistic and corresponding cumulative distribution function, respectively - see related footnote in Section 4.1. For ease of comparing the t_{cdf} values, all "t" values were taken to be negative.

Table 5. Comparisons of the Effect of Condition of Wetness on Compressive Strength: Dry("D")as Compared to Immersed Prior to Testing in Distilled Water ("WDIST") or Sea Water ("WSEA")

Set No.*	n	Compressive Strength** mean (psi)	s.d. (psi)	Test Conditions	mean of "D" / mean of "WDIST" or "WSEA"	t***	t_{cdf}***
H-1	9	147	21.2	D,PER,1.1			
H-2	4	126	25.5	WSEA,PER,1.1	1.17	-1.5	7.8×10^{-2}
H-1	9	147	21.2	D,PER,1.1			
H-3	5	128	26.4	WDIST,PER,1.1	1.15	-1.4	9.0×10^{-2}
H-4	3	279	111.	D,PAR,1.1			
H-5	3	325	88.5	WDIST,PAR,1.1	0.858	-0.56	3.0×10^{-1}
NH-2a	6	116	25.3	D,PER,1.6			
NH-3	5	103	10.4	WDIST,PER,1.6	1.13	-1.1	1.5×10^{-1}
NH-2b	6	100	8.7	D,PER,1.1			
NH-4	6	87.3	14.9	WSEA,PER,1.1	1.14	-1.8	5.3×10^{-2}
NH-5	3	327	52.7	D,PAR,1.6			
NH-6	3	250	11.5	WDIST,PAR,1.6	1.31	-2.5	3.4×10^{-2}

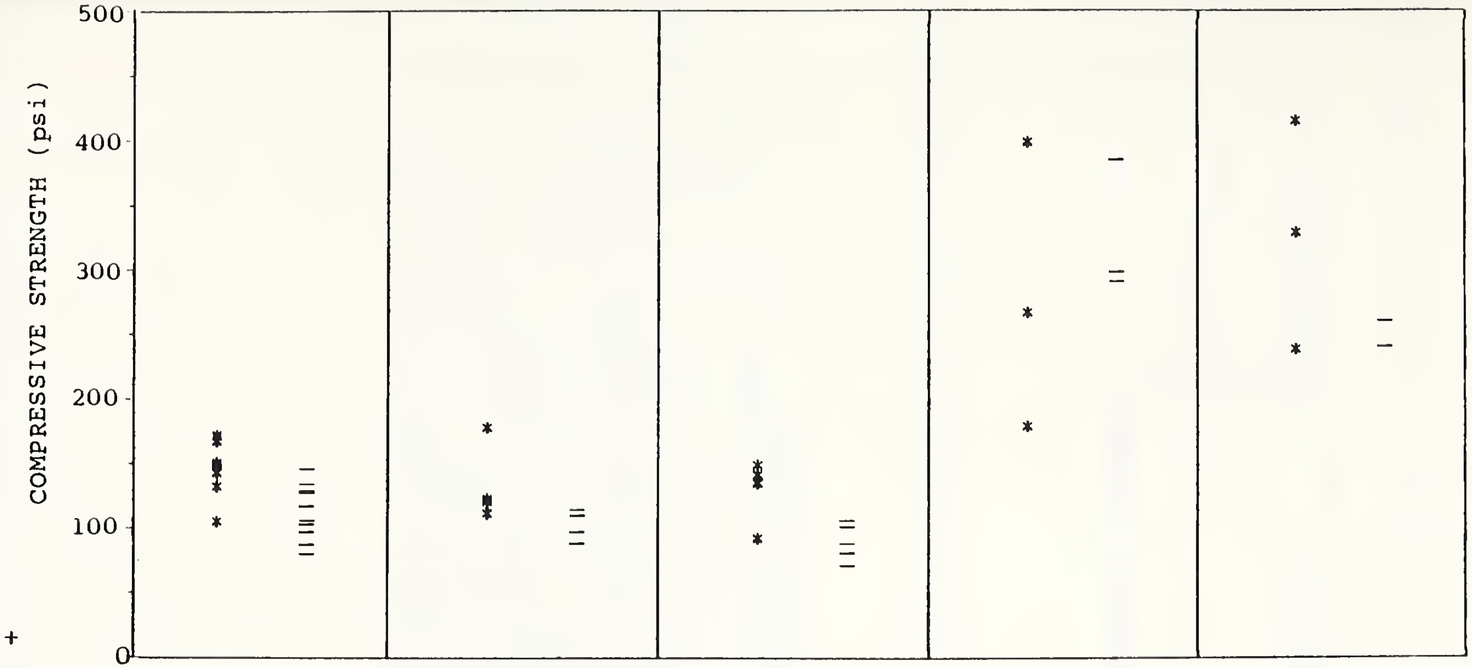
* H = historic stone sample; NH = nonhistoric stone sample - see tables 1 and 2.

