US Department of the Interior
National Park Service
National Center for
Preservation Technology and Training
Publication No. 1999-02

# Project Report

# Nondestructive Method for Hardness Evaluation of Mortars

---

Prepared by:

Rocky Mountain Masonry Institute
1780 South Bellaire Suite 402
Denver, CO 80222

University of Colorado at Denver
Department of Civil Engineering
Campus Box 113 • P.O. Box 173364
Denver, CO 80217-3364

Atkinson-Noland & Associates
2619 Spruce Street
Boulder, CO 80302
303-444-3620

Prepared for:

National Center for Preservation Technology and Training
United States Department of the Interior
National Park Service
P.O. Box 37127
Washington, D.C. 20013-7127

Funded by:
Grant Agreement No. MT-2210-7-NC-013

Funding for this report was provided by the National Park Services National Center for Preservation Technology and Training. NCPTT promotes and enhances the preservation of prehistoric and historic resources in the United States for present and future generations through the advancement and dissemination of preservation technology and training.

NCPTT's Preservation Technology and Training Grants program develops partners in non-profit organizations, universities and government agencies throughout the United States to complete critical research, training, and information management work, and lends significant support to developments in the conservation and preservation community.

This publication was developed with funds from the Preservation Technology and Training Grants program. Its contents are solely of official position or policies of the National Park Service or the National Center for Preservation Technology and Training.

## EXECUTIVE SUMMARY


The objective of this study was to develop a test method to measure the hardness of masonry mortars with a pendulum hammer. The results of this test method are to be used as an aid in the selection of pointing mortars and for the evaluation and quality control of in-place mortars. Eight mortar formulations were investigated in the laboratory. These tests included measures of the plastic properties of the mortars, the compressive strength, and the water vapor transmission. The laboratory tests were conducted in accordance with American Society for Testing and Materials (ASTM) standard test procedures where appropriate. Masonry piers for pendulum hammer hardness testing were built using the same eight mortar formulations. One set of piers was constructed using reclaimed masonry units and historic construction techniques to simulate old masonry in a controlled environment. Other piers were constructed using modem materials. The results of mortar hardness measurements from these piers were compared to the properties determined in the laboratory testing program.

Field tests were conducted on historic masonry structures in Colorado and across the United States. The experience gained from the field testing and the results of the laboratory comparisons were used to develop a test method for hardness determination using the pendulum hammer. This method includes guidelines for use of the equipment and provides a method for obtaining statistically significant results. A standard test method for this technique has been drafted and submitted to ASTM for consideration as a new standard.

A literature review was performed focusing on existing techniques of evaluating historic and modem mortars, including hardness testing, penetration and pullout techniques, drilling resistance, and chemical testing.

Impact heads were machined in a range of lengths for the purpose of testing mortar at depth.

The results reported herein indicate that the results of pendulum hammer testing correlate well to the mortar type and compressive strength. The hardness results do not correlate well with the results of the water vapor transmission tests nor with the mortar plastic properties. The correlation with compressive strength, economy, and the ease of use of the device make the pendulum hammer a practical device to aid in the evaluation of in-place mortar. Drawbacks to the use of the device include the need for frequent calibration and maintenance.

# TABLE OF CONTENTS

# 1.0 INTRODUCTION

## 1.1 Background

Most masonry preservation projects include some degree of pointing work to repair deteriorated mortars, yet there is no standard methodology for in-place evaluation of masonry mortars or qualification of repair mortars following repointing. The current state of practice is to use chemical and petrographic testing to determine mortar composition. Although these procedures work well, the time and expense required for chemical and petrographic testing usually limit the investigation to only a few samples. Many masonry preservation projects have failed where inappropriate mortars were specified and used for pointing. For example, the use of a stiff repointing mortar can cause brick spalling and durability problems. Hence a need exists for a simple, preferably nondestructive, technique to evaluate hardness of in-place mortars.

## 1.2 Purpose

The objective of this research program was to develop a method for the use of the Schmidt Type PM pendulum hammer to evaluate and characterize in-place masonry mortars. The method is intended to be used as an aid in the selection of pointing mortar, for quality control of new construction, and for general nondestructive evaluation of in-place mortar.

## 1.3 Scope

Mortar properties were investigated and compared to rebound hardness data. These properties include mortar compressive strength, masonry unit compressive strength, water vapor transmission, and mortar plastic properties. Eight different mortar formulations were investigated, including seven mortars containing different ratios of lime to cement as the binder, and one mortar using hydraulic lime as the binder. Pendulum hammer rebound data collected from laboratory test piers was analyzed in order to develop a test methodology that provides statistically significant results. The rebound data was then compared to the mortar properties to determine whether or not the rebound data could be used as an indicator of those mortar properties. A set of field trials were conducted on historic structures in Colorado and across the United States to compare the results of pendulum hammer testing with other evaluation methods and to develop guidelines for field use of the device. The experience gained from the field testing and the results of the laboratory comparisons were used to develop a test method for hardness determination with the pendulum hammer. This method includes guidelines for use of the equipment and provides a method for obtaining statistically significant results. A standard test method for this technique has been drafted and is included in Appendix A.

# 2.0 LITERATURE REVIEW

## 2.1 Mortar History

Masonry mortars of lime, sand, and water were used as early as 2450 BC (Speweik, 1997). The slaking of lime was well known to Roman culture by the time of Vitruvius (20 AD). Vitruvius gives mortar recipes in his "Ten Books of Architecture" that describe the state of the art in mortars until the introduction of Portland cement in the 1870's (Sickels-Taves, 1997). The formulation of mortar with lime and sand was most likely passed from Greece to Italy, where the practice was refined and used in brick and tile construction (Blake, 1947). The Romans had easy access to natural deposits of pozzolana, a volcanic product containing silica and alumina, which further strengthened their mortars (Blake, 1947).

Since about 1870, mortars have been made from various combinations of lime, Portland cement, and sand. Buildings constructed in the United States from 1870 to 1930 contain mortars of various ratios of lime and cement, but after 1930 one part lime putty to one part Portland cement was the most common mix (Speweik, 1997). In 1954 a mortar classification scheme was introduced to distinguish between mortars of different mix proportions and strength. The letters M, S, N, O, K (from MaSoNwOrK), distinguish the five mortar types.

Table 2.1. Mortar Classification Chart (developed from ASTM C 270, *Standard Specification for Mortar for Unit Masonry).*

| *Mortar Type* | *Proportion by volume* | | | *Compressive Strength* | |
|---|---|---|---|---|---|
| | | | | *Minimum* | *Typical** |
| | *Cement* | *Lime* | *Sand* | *psi* | *psi* |
| M | 1 | 1/4 | 2¼ to 3 times | 2500 | 6400 |
| S | 1 | 1/2 | the sum of the | 1800 | 3625 |
| N | 1 | 1 | volumes of | 750 | 1850 |
| O | 1 | 2 | cement and | 350 | 540 |
| K | 1 | 3 | lime | 75 | 190 |

*Typical strengths are from Frey, 1975, for mortars prepared and tested in the laboratory per ASTM C 27O.

## 2.2 The Chemistry of Mortars

### 2.2.1 Chemistry of lime mortars

Traditional lime mortars are manufactured by burning limestone or other material containing calcium carbonate to produce quicklime, and then slaking the quicklime to produce lime putty or dry hydrated lime. Quicklime is made by heating calcium carbonate to over 850 degrees Celsius. At this temperature, the heat drives off carbon dioxide from calcium carbonate leaving calcium oxide:

$$\underset{\text{(Calcium Carbonate)}}{CaCO_3} + \text{Heat } (850°C) \longrightarrow \underset{\text{(Calcium Oxide)}}{CaO} + \underset{\text{(Carbon Dioxide)}}{CO_2 \text{ (gas)}}$$

The calcium oxide, or quicklime, is then slaked with water. Slaking is an exothermic reaction of water and quicklime that produces calcium hydroxide, referred to as lime putty or dry hydrated lime depending on whether the end product is dry or left in excess water.

$$\underset{\text{(Calcium Oxide)}}{CaO} + H_2O \longrightarrow \underset{\text{(Calcium Hydroxide)}}{Ca(OH)_2} + \text{Heat}$$

Lime putty is traditionally sieved and left to mature in a pit or box for 2 weeks to one year. During this maturation process, the slaking reaction continues and the particles of the putty will decrease in size, resulting in a higher quality material (Gibbons, *1995)*. The lime putty is then mixed with sand at the site prior to use. The mortar then hardens as it reacts with carbon dioxide from the atmosphere to reform the original limestone component, calcium carbonate.

$$\underset{\text{(Calcium Hydroxide)}}{Ca(OH)_2} + \underset{\text{(Carbon Dioxide)}}{CO_2} \longrightarrow \underset{\text{(Calcium Carbonate)}}{CaCO_3} + H_2O$$

2.2.2 Hydraulic and non-hydraulic mortars

The reactions discussed in section 2.2.1 describe non-hydraulic mortar, as distinguished from mortar containing hydraulic cements. Hydraulic cements harden by incorporating water into the molecular structure of the cement. Portland cement, derived from firing alumina silicate (clay) with calcium carbonate (limestone), is an example of an hydraulic cement. Roman pozzolana, similar to Portland cement in that it contains alumina and silica, also provides hydraulic qualities to mortar (Blake, 1947). Lime can also have hydraulic properties when it is made from argillaceous, or clayey, limestone. These hydraulic limes are further classified as feebly, moderately, and eminently hydraulic limes (Gibbons, *1995)*. Hydraulic mortars have the advantage of faster hardening and the ability to set under water.

2.3 Problems with Repointing Historic Masonry

Historic masonry structures require periodic pointing as mortars decay. In older structures built with soft mortar, the mortar is intended to be a sacrificial material, relieving brick stresses by absorbing movement and protecting the bricks from water by providing a path for the movement of moisture (Speweik, 1997). A mortar that plays this sacrificial role for the bricks of a building will wear out in time, typically in about fifty years. The exposed face of the mortar will recede, especially when the mortar is exposed to frequent wetting and drying cycles (Williams, 1979).

The repointing of masonry consists of removing the mortar in a wall to some depth, typically the outer three-quarters of an inch to one and a half inches, and replacing it with fresh mortar. Historic preservationists strive to match the color, ingredients, and material properties of the original mortar when repointing historic structures (Williams, 1979; Sickels-Taves, 1997).

### 2.3.1 Mortar stiffness

Since the introduction of Portland cement, many structures have been damaged by the use of repointing mortars that are stronger and more dense than the original mortar. Flexible lime mortars of low elastic modulus allow for small movements in walls from settlement, temperature change, etc., whereas stiff, relatively inflexible mortars with high cement content force the masonry units to absorb this movement (Sickels-Taves, 1997). This rigid restraint can cause bricks and stones to crack and spall, particularly in older buildings with bricks of low strength (Williams, 1979). This effect is exacerbated in repointed masonry because the replacement of the original mortar is partial. Thus the bricks are supported by two materials of different strengths, resulting in stress concentrations.

### 2.3.2 Moisture migration

A further problem that can be caused by repointing with cement mortar is a change in the migration paths of water through masonry. Lime mortars are porous and allow moisture ingress and egress, while cement mortars are much less porous (Williams, 1979; Speweik, 1997). Non-porous mortars can force moisture transmission through bricks and thus cause the bricks to deteriorate rapidly (Gibbons, *1995)*. Figure 2.1 illustrates the migration of moisture in cement and lime mortar joints. Moisture transmission through bricks is also encouraged by cement mortars because cement mortars can shrink upon setting, and can thus leave spaces for water to penetrate a wall at the mortar-brick interface (Speweik, 1997).

### 2.3.3 Crystallization of soluble salts.

Mortars can also be damaged by the presence of soluble salts (Gibbons, *1995;* Duffy et al., 1993; Speweik, 1997). Cement mortars have higher levels of soluble salts naturally present in their components than do lime mortars (Duffy et al., 1993). Transfer of these salts to adjacent porous stones or bricks can result in damage as the salts crystallize (Gibbons, 1995). Salts from natural sources and pollution can also damage masonry. In coastal areas, windborne salts can contribute to the dissolution of calcium compounds. Crystallizing salts in the pores of masonry develop destructive pressures (van der Klugt, 1991).

## 2.4 Mortar Testing and Analysis

### 2.4.1 Relevant American standardized tests

There are standardized tests commonly used for the analysis of mortars prior to and during construction (American Society for Testing and Materials [ASTM] C 780, *Test Method for Preconstruction and Construction Evaluation of Mortars or Plain and Reinforced Unit Masonry)*, but there are no accepted American standards for the analysis of *in-situ* mortar. ASTM subcommittee E6.24 on Building Preservation and Rehabilitation Technology was formed in the 1980's to "develop standards in the technology of conservation, preservation and rehabilitation of buildings and structures (Kelly and Slaton, 1994)." The United States Secretary of the Interior's *Standards for Rehabilitation and Guidelines for Rehabilitating Historic Buildings* recommends that "old mortars be replaced with mixtures that match the original in strength, composition, color, and texture (Doebley and Spitzer, 1996)."

There are, however, tests that are related to *in-situ* mortar strength. The bond wrench test (ASTM C 1072, *Test Method for Measurement of Masonry Flexural Bond Strength)* uses a special wrench to test the bond strength of one masonry bed joint. This test has been modified for field use using a special clamping head. The in-place push test (Uniform Building Code [UBC] Standard Number 21-6) is used to test the shear resistance of one masonry unit by removing a brick and inserting a hydraulic piston. The head joint next to an adjacent brick is removed and a load vs. deflection test is performed. Figure 2.2 shows a schematic of this test. This test can also be performed by removing the head joints on either side of a brick and using a small flatjack in one of the empty joints to apply the load (Schuller and Suprenant, 1994).

There are tests available for the indirect *in-situ* determination of mortar compressive strength, but none of these are standardized in the United States. A discussion of these tests follows.

### 2.4.2 Tests for the indirect determination of *in-situ* mortar strength

*In-situ* tests that can be correlated to the strength of mortar include the pendulum hammer rebound test, the pull-out test, penetration tests, and drilling resistance tests. The results of these tests are correlated empirically to strength.

*The pendulum hammer rebound test*

The pendulum hammer rebound test uses a Schmidt type PM hammer to obtain a measure of the hardness of mortar. Figure 2.3 shows the pendulum hammer in use. A test method using the Schmidt hammer to evaluate mortar quality has been adopted as a suggested method by the International Union of Testing and Research Laboratories for Materials and Structures (acronym: RILEM), RILEM MS.D.7: *Determination of Pointing Hardness by Pendulum Hammer.* ASTM C 805, *Test Method for Rebound Number of Hardened Concrete,* offers a standard method for the evaluation of concrete using the higher energy spring loaded Schmidt hammers. The International Society for Rock Mechanics (ISRM) has adopted a method for using the Schmidt hammer to measure rock hardness, the *Suggested Method for Determination of the Schmidt Rebound Hardness.*

The RILEM method specifies that nine rebound readings are to be taken at different locations with the type PM pendulum hammer. Specifically, RILEM MS.D.7 states: "Perform nine measurements uniformly divided over the area to be judged, e.g. three times three measurements horizontally and vertically at one third from the boundaries of the area or the edges of the panel to be measured." The median of these readings is taken as the rebound value. Figure 2.4 shows a graphical interpretation of this method.

ASTM C 805 specifies that 10 individual hits are to be made in a test area, and the average of these (less the outliers) is taken as the rebound number. The test area is to be at least six inches in diameter, and the concrete is to be at least four inches thick and fixed within a structure. Figure 2.5 shows an example of the spacing of impact points for ASTM C 805. This method is intended to identify regions of poor quality or deteriorated concrete in a structure by testing several areas (ASTM C 805).

The ISRM method is to impact a rock sample at least 20 times. The impact locations are to be separated by at least the diameter of the plunger. The test surface is to be smooth and flat, and away from any local discontinuity or cracks in the rock. Small specimens are to be securely clamped to a rigid base. It is noted that the hammer should be calibrated using a calibration test anvil from the manufacturer. A correction factor is calculated as the specified standard value of the anvil divided by the average often readings on the calibration anvil. The rebound value of the rock is taken as the average of the upper 50% of the values obtained, multiplied by the correction factor (International Society of Rock Mechanics, 1978).