** n = number of replicates; s.d. = standard deviation; D = tested after drying; PER = loaded perpendicular to bedding planes; PAR = loaded parallel to bedding planes; 1.1 = loaded 1000-1200 lbf/min and 1.6 = 1600 lbf/min, approximate load rates; WDIST = tested wet after immersion in distilled water; WSEA = tested wet after immersion in sea water.

*** t and t_{cdf} are the "t" statistic and corresponding cumulative distribution function, respectively, - see related footnote in Section 4.1. For ease of comparing the t_{cdf} values, all "t" values were taken to be negative.

(a) (b)

Figure 1. Coquina stone from Castillo de San Marcos



Test Conditions+										
Condition of Wetness	D	D	WDIST	WDIST	WSEA	WSEA	D	D	WDIST	WDIST
Loading Direction	PER	PER	PER	PER	PER	PER	PAR	PAR	PAR	PAR
Loading Rate	1.1	1.1 or 1.6	1.1	1.6	1.1	1.1	1.1	1.6	1.1	1.6
SET NOS. (Tables 1,2)	H-1	NH-1++ NH-2a NH-2b	H-3	NH-3	H-2	NH-4	H-4	NH-5	H-5	NH-6

+ D = tested after drying; PER = loaded perpendicular to bedding planes; PAR = loaded parallel to bedding planes; 1.1 = 1000-1200 lbf/min and 1.6 = 1600 lbf/min, approximate load rates; WDIST = tested wet after immersion in distilled water; WSEA = tested wet after immersion in sea water; H = historic stone sample; NH = nonhistoric stone sample.

++ Set NH-1 was dried at 48°C as compared to all other sets which were dried at 105-108°C (see text and table 2).

Figure 2. Cube compressive strength data plotted for the data sets shown in tables 1 and 2 ("*" = historic stone sample, "-" = nonhistoric stone sample).

NBS-114A (REV. 2-8C)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET *(See instructions)*	1. PUBLICATION OR REPORT NO.	2. Performing Organ. Report No.	3. Publication Date
	NBSIR 88-3714		JANUARY 1988

4. TITLE AND SUBTITLE

Mechanical and Physical Properties of Coquina Stone from the Castillo de San Marcos National Monument

5. AUTHOR(S)

Lawrence I. Knab and James R. Clifton

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

NATIONAL BUREAU OF STANDARDS
U.S. DEPARTMENT OF COMMERCE
GAITHERSBURG, MD 20899

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

National Park Service
Historic Architecture Division
1980 Island Ford Parkway
Dunwoody, Georgia 30350

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Some important mechanical and physical properties of coquina stone, which was used to construct the Castillo de San Marcos National Monument, were determined to aid in the condition assessment of the monument. Mechanical properties determined included compressive strengths under several different testing conditions, including testing wet as compared to dry, and the direction of the applied load relative to the bedding plane orientation. Physical properties determined included water absorption and dry density. The results indicated that the coquina stone has an extremely low compressive strength relative to common building stone. The low compressive strength was believed to be caused, at least in part, by the friable and very porous nature of the coquina stone.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Castillo de San Marcos; compressive strength; coquina stone; dry density; mechanical properties; physical properties; water absorption

13. AVAILABILITY

[X] Unlimited
☐ For Official Distribution. Do Not Release to NTIS
☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.
[X] Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

22

15. Price

$9.95