*Pull-out tests*

Pull-out tests involve measuring the load required to pull an anchor bolt or a helical tie out of a mortar joint. Figure 2.6 shows a schematic of a pull-out test. This test is also known as the helix test. The Building Research Establishment (BRE) of Britain has published a digest describing this screw pull out test, including the technical background, calibration, and interpretation of results (BRE Digest 421). Pilot holes at least thirty millimeters deep are drilled into the mortar at ten locations within a two meter square area. The holes are to be of the size to make an interference fit with the ties that have been selected. The helical ties are then tapped into the holes with a hammer. A proofloading device is attached to the tie, and the tie is loaded to failure. The peak load recorded during the test is the pullout load. The pullout load can be related to the mortar strength using a curve that correlates pullout loads to mortar cube strength, or used as means to compare the mortar of various regions of a structure. There are other pull-out tests for other sorts of masonry connectors, such as anchors and expansion bolts.

*Penetration tests*

Two types of penetration tests are common. The Windsor Penetrometer uses an explosive charge to propel a probe into a mortar joint (Grieve et al.). The probe penetration is measured and correlated to mortar cube compressive strength. Two probes are available for different ranges of compressive strength. A silver probe of 3/16 inch diameter is used for materials having a compressive strength in the range of 3000 to 5000 pounds per square inch. A gold probe of 5/16 inch diameter is used for materials of lower strength.

The Pin Penetration Resistance test (PPR) uses a spring-loaded rod to drive a steel pin into the test material. The pin diameter is 0.140 inches and it projects 0.3 inches beyond its holding rod. The pin strikes the test material and leaves an indentation. A depth gauge is used to measure the depth of penetration, which can be correlated to mortar compressive strength.

Recently, Italian researchers have developed a penetration test that uses the controlled impact energy of a Schmidt rebound hammer to drive a steel pin into mortar (Felicetti and Gattesco, 1998). A series of blows are used to drive the pin into the joint and the penetration depth is measured with each successive blow. This test is similar to the Standard Penetration Test that is commonly used for *in-situ* soil testing in the United States. Felicetti and Gattesco conducted an extensive laboratory study correlating the results of this test to the compressive strength of mortars. This test has the advantage of measuring the resistance of the mortar at many discrete depths, but does leave a hole in the mortar.

*Drilling resistance tests*

The drilling resistance test correlates the energy required to drill a hole of a certain depth to the strength of the mortar. One technique using this principle is the PNT-G penetrometric method (de Vekey and Sassu, 1997). This method uses a drill and an energy gauge manufactured and calibrated for this purpose.

Another drilling resistance test has been developed in Czechoslovakia by Vaclav Kucera. This test uses a hand turned impact drill that is held against the test material with a constant, measured force. The strength is taken as a function of the force, the number of turns, and the depth and diameter of the hole. A calibrating table is made from tests of mortars of known strength.

### 2.4.3 Evaluations and comparisons of *in-situ* mortar test methods

L.J.A.R van der Klugt of the Dutch organization *TNO Building and Construction Research* has adapted the Schmidt pendulum hammer to test the hardness of pointing mortar (van der Klugt, 1991).

The lightest Schmidt pendulum hammer was fitted with a 5 mm diameter shaft and impact head for mortar testing. The instrument was "equipped with an adjustable distance holder and a spirit level vial to keep it vertical" when testing the slanting masonry of a windmill. Many readings (usually nine) were taken on all test specimens, and rather than the average, the median of the readings was taken as the rebound number.

Tests were conducted on walls built in a laboratory with mortars of different formulations. Fourteen mortars were tested, ranging from 1:3 Portland cement to sand to 1:3 lime to sand. The hardness of these mortars was measured weekly as the mortar cured.

Tests were conducted to compare the hardness of mortars that were dry to those which were saturated. The effect of three different brick types on the hardness number of the mortars was also investigated. Some qualitative results of interest include:

- Bed joints were stronger than head joints.
- Mortar hardness in walls built with molded bricks and those built with extruded bricks were equivalent. The same mortar in walls built with sand-lime bricks gave significantly lower rebound numbers.
- Mortar in walls which were kept damp during curing gave higher rebound numbers than mortar in walls which were kept dry.
- Mortar in walls which were measured when wet gave lower rebound numbers than when measured dry.

A classification table of rebound number as a function of mortar quality is offered. This table is shown in Table 2.2.

Table 2.2. Pointing hardness classification (from RILEM MS.D.7).

| **class** | **hardness** | **indicated quality** |
|---|---|---|
| 0 (zero) | <15 | very soft |
| A | 15-25 | soft |
| B | 25-3 5 | moderate |
| C | 3 5-45 | normal |
| D | 45-55 | hard |
| E | 55 | very hard |

Grieve, Marshall and Willoughby conducted a study comparing three types of mortar strength tests for the Ontario New Home Warranty Program (Grieve et al.). The Windsor Penetrometer test, the pendulum hammer rebound test, and the pin penetration resistance test were evaluated and compared. Each technique was used to test five different mortar mixes in laboratory test walls. The object was to find a simple, *in-situ*, non-destructive method for the evaluation of mortar.

The Windsor Penetrometer was found to de difficult to use, unreliable, and dangerous for mortar testing. The Schmidt hammer was found to be convenient to use and to give reasonable results. However, the rebound numbers were found to be more affected by brick type than mortar mix proportions. Figure 2.7 shows the rebound numbers recorded for test walls of clay and calcite bricks. Notice that the values for the calcite bricks are consistently lower yet show the same trend for the different mortar mixes.

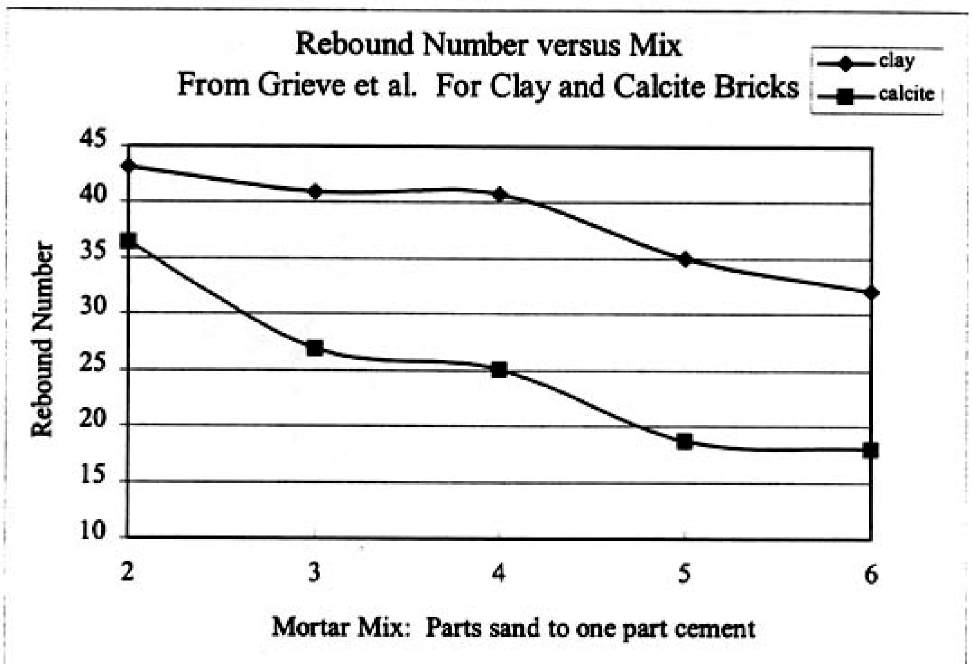



Figure 2.7. Rebound numbers from various mortar mixes in laboratory walls of clay bricks and calcite bricks (Grieve et al.).

The results were in agreement with the quality scale suggested by the RILEM standard MS.D.7: *Determination of Pointing Hardness by Pendulum Hammer.* Preparation of the mortar surface with a surface grinder to provide a flat striking surface provided more consistent results. The authors note that the main drawback to this test is that the striking head of the hammer is of a fixed length. The authors suggest that different impact heads would be useful. Mother drawback was the problem of accurately striking the surface of a curved joint. "Despite this drawback, the vast majority of mortar joints are accessible to this instrument and it should prove eminently suitable for site quality control and laboratory research (Grieve et al.)."

The Pin Penetration Resistance test was found to be simple to operate but required meticulous care in measuring the gap between the device and the mortar joint. Testing with this device was much slower than with the Schmidt Hammer. The results obtained with the PPR meter were similar to those of the Schmidt hammer in accuracy, and in that the test was more sensitive to brick type and joint tooling than to mortar mix proportions.

The Schmidt hammer and the PPR meter yielded good results on the test panels. The Schmidt hammer gave reasonable results but has the problem of not being able to test at various depths. The type PM hammer and the PPR meter test demonstrate that the absorption characteristics of bricks play a dominant role in the *in-situ* measurement of the mortar. Grieve et al. suggest that the calcite bricks did not adequately absorb the water in the mortar mix, resulting in significantly lower joint strengths.

De Vekey and Sassu compared the PNT-G drilling resistance method and the Helix screw pullout methods for the determination of the compressive strength of masonry mortars (De Vekey and Sassu, 1997). The researchers statistically correlated the results of these two methods to results of mortar cube compression tests. The PNT-G penetrometer was found to give good results for weak and very weak mortars. The Helix pull-out test gave the best results for medium and strong mortars. Neither method yielded good results for very strong mortars. De Vekey and Sassu conclude that both of these tests give more reliable and accurate values for mortar strength than other techniques such as the Windsor Penetrometer, the Schmidt hammer, and strength estimates based on chemical analysis.

RILEM committee 127 MS conducted round robin tests to verify and calibrate proposed test methods, one of which was the rebound hammer test to measure the surface hardness of porous materials (Binda, 1997). Binda reports that the hammer rebound hardness measurement can be correlated to strength for homogenous, isotropic, elastic materials. Although this does not describe masonry, the rebound number can be correlated to the condition of the material. To calibrate the method to different masonry types and to understand if extended applications could be made, three series of measurements were carried out in Italy on mortar, brick, and stone laboratory specimens in Milan. Results show that the technique can be used to classify repointing mortars of cement, cementlime, or hydraulic lime mortars. The tool is not able to classify lime putty mortars as they are too soft. A pendulum hammer that delivers less impact energy should be produced for these mortars (Binda, 1997).

## 2.5 Current Practice in Mortar Evaluation for Historic Preservation Projects

### 2.5.1 On-Site visual evaluation

There are some simple rules of thumb that are applied frequently to evaluate in-place mortar. Lime mortars appear white and often will leave white dust on one's finger when rubbed. Cement mortars have a grey color and should not produce dust when rubbed. Further clues to the age of the mortar can be gleaned from the nature of the bricks (Sickels-Taves, 1997). Non-standard sizes indicate old mortars (pre 1899), as do porous, handmade bricks. Later, twentieth century bricks have been produced with manufacturing techniques that have eliminated such variability. It is common to scrape the mortar with a hard object such as a key to gain a rough idea of the hardness of the mortar (Speweik, 1997).

### 2.5.2 Aggregate gradation, color, particle size and shape

The gradation of the original aggregate of a mortar can be determined by acid digestion of the binder matrix followed by sieving with ASTM standard sieves (Speweik, 1997). Care must be taken to account for the possibility that limestone aggregate is present, as it can be dissolved along with the binder. The sand used for new pointing mortar should have a similar gradation curve. The shape of the sand particles also is important to the behavior of the resultant mortar. Round particles, as found in natural river or beach sand, provide less cohesion than sharp, angular particles such as those found in pit sand or manufactured sand. However, natural sands produce more workable mortars that may more closely approximate the behavior of an historic mortar (Speweik, 1997).

The shape of sand particles can be approximated by examination with a hand lens (Sickels-Taves, 1997). If an in-depth study of the source of a sand is desired, more advanced methods are available, such as optical stereology, petrography, and mineralogical analysis of the aggregate (Sickels-Taves et al, 1997). Also, the U.S Heritage Group, Inc., has established the "National Sand Library" in Chicago, Illinois, where sands from across the country are catalogued geographically for the purpose of providing matching sands for mortar.

It is vital to the historic preservationist to match the color of pointing mortar to the original mortar (Higgins, 1984). The residue of Portland cement is medium to dark gray; clay produces a reddish to light tan color; and the residues of natural, non-manufactured cement are brown (Sickels-Taves, 1997). Additives such as lumps of partially burned lime, animal hair, cows blood, egg whites, brick dust, seashells, or carbon from inadvertent mixture during the firing of the quicklime may be present (Speweik, 1997). The color of the replacement mortar should match the unweathered original mortar. This can usually be achieved by closely matching the original aggregate and binder, but color additives are available (Higgins, 1984).

### 2.5.3 Analyzing mortar composition in the laboratory

Treatment of a mortar sample with hydrochloric acid can indicate the presence of lime or cement binders. Vigorous bubbling and amber color indicate the presence of lime, while weak agitation and a murky green color indicate cement (Sickels-Taves, 1997).

By means of analytical chemistry and petrography, hardened mortar can be studied to reveal (Erlin and Hime, 1985):

- Composition and proportions
- Admixtures
- Air-void systems
- Hydration of the Portland cement, hydration reactions, and water/cement ratio
- Textural features related to original mortar consistency and workmanship
- Water migration paths
- Chemical and physical soundness of the components
- Features of the mortar related to performance

More advanced chemical techniques can be used in tandem with petrographic studies to quantitatively evaluate mortar samples. ASTM C 1324, *Standard Test Method for Examination and Analysis of Hardened Masonry Mortar*, provides explicit guidelines for chemical and petrographic analysis.

## 2.6 Hardness Testing

Tests commonly used to measure the hardness of rocks, concrete, and similar materials include scratch tests, indentation tests, and rebound tests. Hardness is considered as a material behavior rather than a fundamental physical property of a material. Hardness is related to or is a function of resistance to scratching, Young's modulus, brittleness, etc. (Atkinson, 1973).

Hardness values are expressed in empirical units relevant to the particular test used.

### 2.6.1 The Mohs Hardness Scale

The Mohs hardness test gives a comparative value of hardness by specifying a hardness scale from one to ten. Each hardness value is represented by a mineral, with diamonds assigned the value ten and talc assigned a value of one. The Mohs scale is given in Table 2.3. The minerals with higher hardness numbers are capable of scratching those with lesser numbers (Atkinson, 1973).

Table 2.3. The Mohs Hardness Scale.

**Mohs Hardness Scale**

| **Mohs Number** | **Mineral** |
|---|---|
| 1 | Talc |
| 2 | Gypsum |
| 3 | Calcite |
| 4 | Flourspar |
| *5* | Apatite |
| 6 | Feldspar |
| 7 | Quartz |
| 8 | Topaz |
| *9* | Corundum |
| 10 . | Diamond |

2.6.2 Indentation rests

Indentation methods are common for metals. The Brinell test uses a spherical metal ball applied to the surface with a specified force. The hardness value is a function of the geometry of the indented surface and the applied load (Boyer, 1977). An adaptation of this type of slow-load indentation device was developed for testing rocks (van der Blis, 1970). Empirical relations were found for the Brinell hardness number and the elastic moduli of the rock. Three methods employing this principle for concrete testing are the Williams Testing Pistol, the Frank Spring Hammer, and the Einbeck Pendulum Hammer. These methods can be used to predict strength with an accuracy of twenty to thirty percent (Malhotra, 1976). The Windsor Penetrometer and the Pin Penetration Resistance Meter described previously in Section 2.4.2 are examples of indentation testers suitable for mortars.

2.6.3 Rebound Tests

*The Shore Hardness Test*

In 1911, Shore described a scleroscope method for determining the hardness of metals. This method involves measuring the height of rebound of a hardened steel hammer that is dropped on the test metal (Malhotra, 1976). In current practice, the Shore Sleroscope hardness test consists of dropping a diamond-tipped hammer from a fixed height and measuring the rebound. The hammer, weighing about two grams, slides inside of a glass tube (Boyer, 1987). The Shore Hardness test is also used to for comparing the hardness of rocks using a diamond or tungsten carbide hammer. The mean of 20 readings is usually taken as the Shore hardness of the rock (Rabia and Brook, 1979). Rabia and Brook found that the Shore Hardness values were a function of the volume of the specimen. The hardness values increased as the volume of the specimen was increased to a value of about 40 cubic centimeters, and then remained constant as volume was further increased. Porous rocks were found to be harder when dry than when wet (Rabia and Brook, 1979).

*The Schmidt Hammer*

In 1948 Ernst Schmidt developed the Schmidt hammer for measuring the hardness of concrete by the rebound principle (Malhotra, 1976). The hammer uses a spring to drive a steel plunger against the specimen with a specified energy. The maximum rebound of the plunger is measured on a scale attached to the frame of the device (ASTM C 805).

Malhotra presents a method for calibrating the Schmidt hammer to specific concrete mixes. Cylinders are cast with the mix of interest and tested with the hammer over time as they cure. The cylinders are restrained in a compression tester at fifteen percent of their yield strength, and tested at several locations. The cylinders are then crushed in the usual manner and the rebound numbers are plotted versus compressive strength. The accuracy of the estimated compressive strength using this technique in controlled laboratory conditions is ten to fifteen percent, and twenty-five percent in the field (Malhotra, 1976). Malhotra notes that that the accuracy of field testing with the Schmidt hammer is affected by the following factors:

1. Smoothness of surface under test.

Troweled surfaces give scattered results. The *Swiss Federal Materials Testing and Experimental Institute* recommends that the Schmidt hammer be used only on concrete which has been cast against forms.

2. Size, shape, and rigidity of the specimen.

Less rigid specimens will give a lower rebound number.

3. Age of test specimen.

The rebound number increases for the first seven days, and then remains relatively constant, despite increases in actual compressive strength.

4. Surface and internal moisture condition of the concrete.

Surface-dry concrete gives higher rebound numbers than surface-wet concrete.

5. Type of coarse aggregate.

For equal compressive strengths, concretes with limestone aggregate test lower than concretes with gravel aggregate.

6. Type of cement.

High-alumina cement concrete can give strengths 100% higher than those obtained using a calibration chart based on concrete made with ordinary Portland cement.

7. Carbonation of concrete surface.

Surface carbonation significantly increases the rebound number.

These variations demonstrate the difficulty involved in comparing the results of the Schmidt hammer test from one location with those from another location.

Poole and Farmer (1980) conducted a study to examine the consistency and repeatability of the Schmidt hammer test on exposed rocks and to determine the best procedure for recording rebound values. For this statistical study, four hundred rebound values were taken with the Schmidt hammer on a large block of dolerite in the laboratory, and similar data sets were taken at field locations. The data consisted often or fifteen impacts at one location. One set of field data was taken on a continuous scan line at one-meter intervals along a 280 m length of tunnel in calcareous, sandy limestone. The other set of field data was taken on a 200 mm squared grid laid out on a limestone abutment. The researchers concluded that the recorded rebound values were statistically representative of the rock only for the rebound values taken after the third impact in a series. The variation was excessively high for the initial three impacts at any point. The F-test was used to determine statistically if the sample sets were equivalent. The data from one of four rocks tested exceeded the F-test statistic. It is recommended that to obtain a repeatable rebound value, the peak value from at least 5 successive rebounds should be selected.

## 2.7 Case Studies

### 2.7.1 Civic Tower of Pavia

The collapse of the Civic Tower of Pavia in 1989 prompted the researchers to study the degradation of the mortar of this medieval construction (Baronio and Binda, 1991). It was suspected that mortar deterioration due to pollution had caused the collapse. Construction of the tower began in the eleventh century and a belfry of granite and brick masonry was added in the sixteenth century.

Samples were taken from the ruins of the tower and chemical, petrographic, and mechanical analyses of the material were performed. The mortars present in the structure were from many different construction phases. All were lime mortars with lime to sand ratios ranging from one to three to one to five. They appeared to be well-carbonated lime putty mortars. The medieval rubble walls were 2.8 meters thick on the ground floor, and the cladding thickness was an average of 0.15 meters thick. Figure 2.8 shows a cross section of the wall.

The deterioration of the mortars was localized, mainly in the cladding of the structure. Baronio and Binda conclude that mortar degradation was not the cause of the collapse. Degradation was evident only in the cladding material of the structure, while the mortars at depth were strong and undamaged.

A procedure is outlined for the testing of mortar samples taken from existing structures. The proposed testing procedure is as follows:

1. Map the various mortar types using all geometrical, stratigraphical, and historic information available.
2. Mortar should be sampled at the surface and at depth. The sampling should reflect the nature of the investigation.
3. Chemical analyses can be used to detect the nature of binder and aggregates, the degree of carbonation of the lime, and the presence of different soluble salts and sulfates.
4. Microscopic investigation of polished specimens will give a sure indication of the hydraulic nature of the binder.
5. Thermal treatment of siliceous aggregates allows the determination of the aggregate's grain size distribution.
6. Petrographical and mineralogical analyses are used to confirm the chemical analyses and can be useful to find the source of the original materials.
7. Examination with a microscope can be used to determine the grain size distribution when the aggregate is of a calcareous or mixed nature.
8. Mechanical tests, when possible, should be used to determine the material properties of the mortar.

This research was intended to be useful to the future establishment of rules and codes for the testing of materials sampled from existing structures. The results obtained show that it is possible to thoroughly characterize historic mortars using a well defined investigative procedure.

### 2.7.2 Conservation of a Historic Stone Building in Trinity College, Dublin

A conservation project was undertaken to restore the Regent House of Trinity College (Duffy et al., 1993). The stonework of the Regent House facade had been badly damaged by atmospheric pollution. In 1989, Trinity college began to clean the blackened and decayed stonework. It was decided that the entire building was to be repointed.

Previously, the building had been repointed with black colored mortar to match the blackened stones. To aid in mortar selection, research into the chemical and mechanical properties of various mortars was conducted. The goal of the testing program was to select a mortar that would fulfill the necessary functions and not damage the stone.

The researchers wanted to use a mortar that would prevent the ingress of moisture and pollutants yet allow the building to dry properly, accommodate movement, and not contain harmful chemicals that would further deteriorate the stone. Impermeable mortars cause water to move through the stones, exposing them to frost and chemical damage. Soluble calcium, sodium, and magnesium salts present in stone and mortar will change their hydrated form and thus their volume. This can lead to cracks that allow further ingress of salt-rich water and more crystals. Mother problem to avoid is the loss of bond between mortar and stone due to shrinkage of a wet mortar mix and overly strong mortars.

The authors conducted a testing program on a series of different mortar mixes to determine which mortar would best meet their needs. The mortars selected for testing were various mixes of well aged slaked lime putty and cement, a mortar containing PFA, a pozzolanic material, in place of cement, a mortar containing barium sulfate in place of lime, a sand and cement mortar with plasticizer, and a plain sand and cement mortar.

The mortars were tested for compressive and flexural strength, and chemical tests were performed to determine the levels of soluble salts. The mechanical tests revealed that the simple sand and cement mortar was the strongest, followed by the lime and cement mortar, the cement and plasticizer mortar, and the barium mix was the weakest. The cement plasticizer mix had the least electrical conductivity and least amount of soluble salts present after 28 days, while the cement and lime mix was the most conductive and contained the most soluble salts after 28 days.

The cement and plasticizer mix was chosen for the repointing for its appropriate weakness and chemical properties.

## 3.0 MATERIALS

### 3.1 Cement

The same Portland cement was used for the seven mortar formulations containing cement binder. Portland cement meeting the requirements of ASTM C 150, *Standard Specification for Portland Cement* for Type I cement was used.

### 3.2 Lime

Three types of lime were used.
1. Type S hydrated lime meeting the requirements of ASTM C 207, *Standard Specification for Hydrated Lime for Masonry Purposes.*
2. Lime putty acquired from the Chemical Lime Company of Henderson, Nevada.
3. Hydraulic Lime acquired from France *(Blanche Hydraulique Naturelle Pure,* from NHL pure, France).

Figure 3.1 shows samples of these three lime types.

### 3.3 Sand

Three types of sand were used.
1. Quikcrete medium sand. This sand will be referred to as *fine sand.*
2. Quikrete all-purpose sand. This sand will be referred to as *play sand.*
3. A mixture of Quikcrete all-purpose sand and #8 aggregate. This sand will be referred to as *coarse sand.*

Figure 3.2 shows samples of these three sand types.

### 3.4 Bricks

Two types of bricks were used to construct the laboratory test piers.
1. Reclaimed “Boulder Bricks.” These bricks were reclaimed from turn of the century structures in Colorado. These hydraulically pressed, molded bricks were made by a local manufacturer.
2. Yellow Clay Bricks. These bricks are typical modem extruded and cored bricks.

Figures 3.3 and 3.4 show samples of these bricks.

### 3.5 Mortar Formulation and Mixing

Two types of mortar mix designs were used and are described in the following section.

#### 3.5.1 Mortars for laboratory characterization

The mortars used for the laboratory characterization of plastic and hardened properties were mixed according to ASTM C 270, *Standard Specification for Mortar for Unit Masonry.* The only exception to this specification was that larger batch sizes were prepared. For this test program, each batch was proportioned using a sand weight of 7200 grams rather than the 1,400 grams required by ASTM C 270. Mortar was prepared in a benchtop mixer with a vertical paddle. The mortar types 5, N, 0, and K were proportioned to conform to ASTM C 270. The hydraulic lime mortar was proportioned according to the recommendations of the distributor. These recommendations conform to historic formulations for mortars with no Portland cement. Table 3.1 shows the mix proportions by volume and weight of the eight mortar types tested.

Table 3.1. Mortar Mix Proportions by Volume and Weight.

| Mix | Mortar Type | Mix Proportions by Volume | | | Mix Proportions by Weight (grams) | | |
|---|---|---|---|---|---|---|---|
| | | Cement | Lime | Sand | Cement | Lime | Sand |
| A | Type S | 1 | 1/2 | 41/2 | 1880 | 400 | 7200 |
| B | Type N | 1 | 1 | 6 | 1410 | 602 | 7200 |
| C | Type O (Lime Putty) | 1 | 2 | 9 | 936 | 2107 | 7200 |
| D | Type O (Fine Sand) | 1 | 2 | 9 | 936 | 806 | 7200 |
| E | Type O (Coarse Sand) | 1 | 2 | 9 | 936 | 806 | 7200 |
| F | Type O | 1 | 2 | 9 | 936 | 806 | 7200 |
| G | Type K | 1 | 3 | 12 | *705* | 900 | 7200 |
| H | Hydraulic Lime Mortar | 0 | 1 | 3 | 0 | 2640 | 7200 |

#### 3.5.2 Mortars for pier construction

The mortars used for the construction of test piers were proportioned as were the mortars for laboratory characterization, except that larger batches were prepared. For each pier construction, 45.4 kg of sand were used instead of 7.2 kg of sand. These batches were mixed in a large floor mixer. The mortar was re-tempered with water and mixed with a trowel as required to maintain a workable consistency. Each mortar batch was used within 2.5 hours of mixing.

# 4.0 CONSTRUCTION OF TEST SPECIMENS

## 4.1 Construction of Piers for Hardness Testing

The piers were constructed in an indoor laboratory on 1/4 in. steel plates elevated from ground level on bricks. Figure 4.1 shows a steel plate with a layer of mortar ready to receive the first course of bricks. As each course of bricks was added, the construction was checked for horizontal and vertical level as shown in Figure 4.2. Six bricks were used for the perimeter of each course, with no bricks in the center to simulate a cavity wall or one and a half bricks in the center to simulate a solid wall. A pier being constructed as a solid wall is shown in Figure 4.3. Solid piers were built with full bed, head, and collar joints.

All piers were constructed with 1/2 in. bed joints. After the piers were constructed and the mortar partially hardened the joints on two faces of the pier were tooled concave, while the other two faces were left struck flush with the surface of the bricks. Figure 4.4 shows the tooled joints of a pier.

With the exception of the hydraulic lime pier, each pier was built with 14 courses of bricks. The pier built with hydraulic lime contained 12 courses. In some cases, piers were built with two types of mortar. The piers were allowed to cure in laboratory air. Figure 4.5 shows several completed piers.

Table 4.1 lists each pier with its respective identification number, type of collar joint, brick type, and mortar type(s).

Table 4.1. Pier specifications.

| Pier Number | Type of Collar Joint | Brick Type | Dimensions (inches) | Number of Courses | Mortar Type(s) |
|---|---|---|---|---|---|
| 1 | Cavity | Modem Yellow | 12 x 20 x 40 | 14 | Type S, play sand |
| 2 | Full | Reclaimed | 13.5 x 22.5 x 42 | 14 | Type O, play sand |
| 3 | Full | Reclaimed | 13.5 x 22.5 x 42 | 14 | Type O, coarse sand*<br>Type O, fine sand |
| 4 | Full | Reclaimed | 13 x 22 x 40 | 14 | Type N, play sand*<br>Type K, play sand |
| *5* | Cavity | Modem Yellow | 12 x 20 x 39 | 14 | Type S, play sand |
| 6 | Full | Reclaimed | 13 x 22.5 42.5 | 14 | Type O, coarse sand |
| 7 | Cavity | Reclaimed | 13 x 22 x 44 | 14 | TypeO, LimePutty and Play Sand |
| 8 | Full | Reclaimed | 13 x 22 x 38.5 | 12 | Hydraulic lime, Play sand |

*Where two mortar types are given, the bottom 7 courses use the first mortar listed, and the top 7 courses use the second mortar listed.

## 4.2 Preparation of Mortar Cubes for Compression Testing

The mortar cubes were formed as described in ASTM C 109, *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (using 2-in, or [50 mm] Cube Specimens)*. Five sets of three cubes were made from each mortar batch. The 2-in, cubes were formed in brass molds. Figure 4.6 shows the molds used. The mortar was placed in the forms in two lifts, each tamped in the pattern described in ASTM C 109. After excess mortar was scraped from the molds with a steel spatula, the forms were covered with a damp cloth and allowed to cure in the mold for 24 hours. The cubes were then removed from the molds and stored in a curing chamber until testing. The curing chamber was heated such that the temperature did not fall below 60° degrees Fahrenheit. The relative humidity in the chamber was monitored and remained between 60 percent and 85percent. This curing method deviates from the procedure described in ASTM C 109, which specifies that the mortar cubes are to be cured at 100 percent relative humidity in a moist room or cabinet. The purpose of this deviation from ASTM C 109 was to allow more carbon dioxide to reach the specimen and thus encourage the lime in the mortar to carbonate.

## 4.3 Preparation of Specimens for Water Vapor Transmission Testing

Integrated Conservation Resources, Inc. (ICR) provided a procedure for preparation of water vapor transmission samples. The mortar for these samples was taken from the batches made for the plastic and hardened mortar tests. For each mortar type, a set of 3 samples was made. These samples were cured and then shipped to ICR for testing.

## 5.0 TEST PROCEDURES

### 5.1 Sieve Analysis of Sands

The particle size gradation of the three sand types was determined using ASTM C 136, *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates.* Sand was sifted through a series of progressively smaller sieves and the weight of sand retained on each sieve was measured. The results are expressed as the percent of the total sand weight that passed through each sieve.

### 5.2 Tests for Mortar Plastic Properties

The following tests were conducted to characterize mortar plastic properties:

- Mortar flow, per ASTM C 230, *Specifications for Flow Table for Use in Tests of Hydraulic Cement.*
- Modified Vicat cone penetration, per ASTM C 780, *Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry, Annex Al, Consistency by Cone Penetration Method.*
- Water retention, per ASTM C 110, *Test Methods for Physical Testing of Quicklime, Hydrated Lime, and Limestone.*
- Air content using the density method, per ASTM C 270.
- Water/binder ratio, calculated from the mix proportions used to obtain the appropriate flow.

Three repetitions of each of these tests were performed on each of the 8 mortar types.

#### 5.2.1 Mortar flow

The mortar flow was measured per ASTM C 230. This test was run immediately after the mortar was mixed. A brass mold and flow table are used for this test. Mortar is placed into the mold and tamped in two lifts. Figure 5.1 shows the mortar being tamped in the mold. Excess mortar is then scraped from the top of the mold as shown in figure 5.2. The mold is then swiftly removed, leaving a slumping mortar pile on the table as shown in figure 5.3. The table is then dropped from a height of ‘A in. 25 times by means of a motorized camshaft, causing the mortar to spread into a pancake shape. Four diameters of this mortar pancake are then measured with calipers along the lines scribed in the table top, as shown in figure 5.4.

The sum of four measurements with the calipers is reported as the mortar flow. The result equals the percent increase in the diameter of the mortar. Samples were mixed to provide a flow of 110+/-5, as required by ASTM C 270 for lab tests. Mixes with a flow greater than 115 were discarded.

### 5.2.2 Modified Vicat cone penetration

The modified Vicat cone penetration depth was measured per ASTM C 780. This test was run immediately after the flow test. A Vicat apparatus, shown in Figure 5.5, is used in this test. First, the dry, empty, brass cup is weighed. Next, the cup is filled with mortar in three lifts, each lift being tamped 20 times with a 1/2 in. flat metal spatula as shown in Figure 5.6. The cup is then tapped at 5 locations equally spaced around the side of the brass cup with a 5/8 in. diameter, 6 in. long maple dowel. Excess mortar is then cut off to a plane surface level with the top of the cup with a spatula. The cup and mortar is then weighed. The tip of the cone is then aligned with the rim of the brass cup, and the cup placed such that the cone is centered over the mortar surface as in Figure 5.5. The scale is adjusted to read zero in this condition. The cone is released by a swift turn of its set screw and the millimeters of penetration are read from the scale. Figure 5.7 shows the cone after it has fallen into the mortar.

### 5.2.3 Water retention

The water retention of the mortar was measured per ASTM C 110. This test was run immediately after the modified Vicat cone penetration test. A perforated dish and a vacuum apparatus are used in this test. Figure 5.8 shows this assembly. A wetted filter is placed in the perforated dish. The dish is filled with mortar and tamped 15 times. Excess mortar is then scraped from the dish leaving a level surface. A vacuum of 50.8 mm is then applied to the perforated side of the dish for 60 seconds. After shoveling the mortar about in the dish for 15 seconds, the flow test as described in Section 5.1.1 is performed using the mortar in the dish. The water retention is calculated as the flow after suction divided by the flow prior to suction.

### 5.2.4 Air content

The air content of the mortar was calculated using the equation for air content in Section 5.5 of ASTM C 270. The weight of 400 ml of mortar was determined by subtracting the weight of the 400 ml brass cup from the weight of the brass cup when filled with tamped mortar. These weights were determined during the Vicat cone penetration test as described in section 5.2.2.

### 5.2.5 Water/binder ratio

The ratio of water to cementitious binder was calculated from the mix proportions that were used to obtain the appropriate flow.

## 5.3 Mortar Hardened Properties

The following tests were conducted to characterize the hardened mortar properties:

- Compressive strength, per ASTM C 109, *Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in, or 50-mm Cube Specimens).*
- Water vapor transmission, per ASTM E96, *Standard Test Methods for Water Vapor Transmission of Materials.*

5.3.1 Mortar compressive strength

Mortar cube compressive strength was measured as described in ASTM C 109.

Three 2-in. cubes, formed and cured as described in Section 4.2, were tested for compressive strength at approximately 7, 14, 28, 60, and 90 days in a hydraulic load machine. The specimens were loaded to failure and the maximum load and mode of failure were recorded. The compressive strength was calculated as:

$$f'c = \frac{P}{A}$$

Where: f'c = compressive strength
P = total maximum load
A = area of loaded surface

The average three tests are reported as the compressive strength of the mortar.

5.3.2 Water vapor transmission

The water vapor transmission was measured as described in ASTM E96, *Standard Test Methods for Water Vapor Transmission of Materials.* The water method, rather than the desiccant method, was used. The water vapor transmission is defined as; *the steady water vapor flow in unit time through unit area of a body, normal to specific parallel surfaces, under specific conditions of temperature and humidity at each surface.* For the water method, the sample is sealed to the top of a dish containing distilled water. The dish and sample are weighed and then placed in a chamber that is maintained at a constant relative humidity and temperature. The relative humidity is maintained at a value of less than *50%* with variation of no more than 2%. The temperature in the chamber is maintained at a value greater than 70° Fahrenheit with variation of no more than 1° Fahrenheit. Water vapor will pass through the sample to the chamber. The dish and sample assembly is weighed regularly to record the amount of water passing through the sample. The water vapor transmission is calculated using the formula:

$$WVT = \frac{W}{tA}$$

Where: WVT = rate of Water Vapor Transmission
W = weight of water loss
t = time between weighings
A = test area (cup mouth area)

## 5.4 Rebound Number

An experimental procedure was developed to gather pendulum hammer rebound data from the laboratory piers. Preliminary data was collected from existing masonry specimens and analyzed. The results of these analyses were used to design the experimental procedure.

### 5.4.1 Preliminary Investigation

Existing masonry test walls at the University of Colorado Structural Engineering Laboratory and at the Atkinson-Noland & Associates Laboratory were used as preliminary test specimens. Grid patterns were established on the faces of the test walls and pendulum hammer rebound data was taken from 50 or more locations on each wall. A series of successive rebounds were recorded at each location without moving the hammer. Analysis of the preliminary data revealed that at all individual locations the rebound number increased significantly with successive impacts for the first 3 to 5 impacts, and then settled down to a narrow range. Figure 5.9 is a plot of a typical series of successive rebound readings from one location.

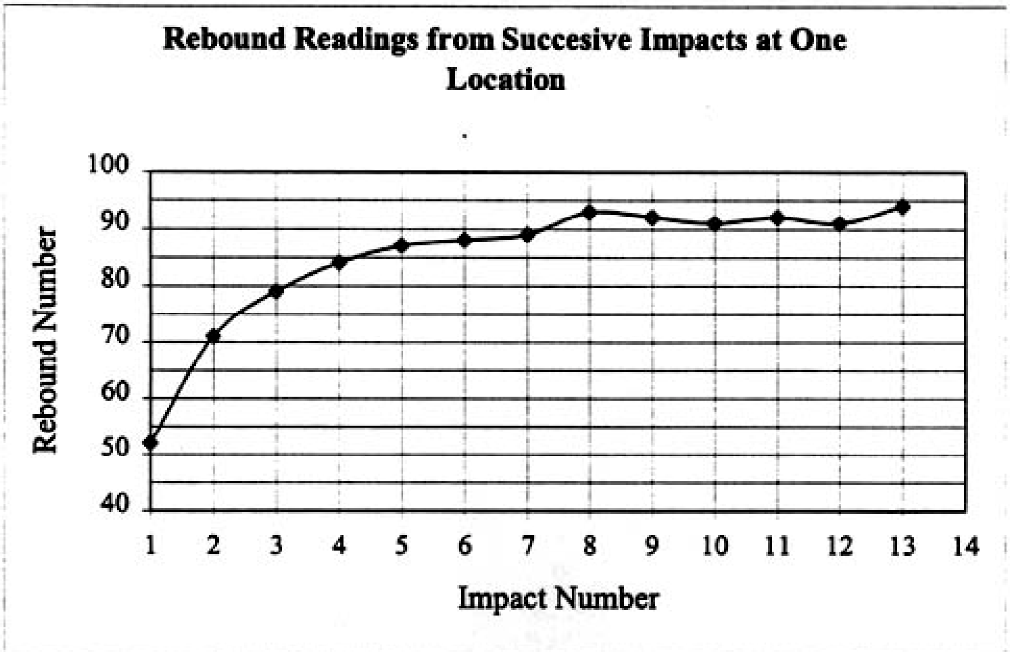



Figure 5.9. Rebound readings for a series of successive impacts taken from a test wall at the University of Colorado Structural Engineering Laboratory.

Several different methods were used to interpret the rebound number. These different methods were analyzed statistically to determine which methods provided useful results. For example, one method was to take the average of the last 5 of 10 impacts of a series as the rebound measurement from that location. Another method was to take the first rebound number as the rebound measurement from that location. The methods were analyzed by calculating the variation of the measurements within the data set and plotting the frequency distribution of the data set. Figure 5.10 shows the results for a data set with the rebound number interpreted as the average of the last 5 of a series of 10 impacts. Figure 5.11 shows the results for a data set with the rebound number taken as the first impact of the series.

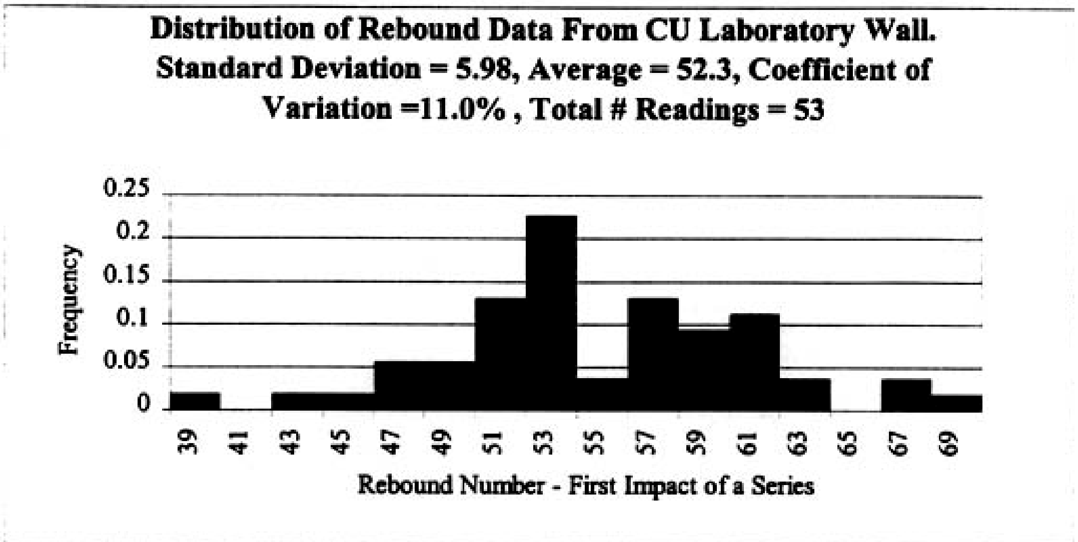



Figure 5.10. Results of a statistical analysis of preliminary rebound number data (rebound number as the average of the last 5 of a series of 10 impacts).

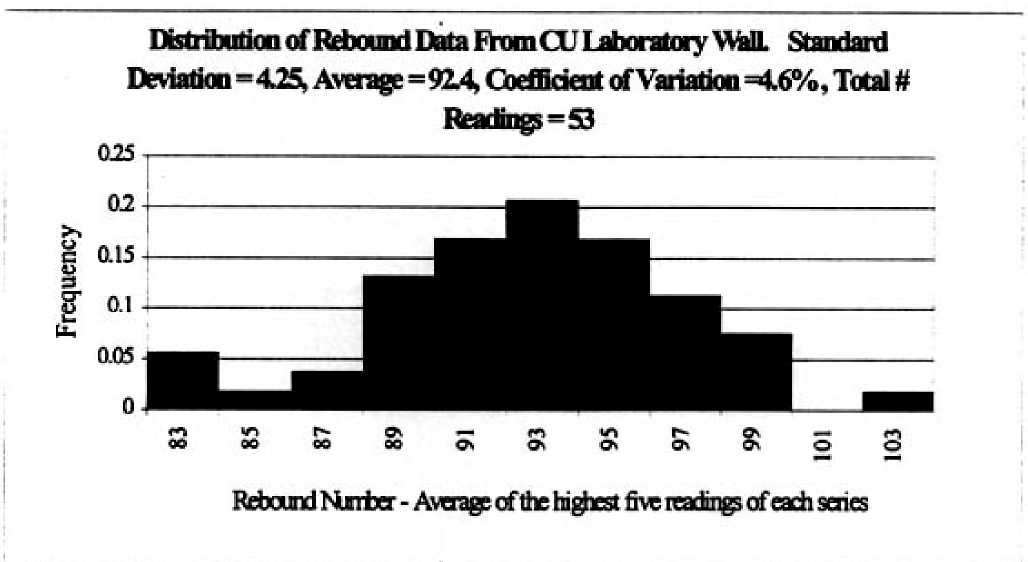



Figure 5.11. Results of a statistical analysis of preliminary rebound number data (rebound number as the first impact of a series).

The coefficient of variation for the first case (using the average of the last 5 of a series of 10 impacts) is 4.6 percent, while the coefficient of variation for the second case (using the first impact) is 11.0 percent. This reduction of variation of the data by more than half is motivation for using a series of impacts to measure the hardness at one location.

### 5.4.2 Experimental Data Collection Procedure

The analysis of the preliminary data sets was used to develop a general data collection procedure for the laboratory study. A numbered grid was drawn on each pier. Sixty-six grid points were established for both the tooled mortar joints and the struck mortar joints of each pier. Figure 4.5 shows laboratory piers with the numbered grids drawn in chalk.

At each point, the pendulum hammer was positioned to strike the mortar joint and a reading was recorded from the scale with the impact head resting on the mortar joint. On a perfectly vertical surface, the scale reading is zero in this position. On non-level surfaces, the scale reading is a positive value or a value below zero. These negative values were estimated, as the scale does not include negative values. This reading was recorded and later subtracted from the rebound result to correct for non-level test surfaces.

The piers were tested at approximately 7, 14, 28, 60, and 90 days of age. Each of these tests consisted of measurements at 30 or more of the numbered locations. At each location, a series of 10 or more successive rebounds were recorded. The last 5 of 10 rebounds from each location were averaged to provide one rebound value for each test location. Then, the 30 or more rebound values were averaged to give one rebound value for the mortar type, joint type (struck or tooled), and mortar age.

## 6.0 RESULTS AND DISCUSSION

### 6.1 Sieve Analysis of Sands

Table 6.1 shows the tabular results of the sieve analysis of the three sands used in this study for construction of test piers. The sieve number gives the number of sieve wires per inch, the diameter is the size of the largest particle that will pass through the sieve, and the percent passing is the percentage of the original weight of sand that passed though a sieve. The gradation curves of these results are plotted below in Figure 6.1.

Table 6.1. Analysis Results.

| Sieve Number | Diameter (millimeters) | Percent Passing | | |
|---|---|---|---|---|
| | | Fine Sand | Play Sand | Coarse Sand |
| 4 | 4.75 | 100 | 100 | 83.1 |
| 10 | 2 | 99.9 | 100 | 72.6 |
| 16 | 1.18 | 98.5 | 90.0 | 61.9 |
| 30 | 0.6 | 67.0 | 52.2 | 42.7 |
| 50 | 0.3 | 20.7 | 15.8 | 15.6 |
| 100 | 0.15 | 4.72 | 0.940 | 4.59 |
| 200 | 0.075 | 0.161 | 0.104 | 0.286 |

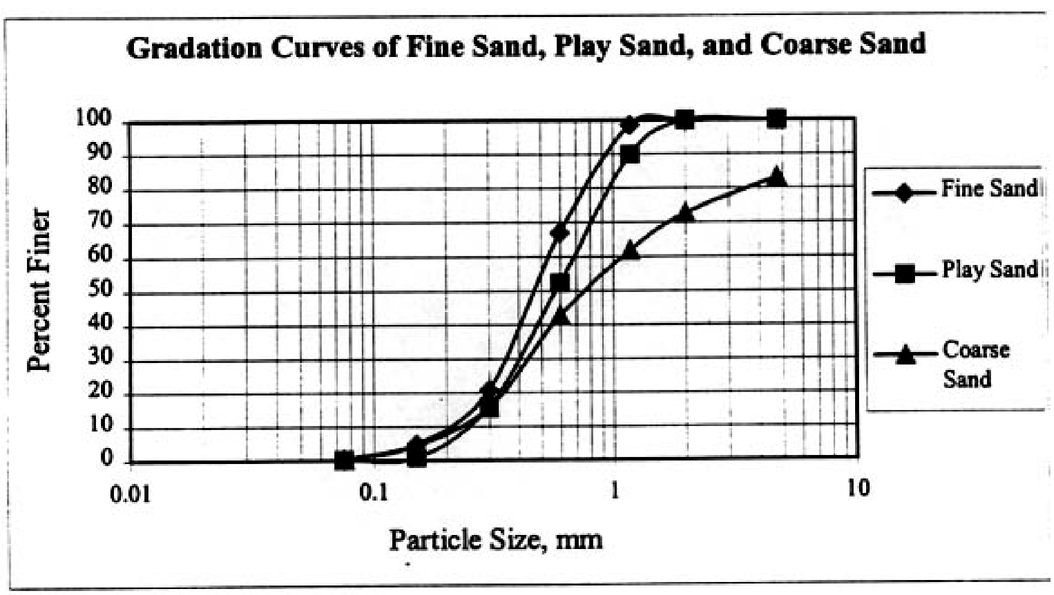



Figure 6.1. Sand gradation curves.

## 6.2 Mortar Plastic Properties

Table 6.2 shows the results of the mortar plastic tests. The results presented are the arithmetic means of 3 or 4 test results. The percentages in parentheses below the numerical values are the coefficients of variation of the test results. The coefficient of variation is defined as the standard deviation of the data divided by the mean. This value gives an indication of the variability of the results. Low values indicate low variation.

Table 6.2. Mortar Plastic Properties.

| Mortar Type | Flow | Water/Binder Ratio | Cone Penetration (mm) | Air Content (%) | Water Retention (%) |
|---|---|---|---|---|---|
| Type S (Play Sand) | 109 (1.6%) | 0.68 | 45.3 (5.6%) | 7.09 (8.7%) | 90.1 (8.0%) |
| Type N (Play Sand) | 108 (4.6%) | 0.84 | 50.3 (17%) | 5.32 (13%) | 90.5 (0.19%) |
| Type O (Lime Putty) | 110 (3.8%) | Not Measured | 60.7 (9.4%) | 2.94 (20%) | 93.0 (2.2%) |
| Type O (Fine Sand) | 110 (2.3%) | 1.10 . | 55.8 (4.7%) | 7.80 (8.1%) | 91.3 (4.9%) |
| Type O (Coarse Sand) | 113 (2.9%) | 1.02 | 59.7 (9.2%) | 5.58 (3.8%) | 87.6 (3.7%) |
| Type O (Play Sand) | 114 (1.5%) | 0.978 | 50.7 (4.1%) | 5.57 (4.5%) | 89.2 (4.5%) |
| Type K (Play Sand) | 107 (2.6%) | 1.12 | 53.5 (7.2%) | 6.16 (5.0%) | 93.7 (0.9%) |
| Hydraulic Lime Mortar (Play Sand) | 106 (2.7%) | 1.28 | 36.3 (7.9%) | ≅ 0 | 49.9 (2.75%) |

Mortar with high lime content has excellent plastic properties, that is, high water retention and moderate air content. The hydraulic lime has extremely low water retention, as was observed at the time of mixing. Mortar mixed with this lime resembled wet sand rather than mortar. This type of mortar may be suitable for pointing work, but it is not suitable for construction of new masonry. The lime putty mortar had excellent water retention and was the most workable of all of the mortar formulations. The low coefficients of variation of this data provide evidence that these results are accurate.

## 6.3 Mortar Hardened Properties

### 6.3.1 Mortar compressive strength

The compressive strength of the eight mortar types over time is plotted in Figure 6.2. Each test result is the average of the measured compressive strength of 3 specimens. Table 6.3 shows the 90-day and later strengths of the eight mortars.

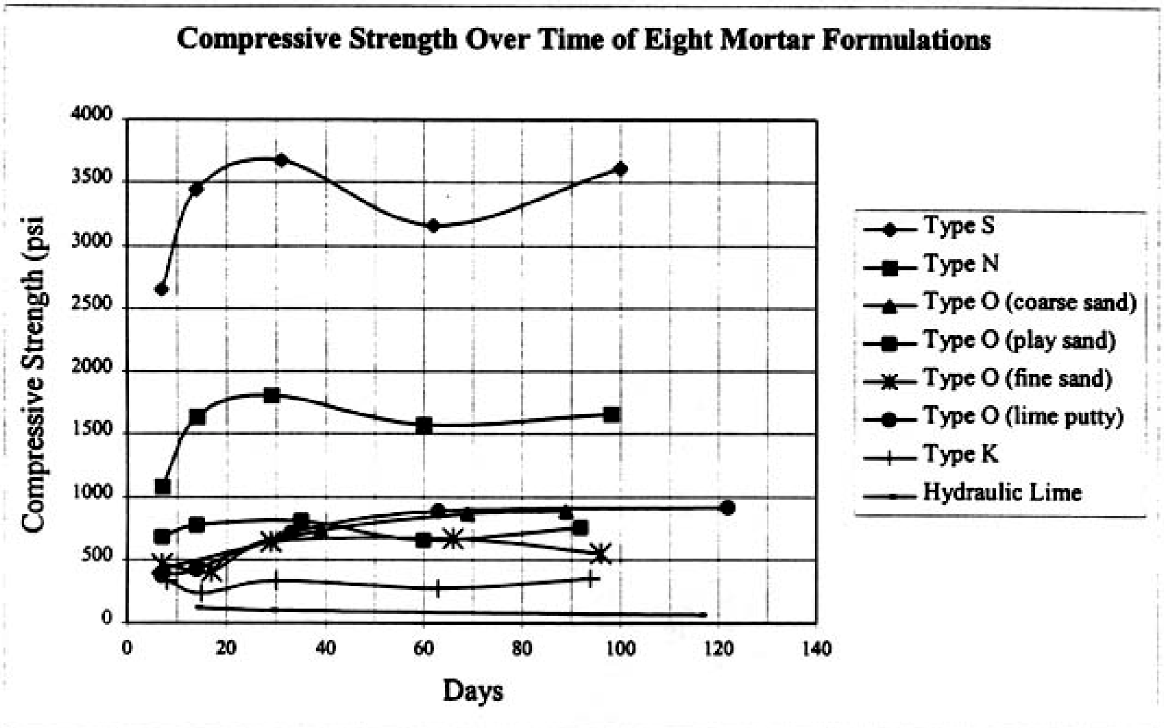



Figure 6.2. Compressive strength of mortars over time.

Table 6.3. 90 day and later compressive strength of mortars.

| Mortar Type | 90 Day and Later Compressive Strength (psi) |
|---|---|
| Type S | 3610 |
| Type N | 1660 |
| Type O(Lime Putty) | 914 |
| Type O (Fine Sand) | 546 |
| Type O (Coarse Sand) | 884 |
| Type O | 753 |
| Type K | 354 |
| Hydraulic Lime Mortar | 66 |

6.3.2 Water vapor transmission

The results of the water vapor transmission tests for the selected mortars are shown in Table 6.4.

Table 6.4. Rate of water vapor transmission of selected mortars.

| Mortar Type | Kate of Water Vapor Transmission in [grams/hour]/square meter |
|---|---|
| Type N (Play Sand) | 14.75 |
| Type O (Fine Sand) | 18.21 |
| Type O (Coarse Sand) | 19.54 |
| Type O (Play Sand) | 18.47 |
| Type K (Play Sand) | 18.26 |

Note that these results are for samples of ¼ inch thickness. These results are not necessarily indicative of the rate of water vapor transmission through different mortar thicknesses.

High water vapor transmission rate (WVTR) values indicate high relative permeability of the material and conversely, low relative WVTR values indicate lower permeability. Notice that the WVTR values for the 3 type 0 mortars follow a trend. The fine sand is the least permeable, followed by the play sand with a higher WVTR, and then the coarse sand with the highest relative WVTR of the three. Integrated Conservation Resources Inc. (ICR) compared these results to data in their company database. Using sands similar to the fine, play and coarse sands used in this study, ICR has noted an inverse trend in type 0 mortars. ICR data shows that fine sand is the most permeable and the coarse sand is the least permeable. Figure 6.3 shows these opposing trends graphically.

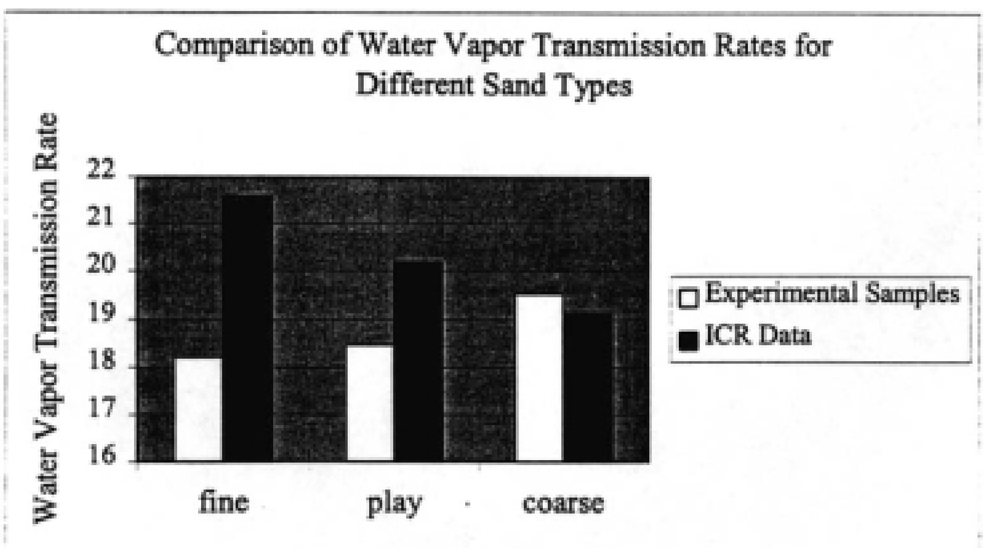



Figure 6.3. Comparison of water vapor transmission rates of type O mortars with different sand types.

These contrary results may be due to differences in sample preparation techniques.

The WVTR results for the type N samples show less permeability than type N mortars in the ICR database. ICR reports that typical results for type N mortars are 18.1 to 21.43 [grams/hour}/square meter, while the type N mortar tested for this study transmitted only 14.75 [grams/hour]/square meter. This indicates that the type N mortar is a particularly dense, or non-permeable, type N mortar. The WVTR results for the type K samples fall within the range of typical values for type K mortar in the ICR database.

6.4 Rebound Hardness of Laboratory Specimens

Rebound hardness testing was conducted over time with the methods described in Section 5.4.2. The data was organized in a database and analyzed.

6.4.1 Determination of the number of tests necessary to characterize rebound hardness

Once a large database of rebound data was established, statistical methods were used to determine the number of measurements necessary to characterize the mortar in an area of masonry. The methods described in ASTM E 122, *Standard Practice for Choice of Sample Size to Estimate a Measure of Quality for a Lot or a Process,* were used to make this determination.

The following equation from ASTM E 122 was used:

$$n = \left( \frac{3 \ x \ C.O.V.}{e} \right)^2$$

Where: C.O.V = the coefficient on variation of the measurements.
e = percent acceptable error.
3 = a factor corresponding to a low probability (3 in 1000) that the difference between the sample estimate and the result of measuring all the units in the lot or process is greater than e. The choice of the value 3 provides practical certainty that e will not be exceeded.
n = number of samples required.

The coefficient of variation for use in this equation is that variation that would result from measurements of all of the members of a lot or all of the measurements of a process. For the case of masonry mortar rebound data, this conception of the coefficient of variation is abstract, as it is not possible to measure all of the locations in an area of masonry. The coefficient of variation was therefore estimated from the variation calculated from the database of rebound data.

Two sample sizes (representing the number of measurements necessary to characterize a mortar) were calculated. One sample size was calculated for the interpretation of the rebound number as the first impact from a location. For this interpretation, the coefficient of variation calculated from the database was 18.6 percent for 8 groups of 30 or more measurements. It was estimated that, if all of the locations were measured (instead of 30), the coefficient of variation would be 17 percent. Another sample size was calculated for the interpretation of the rebound number as the average of the last 5 impacts of a series of 10. For this interpretation, the coefficient of variation calculated from the database was 11.0 percent for 8 groups of 30 or more measurements. It was estimated that, if all of the locations were measured, the coefficient of variation would be 10 percent.

The number of samples required was then calculated for a range of acceptable errors for each interpretation of the rebound number. The results of these calculations are presented in Figures 6.4 and 6.5.

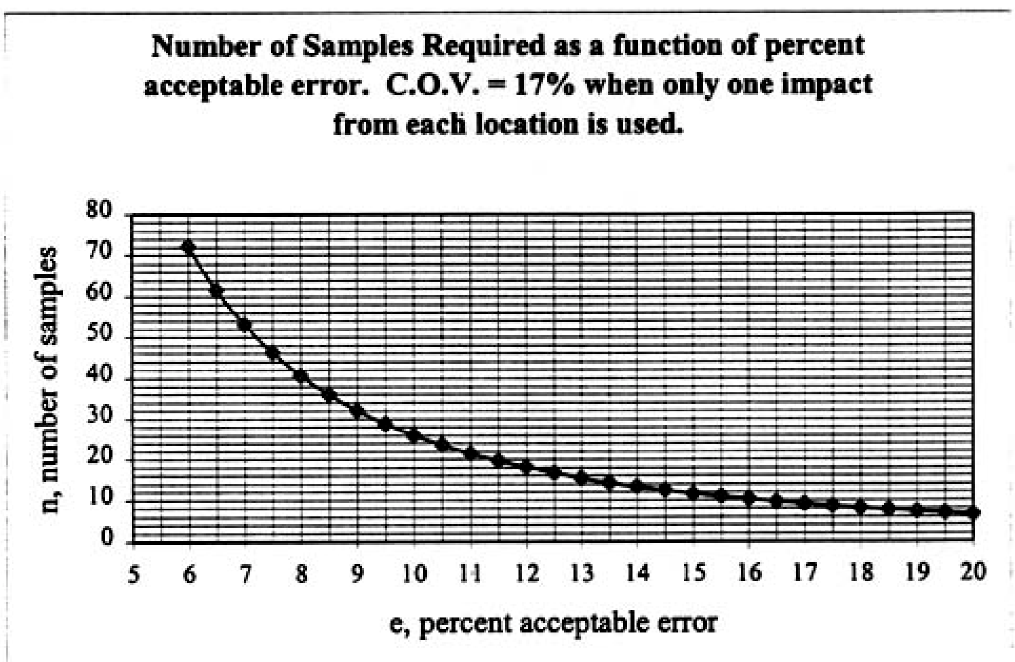



Figure 6.4. Number of samples required when only one rebound is measured from each location.

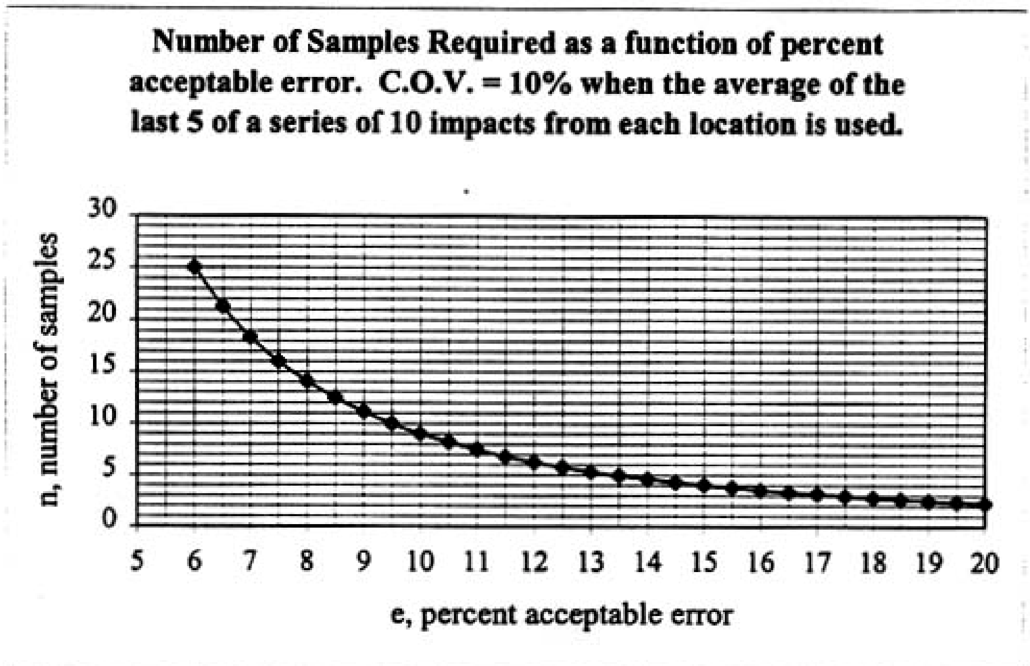



Figure 6.5. Number of samples required when the average of the last 5 of a series of 10 impacts from each location is used.

Choosing an acceptable error (e) of 10 percent, the number of measurements required using only one rebound is twenty-six. The number of measurements required when the last 5 of a series of 10 impacts are used is nine.

6.4.2 Calibration of the rebound hammer

A large block of hardened steel was used as a reference material for calibration. Several series of 10 or more rebounds for the block were used for each calibration check. The hammer was calibrated soon after it was first received from the purveyor, and then periodically checked for the duration of the study.

At the midpoint of the study, after more than 5000 rebounds, the arresting brake of the hammer failed. The arresting brake slides with the pendulum mass along a track in the frame of the device, and after impact, it arrests the rise of the pendulum at its apex. The brake wears with use until it no longer has sufficient length to stop the pendulum from descending after the rebound apex. When thus worn, the brake must be replaced.

After the brake was replaced, the calibration was checked against the steel block, and it was determined that the rebound from the block was 14 percent less after the repair than when the hammer was new. The hammer was sent to the calibration lab of the purveyor for repair and re-certification. However, the rebound reading from the calibration block remained unchanged after this procedure.

The hammer rebound value from the calibration block was lower than the original value for the remainder of the study. Efforts to fix the problem by cleaning, abrading, and polishing the brake track were ineffective. The values from the calibration block eventually leveled out at 20 percent less than the original value.

### 6.4.3 Rebound hardness development over time

The rebound number results for selected mortar types over time are shown in Figure 6.6. This data was taken early in the study during a time period when the pendulum hammer was new and calibration problems had not yet manifested. Later data is unreliable for comparison overtime. These results are of data taken from tooled joints, using the procedure described in Section 5.4.2.

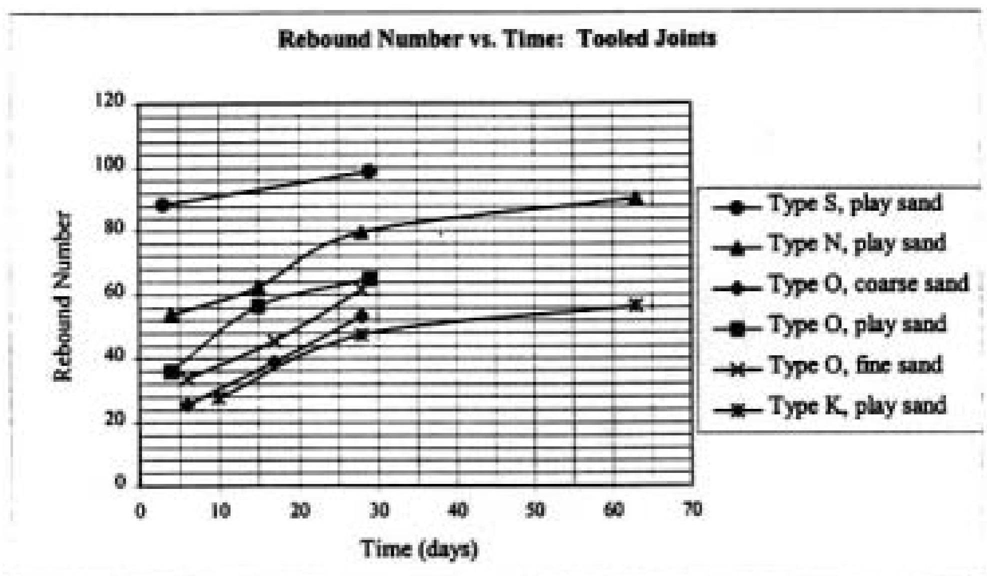



Figure 6.6. Rebound number versus time for selected mortars.

In all cases, the hardness of the mortar increased as it cured, as would be expected. However, the increase in hardness does not mirror the increase in compressive strength. For example, the compressive strength of the type N mortar increased by 67 percent from 7 to 28 days of age, while hardness of the type N mortar increased by 47 percent from 4 to 28 days. This mortar exhibited larger increases in strength than in hardness during its initial cure. However, the weaker type O and K mortars demonstrate an opposing trend. These mortars exhibit larger increases in hardness than in compressive strength during the initial cure. For example, the type O mortar with fine sand increased in strength by 37 percent from 7 to 28 days, while its hardness increased by 82 percent. Table 6.5 presents the relative increases in compressive strength and in rebound hardness of mortars from the first week to the fourth week of curing.

Table 6.5. Development of compressive strength and rebound hardness of mortars from the first week to the fourth week of curing.

| Mortar Type | Percent Increase in Compressive Strength | Percent Increase in Rebound Hardness |
|---|---|---|
| Type S(PlaySand) | 38% | 11% |
| Type N (Play Sand) | 67% | 47% |
| Type O (Fine Sand) | 72% | 67% |
| Type O (Coarse Sand) | 18% | 80% |
| Type O (Play Sand) | 37% | 82% |
| Type K(PlaySand) | 68% | 71% |

This trend provides evidence that the rebound number is more sensitive to strength differences in the lower range of mortar compressive strength (type O and weaker) and less sensitive to strength differences in the higher range of mortar compressive strength (type N and stronger).

6.4.4 Hardness of mortars after 90 days of curing

Rebound hardness results for 4 mortar types at an age greater than 90 days and the compressive strength values of these mortars are presented in Table 6.6. Each data point is the average of hardness readings from at least 30 points, the reading at each point taken as the average of the last 5 of a series of 10 impacts. All four of these mortars contain the same Type 1 cement, Type S lime, and play sand. All data was taken from tooled mortar joints. The piers containing the type N, O and K mortars were built with reclaimed “Boulder bricks” and the pier cavity was filled as described in section 4.1. The pier containing the type S mortar was built using modem extruded bricks and the pier cavity was empty.

Table 6.6. Rebound hardness of laboratory piers after more than 90 days of curing. All mortars contain the same cement, lime, and sand.

| Mortar Type | Hardness of Tooled Mortar Joints (C.O.V) | Compressive Strength (psi) |
|---|---|---|
| Type S, play sand | 81.3 (8.5%) | 3612 |
| Type N, play sand | 79.9 (5.6%) | 1657 |
| Type O, play sand | 70.5 (7.3%) | 546 |
| Type K, play sand | 47.3 (23%) | 354 |

Rebound hardness results for all 8 mortar types at an age greater than 90 days and the compressive strength values of these mortars are presented in Table 6.7. Each data point is the average of hardness readings from 9 points, the reading at each point taken as the average of the last 5 of a series of 10 impacts. These results are from data taken after calibration problems with the hammer were noted. For this reason, these results are not comparable to results reported earlier in this report. However, it is reasonable to presume, based on subsequent comparative data, that the hammer calibration remained constant while this data set was collected.

Table 6.7. Rebound hardness of tooled and struck joints of all mortar types.

| Mortar Type | Hardness of tooled mortar joints (C.0.V) | Hardness of struck mortar joints (C.0.V.) | Compressive Strength (psi) |
|---|---|---|---|
| Type 5, play sand”[2] | 74.1 (8.2%) | 64 (11%) | 3610 |
| Type N, play sand | 80.1 (3.6%) | 71(6.8%) | 1660 |
| Type 0, coarse sand | *62.5* (6.7 %) | 54.7 (8.2%) | 914 |
| Type 0, play sand | 76.7 (3.2%) | 67.5 (13%) | 546 |
| Type 0, fine sand | 58.9 *(8.5%)* | 59.6 (5.8%) | 884 |
| Type 0, lime putty and play sand’ | 46.4 (7.9%) | 43.8 (13%) | 753 |
| Type K, play sand | 33.8 (19%) | 38.3 (17%) | 354 |
| Hydraulic lime, play sand | 60.5 *(5.6%)* | 36.8 (26%) | 66 |

[1]pier constructed as a cavity wail.

[2]pier constructed with modem, cored bricks

6.4.5 Rebound hardness versus compressive strength

Figure 6.7 is a plot of the rebound hardness results for the mortars containing the type S lime, cement, and play sand plotted versus the compressive strength of these mortars. This data is in tabular form in Table 6.6.

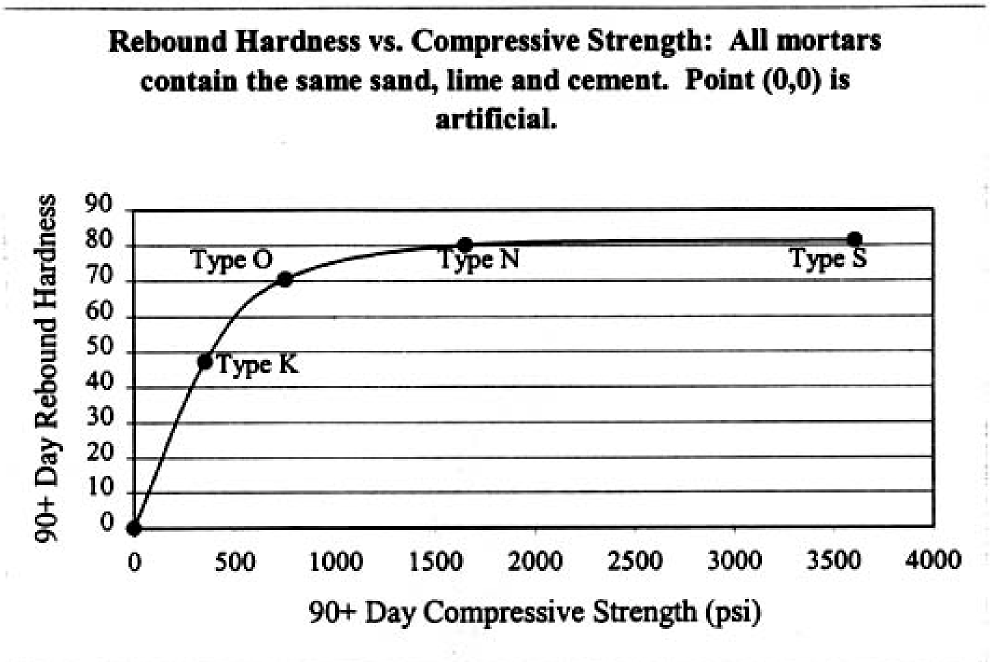



Figure 6.7. Rebound hardness versus compressive strength for mortars made with the same sand, lime and cement.

Notice that there is little difference in the rebound hardness of the type N and type S mortars although the compressive strength of the type S mortar is more than double that of the type N mortar. Conversely, there is a significant difference in hardness between the type K and type O mortars with a similar difference in compressive strength. Again, the rebound number appears to be more sensitive to changes in compressive strength in the lower range of mortar compressive strength (type O and weaker) and less sensitive to strength differences in the higher range of mortar compressive strength (type N and stronger). However, this observation should be tempered by the fact that the data for the type S mortar was taken from a pier with an empty cavity, while the data for the other 3 mortars were taken from piers with full cavities. The empty cavity could cause the type S rebound hardness to be less than if the cavity were full.

6.4.6 Rebound hardness versus joint tooling

Figure 6.8 is a plot of the rebound hardness results for all of the mortar types used. This data is in tabular form in Table 6.7.

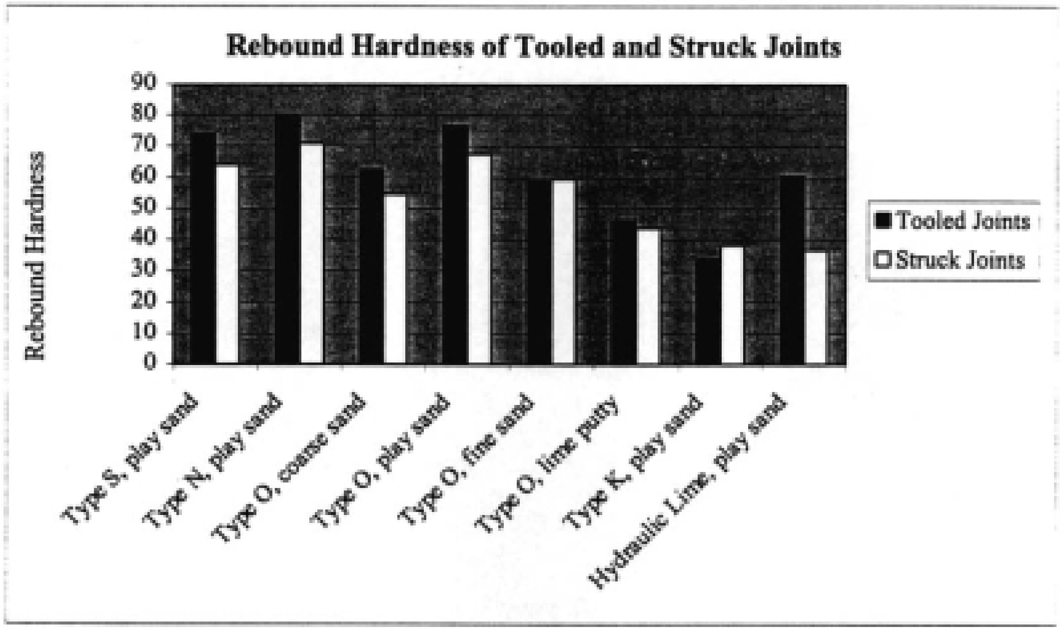



Figure 6.8. Rebound hardness versus compressive strength for all mortars.

Overall the tooled joints were harder than the struck joints. This result is sensible given that the tooling process compacts the mortar and thus the joint presents a denser surface for testing. The type K mortar and the type O mortar with fine sand were exceptions to this pattern. These exceptions are likely due to differences in the workmanship of these piers.

This data set was taken late in the study, 6 months after the data presented in Table 6.6 and Figure 6.7. Notice that the results of this later data do not show the same relationship as between rebound hardness and compressive strength as the earlier, 90-day data. Specifically, the mortars with a higher lime content now show more hardness relative the mortars with higher cement content. This trend is likely due to the carbonation of the lime, which is a slower process than the hydration of cement. With the additional curing time, the lime continued to carbonate while the cement hydration was essentially complete.

The hydraulic lime mortar, which contains no Portland cement, has very little compressive strength yet displays rebound hardness comparable to a type O mortar. This phenomenon is noted only in the data from the tooled joints of this pier. This observation provides evidence that joint tooling has a more significant effect on rebound hardness than does compressive strength.

Finally, the data from the struck joints shows less variation than the data from the tooled joints. The average coefficient of variation of data from the tooled joints is 7.8 percent, while the average coefficient of variation of data from the struck joints is 13 percent.

This result is sensible given that the tooled joints were carefully tooled while the struck joints were simply struck flush the trowel. The act of striking the joints flush leaves a much less consistent joint surface than the tooling procedure.

### 6.4.7 Rebound hardness versus sand gradation

The rebound hardness results of the type O mortars containing coarse sand, play sand and fine sand did not show any regular trend that can be attributed to the different sand gradations.

## 7.0 FIELD TESTS

Following laboratory development of the test method, a series of field tests were conducted to determine if the method was viable for in-place evaluation of mortars. Historic and modem structures were tested. During these tests, attempts were made to recognize differences in rebound hardness related to different conditions within one structure, and to catalog the range of mortar hardness results to be expected in the field.

### 7.1 Basilica of the Assumption

The Basilica of the Assumption, located in Baltimore, Maryland, was designed by the prominent architect Benjamin H. Latrobe. Construction of the Roman Catholic cathedral was undertaken in 1805 and completed in 1837, 17 years after the architect’s death.

The undercroft, or basement, of the Basilica is a system of masonry vaults. The masonry is red brick with lime mortar. The lime mortar in this undercroft has carbonated undisturbed by the elements since its construction.

A series of pendulum hammer tests were conducted on an area in the undercroft. Figure 7.1 shows the testing in progress. The mortar had developed enough strength to gather data using the method of repeated impacts. The results showed a rebound hardness of 45, with an error of 13%.

This mortar is the hardest of all the lime mortars measured during this study. This exceptional hardness is likely due to the length of time that the mortar has carbonated and the quality of the materials and craftsmanship.

### 7.2 Saint Alphonsus Church

Saint Alphonsus Church, located in Baltimore, Maryland, was designed by the architect Robert Cary Long, Jr. Construction was completed in 1845. The exterior of the church is red brick, and has been pointed with a Portland cement and lime mortar. Some of the original lime mortar is present in the basement storage rooms of the church.

Hardness tests were attempted on both of the mortar types. The original lime mortar was not strong enough to withstand testing. The method of repeated impacts was used on the exterior pointing mortar. This mortar gave a rebound hardness of 54, but with a 14% coefficient of variation. Also, on several of the impact sites, the mortar caved into voids behind the pointing mortar. The high coefficient of variation of the data and the voids behind the pointing mortar indicate that the pointing work was of low quality.

## 7.3 Mahan Hall

Mahan Hall was built on the campus of the West Point Military Academy in 1970. The building is built into rock cliffs above the Hudson River. Figure 7.2 shows the south elevation of Mahan Hall.

The exterior mortar joints are cracked and delaminated from the surrounding stonework. The original construction documents specified that the mortar joints were to be raked back to 3/4 inch deep and pointed with a hard, cement-sand mortar. This pointing mortar was not well compacted into the joints, resulting in a poor bond to the setting mortar and prevalent voids between the two mortars. The pointing mortar is debonded and in many cases has fallen out of the joints. Figure 7.3 shows a joint with both poorly bonded and absent pointing mortar.

Portions of the building were repointed with a type N mortar in 1996 to match the mortar on the interior. This work was done carefully as a test repair. Hardness tests were conducted on the original bedding mortar, accessed from the interior, and on the exterior type N pointing mortar. Both mortars were tested using the method for harder mortar as described in the draft standard test method (Appendix A). The rebound hardness from measurements of the interior mortar was 50.8 with a coefficient of variation of 7.2 percent. The rebound hardness from measurements of the exterior mortar was 65.3 with a coefficient of variation of 19.5 percent.

A petrographic evaluation of the mortars was performed by the Erlin Company of Latrobe, PA. For the interior mortar, the ratio of cementitious material to sand was estimated to be 1:3. The mortar was judged to be equivalent to an ASTM C 270 type N mortar made with masonry cement. The exterior pointing mortar was estimated to have a ratio of cementitious material to sand of 1:3 to 1:3 1/2. This mortar was judged to be borderline between an ASTM C 270 type N or S mortar made with masonry cement, Portland cement, and lime. These results are summarized with the rebound number results in Table 7.1.

Table 7.1. Results of petrographic analysis and rebound hammer testing of mortars at Mahan Hall.

| | **Interior Mortar** | **Exterior Pointing Mortar** |
|---|---|---|
| Rebound Number (C.O.V.) | 51(7.2%) | 65 (19.5%) |
| Ratio of Cementitious Material to Sand | 1:3 | 1:3 to l:3 ½ |
| Estimated Mortar Type | Type N | Type N or Type S |

The surface of the interior mortar was struck flat with the wall, while the surface of the exterior mortar was carefully tooled as a test repair. This difference in surface compaction is likely responsible for the higher magnitude of the rebound number from the exterior pointing mortar. The high variation, 19.5 percent, of the data from the exterior is likely due to the test conditions. The exterior of the building is faced with irregularly shaped granite stones that presented an awkward surface for pendulum hammer testing.

## 7.4 Chamberlin Observatory

The Chamberlin Observatory was built in Observatory Park in Denver Colorado in 1890. Figure 7.4 shows the south elevation of the observatory.

The foundation is stonework with lime mortar. This foundation has suffered damage from water seeping through the masonry. At lower elevations, the binder appears to have been leached out of the mortar, leaving a loose, brown sandy material. At higher elevations in the basement and in the interior telescope foundation, the original mortar is present in an undamaged state. Several pointing and patching jobs have been done in this basement with a variety of different mortars. Most of this work utilized various cement mortars, and one repointing job was done with a lime mortar containing little or no cement. None of these pointing jobs were comprehensive, so the mortars of each job are present.

Rebound hardness tests were conducted on the original foundation mortar in its damaged and undamaged state, on the five pointing mortars, and on original mortar in the telescope foundation and in an interior brick wail in the cold room of the observatory.

Two test methods were used. For the softer mortars, the tests were conducted in accordance with the European standard RILEM MS.D.7: *Determination of Pointing Hardness by Pendulum Hammer*, which uses one hit at each test locations. The harder mortars were tested using multiple impacts at each location. Ten rebound readings were taken from each test location, and the average of the last five readings was taken as the result from that location. The results of these tests are given in Table 7.2. Higher rebound numbers indicate a harder, denser material. The rebound hardness of the original mortar ranges from 10 to 12 for the mortar subjected to moisture infiltration, to 23 for the undamaged mortar in the telescope foundation. The rebound hardness of the pointing mortars vary widely, varying from 15 to 79.

Table 7.2. Rebound number test results from the Chamberlin Observatory.

| Mortar location and description | Method* | Rebound Number |
|---|---|---|
| Original mortar, interior foundation, deteriorated lower courses on north wall | A | 10 |
| Original mortar, interior foundation, intact mortar at upper courses on south wall | A | 12 |
| Original mortar, telescope foundation, east side | A | 23 |
| Original mortar, interior of coal room brick wall | A | 20 |
| Pointing mortar (soft, light-grey colored), prevalent on northeast of foundation | A | 15 |
| Pointing mortar (dark grey), used extensively, tested at lower courses on east side | A<br>B | 50<br>67 |
| Pointing mortar, (light grey, slightly glossy), used extensively above heavy efflorescence on northeast side | A<br>B | 35<br>46 |
| Pointing mortar, (crumbly dark grey), tested on west side | A<br>B | 18<br>25 |
| Pointing mortar, cement patches prevalent throughout south side | A<br>B | 65<br>79 |

*Method A: Value is the median of initial rebound number at 9 different location (RILEM MS.D.7).
*Method B: 10 rebound hits recorded, greatest 5 values are averaged; the final rebound number is the average for either 4 or 5 separate locations.

The rebound hardness results from the Chamberlin Observatory clearly differentiated between the various repair mortars. Some of the pointing mortars were inappropriately hard for the conditions, and the rebound results for these mortars proved to be very high compared to the original, undamaged mortar. Some of the pointing mortars were more carefully matched, and the rebound results from these mortars were closer to the results from the original, undamaged mortar.

## 7.5 The Graham Bible House - Carriage House

The carriage house of the Graham Bible House is located in City Park in Denver, Colorado. This turn of the century construction is a registered landmark (Landmark No. 221) with the City and County of Denver Landmark Preservation Commission. Figure 7.5 shows the carriage house from the southwest.

The carriage house masonry walls are soft molded brick with lime mortar. The exterior is painted. The masonry is decayed, largely due to damage from lawn sprinklers. Pendulum hammer hardness tests were conducted on the north and south walls. The north wall was painted, and the paint was removed from the test locations. The paint on the south wall had fallen off from the test locations, which were in the path of the sprinkler water spray.

Both locations were tested using the method for harder mortar as described in the draft standard (Appendix A). The rebound hardness result from measurements of the north wall was 32.4 with a coefficient of variation of 27 percent. The rebound hardness result from measurements of the south wall was 35.0 with a coefficient of variation of 13.2 percent.

It was noted that the mortar on the north wall consisted of a hard, external layer to a depth of 1/8 inch to 3/16 inch, and much softer mortar beneath that harder shell. It is likely that the wall had been repointed. On a few occasions the pendulum hammer impact penetrated the hard exterior after several impacts, and then subsequent impacts gave lower values. These occurrences help to account for the large coefficient of variation of the data set taken from this wall.

On the south wall, the extent of deterioration of many regions was such that those regions could not be tested. The regions that were intact, however, demonstrated hardness values that can be considered healthy for a lime mortar. Thus these results may give a false impression of the hardness of the mortar, as the weaker mortar has been washed away, leaving only the sound material.

7.6 B. Jr.'s Auto Parts Store

B. Jr.'s Auto Parts store of Casper, Wyoming, is a masonry building constructed of nominal 8" by 8" by 16" concrete masonry units with a rectangular plan of approximately 100' by 35'. The building sustained fire damage on July 21, 1998. Pendulum hammer rebound testing was conducted on damaged and undamaged mortar in the building. Table 7.3 shows the results of the pendulum hammer testing.

Table 7.3. Pendulum hammer test results from B. Jr.'s Auto Parts Store.

| Condition | Mean | Coefficient of Variation | Number of Samples |
|---|---|---|---|
| Fire Exposed | 48 | 6.9% | 25 |
| Fire Sheltered | 62 | 5.0% | 25 |

These results show that the fire had reduced the hardness of the mortar. The decrease in hardness implies a decrease in strength. The rebound hardness method was used to identify damaged regions requiring repair. This case is an example of another useful application of pendulum hammer mortar testing. The problem in this case, the evaluation of comparative deterioration within one structure, is well addressed with pendulum hammer rebound testing.

## 7.7 The Centennial School Gymnasium Addition

Centennial Elementary School is located in Colorado Springs, Colorado. The addition of a new gymnasium was completed in the summer of 1998. The results of compression tests of mortar and prism specimens cast during construction showed that some of these specimens had less than the allowable strength specified by the project engineer. Pendulum hammer hardness tests were performed in conjunction with petrographic analysis to evaluate the mortar.

Three mortar samples were removed from the building for petrographic analysis. The sampled areas were also tested for hardness with the pendulum hammer. Further hardness testing was done on other areas in order to determine if the three sampled areas were representative of the mortar throughout the structure. The testing was conducted using the method for harder mortar as described in the draft standard (Appendix A).

Three wall types were present and tested at several locations. The three wall types tested were a brick veneer, a concrete block wall, and a composite, grouted concrete block and brick wall that was tested from the brick side. The highest rebound magnitude was recorded from tests of the composite wall, which is very rigid and thus unlikely to be moved by the energy of the hammer impact. A sample was removed from this wall for petrographic analysis. The petrographer estimated that the original mix proportions of this mortar were 1 part cement, 1/2 part lime, and 7 1/2 parts sand by volume. These proportions describe an over-sanded type S mortar. The lowest rebound values were recorded from mortar between ungrouted concrete masonry units, which present a less rigid surface for impact resistance. The petrographer estimated that the original mix proportions of a mortar sample from this wall were 1 part cement, 1/2 part lime, and 4 1/2 parts sand, which describes a type S mortar. The results from the brick veneer, which is more rigid than the concrete masonry units but less rigid than the composite, grouted wall, showed rebound magnitudes in-between the other two cases. The petrographer estimated that the original mix proportions of a mortar sample taken from this wall were also those of a type S mortar. Thus the results of hardness testing did not correlate to the petrographic mortar analysis. It would be reasonable to expect that the over-sanded mortar would give a lower rebound value, but instead this mortar gave the highest rebound value. Thus it is likely that in this case the type of wall construction had a greater influence on the rebound number than did the mortar quality. Table 7.4 summarizes these findings.

Table 7.4. Hardness results from the three types of wall construction at the Centennial School Gymnasium Addition.

| Type of wall construction | Relative rigidity | Average rebound number | Estimated mortar mix proportions from petrographic analysis (cement: sand: lime) |
|---|---|---|---|
| Composite brick, block, and grout. | Very rigid | 79.3 | 1: 1/2 : 7 ½ |
| Brick veneer with insulated cavity | Less rigid | 73.2 | 1: ‘/2 : 4 ½ |
| Ungrouted concrete masonry unit | Least rigid | 62.7 | 1: ½ : 4 ½ |

This case is an example of another useful application of pendulum hammer mortar testing. The pendulum hammer testing provided evidence that the mortar samples taken for petrographic analysis were representative of the mortar in the whole wall rather than just the sampled area. This is important evidence because petrographic analyses are very expensive and somewhat destructive.

## 8.0 CONCLUSIONS AND RECOMMENDATIONS

Mortar hardness testing using the pendulum hammer is a quick, nondestructive method that is useful for the evaluation of in-place mortars. Mortar hardness measurements were conducted on laboratory specimens, historic and recent masonry structures, a fire-damaged structure, and on a newly constructed structure. Both original mortar and pointing mortar were tested. A test method was developed after analysis of these measurements. Rebound hammer testing proved useful for many evaluation applications. Problems encountered during the study are discussed here and solutions are recommended.

### 8.1 Factors Affecting Rebound Hardness

The effects of mortar type, compressive strength, sand type, joint tooling, and curing time on mortar rebound hardness were investigated. It was found that rebound hardness was dependent on mortar type. Mortar types with higher cement content, and thus higher compressive strength, tended to be harder than those containing less cement. Mortar joints which were tooled tended to be harder than those which were struck flush with the brick surface. Mortar hardness also increased with additional curing time. No correlation was noted between sand gradation and rebound hardness.

It was noticed that rebound hardness was affected by the rigidity of the masonry construction. Mortar in rigid construction such as composite, grouted brick and block walls give higher rebound numbers than mortar in less rigid construction such as facing brick in a cavity wall.

### 8.2 Development of Test Methods

Two methods of rebound hardness testing were developed. These methods were designed based on statistical analysis of the database of rebound hardness results collected from the laboratory specimens. The variability of the data was used to choose the number of tests required to produce statistically significant results. One method, designed for hard mortars, is to impact 9 locations in an area of masonry 10 times in succession. The rebound hardness at each of these 9 locations is taken as the average of the last 5 of the 10 hits, and the rebound hardness for the masonry area is taken as the average of the rebound hardness from the 9 locations. The other method, designed for soft mortars, is to impact 26 locations in an area of masonry once at each location. The mortar rebound hardness for the masonry area is taken as the average of these 26 impacts. A test method has been written and submitted to ASTM for consideration as a standard test method. This method can be found in Appendix A of this report.

## 8.3 Usefulness of Rebound Hardness Results

The method proved useful for comparing deterioration, damage, or quality of mortar within a structure. The method was used to delineate fire-damaged regions of a structure. The rebound hardness of the fire-damaged regions was less than the hardness of undamaged regions. The results were used to specify which sections of the building required repair. Another application was the investigation of mortar quality of a recently constructed structure. Samples were removed for petrographic analysis, and rebound hardness measurements were used to compare the sampled areas to the rest of the structure. In this way it was possible to generalize the results of the petrographic analyses of the local samples. In several field trials, poor quality pointing was identified when the hammer fractured the pointing mortar, revealing voids behind the pointing mortar. In other applications, it was possible to determine whether pointed mortar matched the original mortar of a structure. These examples emphasize the usefulness of comparative mortar hardness results from within one structure. The use of quantitative results alone is discouraged, except for the determination of an appropriate range of pointing mortar strength. The results of rebound hammer testing are precise enough to be used for the type-matching of repointing mortar to original mortar.

## 8.4 Problems and Limitations

Problems encountered during rebound hammer testing include calibration difficulties and the need to frequently repair the hammer, joint depth and thickness limitations, removal of surface coatings, and the dependency of the results on the mass and stiffness of the element tested.

During this study, the hammer calibration reference values changed with time. The hammer gave lower readings from the calibration block with extended use. This was Likely due to roughening of the hammer brake slide. Also, it was necessary to replace the hammer brake periodically. It is possible that these problems were due to malfunctioning of the particular hammer used, and that other hammers of the same model do not have this problem.

Rebound hammer testing was not possible on masonry with joint thickness of less than 3/8 inch, nor on masonry with joint depth of more than 3/8 inch. The depth limitation was problematic during field testing of masonry with deteriorated mortar.

The effect of mass and stiffness of the masonry element tested inhibits the comparison of rebound hardness data from different structures. In addition, when testing a single structure, care must be taken to avoid comparing results from regions of different stiffness.

## 8.5 Future Work and Recommendations

A database of rebound hardness results of mortar types from around the country would expedite the use of quantitative hardness results. Calibration difficulties will have to be addressed prior to this undertaking. The beginnings of such a database have been produced during this study.

The quantification of the effects of the stiffness and mass of the specimen tested on the rebound hardness would be a useful addition to the test method. By measuring the rebound hardness of masonry specimens of different thickness and measuring the vibrations of the specimens, guidelines could be created to remove these effects from the results.

The brake mechanism of the hammer is the cause of the calibration difficulties encountered in this study. Replacing this mechanism with another may produce more reliable results. Possible replacements include a ratchet mechanism and a slave indicator needle.

The limitations of joint thickness and depth could be overcome with the use of different impact heads. As equipped, the impact head is not replaceable. An assortment of interchangeable impact heads and pendulum masses could be developed such that all mortar joints would be accessible.

## 9.0 REFERENCES


1. Atkinson, R.H., "Hardness," The University of Colorado, 1973. Prepared for the International Society of Rock Mechanics.

2. Binda, L., Role of a RILEM Committee: Calibration of Proposed Test Methods, *Evaluation and Strengthening of Existing Masonry Structures,* Proceedings of the Joint International Workshop proposed by RILEM TC 127-MS and CIB W23, Edited by L. Binda and C. Modena, The University of Padua, Italy, 1997.

3. Baronio, G, and L. Binda, "Experimental Approach to a procedure for the investigation of Historic Mortars," Proceedings of the 9$^{TH}$ international Brick/Block Masonry Conference, Berlin, Germany, 1991.

4. Blake, M.E., *Ancient Roman Construction in Italy from the Prehistoric Period to Agustus,* Carnegie Institution of Washington, Publication 570, Washington D.C., 1947.

5. Boyer, H.E., (Editor), <u>Hardness Testing</u>, ASM International, Metals Park, OH. 1987.

6. de Vekey, R.C. and M. Sassu, "Comparison on Non-destructive In-situ Mechanical Tests on Masonry Mortars: The PNT-G Method and the Helix Method," 11$^{th}$ International Brick/Block Masonry Conference, Tongji University, Shanghai, China, 1997.

7. Doebley, C.E. and D.S. Spitzer, "Guidelines and Standards for Testing Historic Mortars," *Standards for Preservation and Rehabilitation,* ed. Stephen J. Kelley, ASTM Special Technical Publication 1258, ASTM, Ann Arbor, MI, 1996

8. Duffy, A.P., T.P. Cooper, S.H. Perry, "Repointing Mortars for Conservation of a Historic Stone Building in Trinity College, Dublin," Technical Note, Materials and Structures, Vol. 26, pp. 302-306, Paris, France, 1993.

9. Felicetti, R, N. Gattesco, "A Penetration test to Study the Mechanical Response of Mortar in Ancient Masonry Buildings," Materials and Structures, Vol. 31, pp. 350-356, Paris, France, 1998.

10. Frey, D.J., "Effect of Constituent Proportions on Uniaxial Compressive Strength of 2 inch Cube Specimens of Masonry Mortars," Master of Science Thesis, Dept. of Civil and Environmental Engineering, University of Colorado, Boulder, CO, 1975.

11. Gibbons, P., *Preparation and Use of Lime Mortars,* Technical Advice Note 1, Historic Scotland, Edinburgh, Scotland, 1995.

12. Grieve, R.G., R. Marshall, R. Willoughby, “Testing Masonry Mortar in New Residential Construction” INCOMPLETE

13. Higgins, S., “Annotated Master Specification for the Repointing of Historic Masonry Surfaces,” Ontario Ministry of Citizenship and Culture, Ontario, Canada, 1984.

14. Hime, E.B. and W.G. Erlin, “Methods for Analyzing Mortar,” Proceedings of the Third North American Masonry Conference, Arlington, TX, 1985.

15. International Society of Rock Mechanics, “Suggested Methods for Determining Hardness and Abrasiveness of Rocks,” Int. J. Rock Mech. Min Sci. & Geomech. Abstr. 15, 89-98, Great Britain, 1978.

16. Kelley, S.J. and D. Slaton, “Preservation Standards,” Building Renovation (magazine), LOCATION, Spring 1994.

17. Malhotra, V.M., *Testing hardened Concrete: Nondestructive Methods,* The Iowa State University Press, Ames, Iowa, and The American Concrete Institute, Detroit, MI, 1976.

18. Malhotra, V.M. and G. Carette, *In Situ Testing for Concrete Strength,* Minerals Research Program, Canadian Government Publishing Centre, Quebec, Canada, 1979.

19. Poole, R.W. and I.W. Farmer, “Consistency and Repeatability of Schmidt Hammer Rebound Data During Field Testing,” Technical Note, International Journal of Rock Mechanics, Mineral Science, and Geomechanics, Vol. 17, Great Britain, 1980.

20. Rabia, H. and N. Brook, “The Shore Hardness of Rock,” Technical Note, Int. J. Rock Mech., Min Sci. & Geomech, Vol. 16, Great Britain, 1979.

21. Schuller, M.P., R.H. Atkinson, G.R. Kingsley, “Nondestructive Evaluation of Masonry Structures: Standardization and Current Practice,” Proceedings of *Research Transformed into Practice, Implementation of NSF Research,* Ed. J. Colville and A.M. Amde, ASCE Press, NY, NY, 1995.

22. Schuller, M.P., R.H. Atkinson, J.L. Noland, “Structural Evaluation of Historic Masonry Buildings,” APT Bulletin, The Journal of Preservation Technology, Vol. XXVI, No. 2-3, Williamsville, VA, 1997.

23. Sickels-Taves, Lauren B., “Selecting Mortar for Historic Preservation Projects,” Aberdeen’s Magazine of Masonry Construction, Vol. 10, No. 10, Addison, IL, October 1997.

24. Sickels-Taves, L.B., M.S. Sheehan, I. Rovner, "Computer-Assisted Optical Stereology in Historic Preservation: Tabby, a Case Study," APT Bulletin, The Journal of Preservation Technology, Vol. XXVIII, No. 2-3, Williamsville, VA, 1997.

25. Speweik, J.P., "Repointing Historic Masonry Buildings to Last - Return of Lime Putty Mortar," Masonry Magazine, The Aberdeen Group, Oak Brook, IL, September/October, 1997.

26. Suprenant, B.A. and M.P. Schuller, *Nondestructive Evaluation and Testing of Masonry Structures*, The Aberdeen Group, Addison, IL, 1994.

27. Van der Blis, A.C., "Rock Classification by a simple Hardness test," Proceeding of the 2~id Congress, Beograd Conference, v.2, 1970.

28. Van der Klugt, L.J.A.R., "The Pointing Hardness Tester - an Instrument to Meet a Need," Materials and Structures, vol. 24, RILEM, Paris, France, 1991.

29. Vitruvius, *The Ten Books of Architecture*, Translated by Moths H. Morgan, Dover Publications, NY, 20 AD

30. Williams, G., "Pointing Stone and Brick Walling," Technical Pamphlet 5, The Society for the Protection of Ancient Buildings, London, England, 1979.

# APPENDIX A - DRAFT STANDARD TEST METHOD

**Standard Test Method for the Determination of the Rebound Hardness of Masonry Mortar**

1. **Scope**
   1.1 This test method covers the determination of the rebound number of hardened mortars using a pendulum hammer with a steel impact head. The test method is limited to masonry mortar with joint thickness greater than or equal to 3/8 in. (9.53 mm) that are accessible for testing with the rebound hammer shown in figure 1.
   1.2 Use of this test method may cause 3/8 in. (9.53 mm) diameter circular indentations in mortar joints up to 5/16 in. (7.94 mm) deep.
   1.3 *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. **Referenced Documents**
   2.1 ASTM Standards:
   E 177 Practice for Use of the terms Precision and Bias in ASTM test methods[1]
   E 122 Standard Practice for Choice of Sample Size to Estimate a Measure of Quality For a Lot or a Process[2]

3. **Significance and Use**
   3.1 The purpose of this test method is to determine a hardness property of masonry mortar in-situ with a simple apparatus. The rebound number has no units and describes the magnitude of the rebound of a mass from a surface when released from a certain height. This test is suitable for use as an aid in the evaluation of masonry and the selection of pointing mortar.

4. **Apparatus**
   4.1 *Pendulum Rebound Hammer—The* pendulum rebound hammer shall be the Schmidt type PM pendulum hammer manufactured by the Proceq Company of Switzerland. This hammer is shown in Fig. 1.

---

[1] *Annual Book of ASTM Standards*, Vol. 14.02
[2] *Book of ASTM Standards*, Vol. 14.02

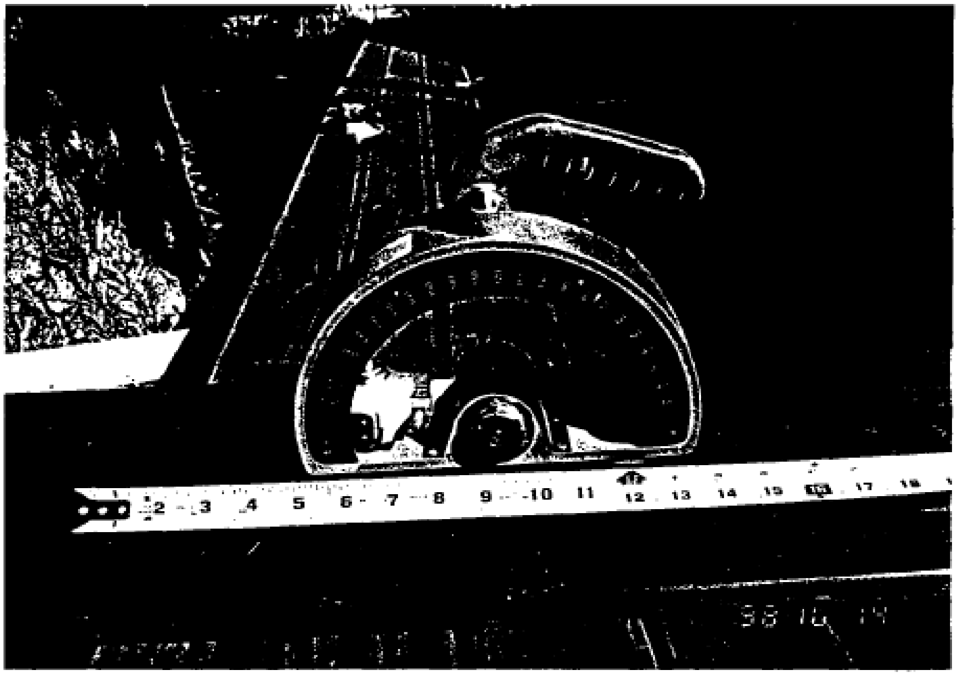



Fig. 1 Pendulum Rebound Hammer

4.2 Calibrate the pendulum rebound hammer using a steel anvil of the type available from the manufacturer or another such mass that gives consistent rebound numbers. It is recommended that the pendulum hammer be calibrated after 1000 impacts. The maximum allowable deviation from the calibrated reference value is *+1*- 2 units. The rebound values are sensitive to temperature variations of the calibration mass and the rebound hammer.

## 5. Test Area

5.1 *Selection of Test Area—Masonry* shall be fixed within a structure or rigidly supported. The surface of the mortar joint must be recessed no more than 5/16 in. (7.94 mm) from the surface of the masonry units. The joint thickness must be 3/8 in. (9.53 mm) or more to accommodate the impact head. The masonry surface must be near vertical. Tooled joints yield higher rebound numbers than struck joints.

5.2 *Surface Preparation*—Paint and other sealants must be removed from the mortar surface prior to testing.

## 6. Procedure for Hard Mortars

6.1 For this procedure, a hard mortar is defined as one that, after being impacted by 10 successive rebound hammer blows on the same location and in the same direction, will be indented a distance less than that distance which will cause the range of motion of the hammer to be exceeded.

6.2 Position the rebound hammer such that the hammer head will fall in a vertical plane and strike a mortar bed joint.

6.3 Prior to impacting the surface, allow the hammer head to rest on the mortar and record the reading from the scale as the initial offset.

6.4 While holding the device firmly in place, impact the mortar surface ten times and record the rebound numbers.

6.5 Repeat this procedure at 9 or more locations in a region of interest that appears to have uniform properties[3].

## 7. Procedure for Soft Mortars

7.1 For this procedure, a soft mortar is defined as one that, after being impacted by 10 successive rebound hammer blows on the same location and in the same direction, will be indented a distance greater than or equal to that distance which will cause the range of motion of the hammer to be exceeded.

7.2 Duplicate the procedure for hard mortars but impact the surface once instead of ten times and at 26 locations instead of 9 locations within the test area[3].

## 8. Calculation of Results

8.1 *Calculation of Average Rebound Number for Hard Mortars*—For each series of 10 rebound readings from one location, discard the first *5* of the 10 readings. Subtract the initial offset recorded for that location from each of the *5* remaining readings. Calculate the arithmetic mean of all of the remaining corrected readings for the 9 or more series of impacts from the test area.

8.2 *Calculation of Average Rebound Number for Soft Mortars*—Subtract the initial offset recorded at each location from the rebound reading from that location. Calculate the arithmetic mean of the 26 or more corrected readings from the test area.

## 9. Report

9.1 The report shall include the following:

9.1.1 The name of the person or persons conducting the tests.

9.1.2 The hammer type, serial number, and evidence of calibration.

9.1.3 Identification of the structure tested and date of construction, if available.

9.1.4 Description of testing conditions (for example, temperature).

9.1.5 Location of each area tested within the structure.

9.1.6 Description of the masonry:

9.1.6.1 Type of masonry unit, including any known material properties and any known history.

[3]The number of impact locations was determined using ASTM 122, *Standard Practice for Choice of Sample Size to Estimate a Measure of Quality for a Lot or a Process*, using a maximum allowable sampling error of 10% of the process mean, and a probability factor of 3 to give a 3 in 1000 probability that the sampling error will exceed the maximum allowable sampling error. For hard mortars, a coefficient of variation of 10% was used. For soft mortars, a coefficient of variation of 17 % was used. These coefficients of variation were determined by calculating the arithmetic mean of the coefficients of variation of 8 groups of more than 30 impacts or series of impacts performed on laboratory test specimens.

9.1.6.2 Type of mortar, including any known material properties or constituents, any known history including age and the date of any pointing work and the type of pointing mortar.

9.1.6.3 Sketch of wall configuration, including joint thicknesses, number of wythes, cavity or collar joint, and wall thickness.

9.1.6.4 Test procedure used (procedure for hard or soft mortar) and the average rebound number for each test area.

## 10. Precision and Bias

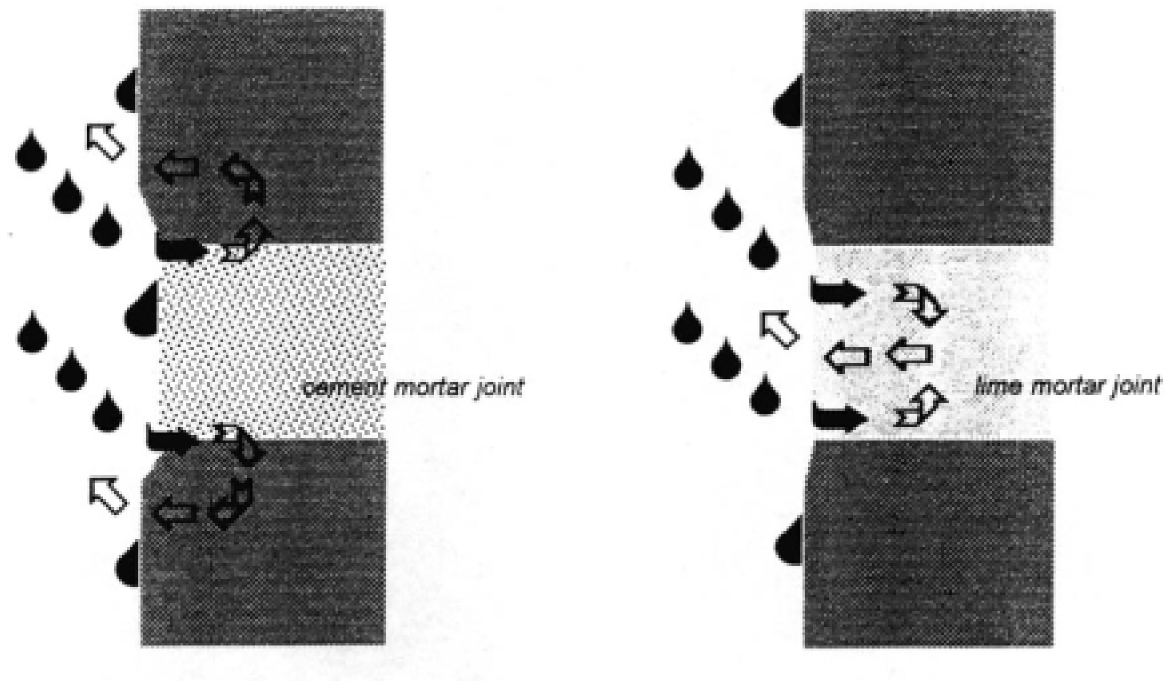
10.1 *Precision*

10.2 The available test data shows the coefficient of variation of this test method to be as great as 10% and it is recommended that a minimum of three tests be conducted in the same general area to verify test results.

## 11. Keywords

in-situ; hammer; hardness; masonry; mortar; nondestructive evaluation; pendulum

# APPENDIX B - FIGURES




*moisture evaporates through stone and face of stone weathers back*

*moisture evaporates through mortar and face of joint weathers back*

Figure 2.1 Moisture transmission through cement and lime mortar joints (from Gibbons, 1995).

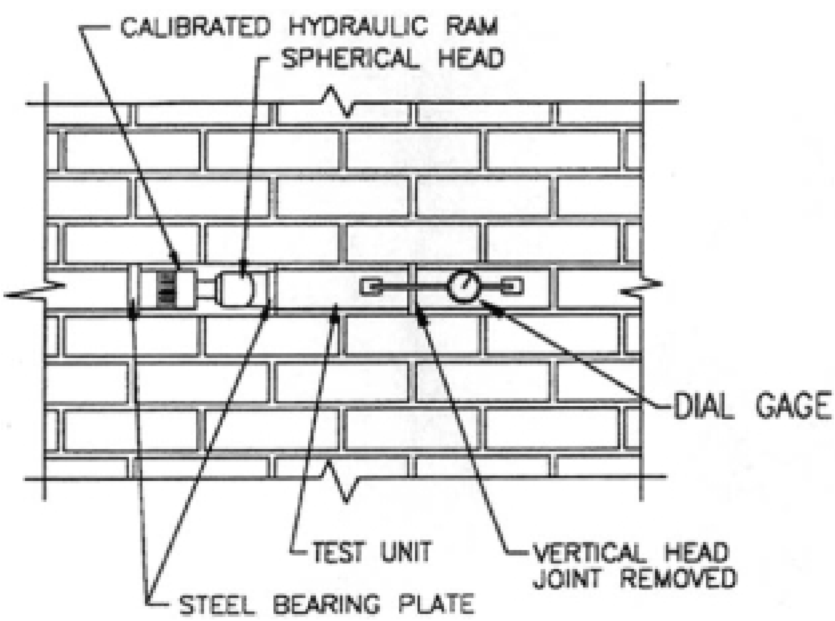



Figure ‘2.2. Schematic of the in-place push test (from Suprenant and Schuller, 1994).

Figure 2.3. The Schmidt type PM pendulum hammer in use.

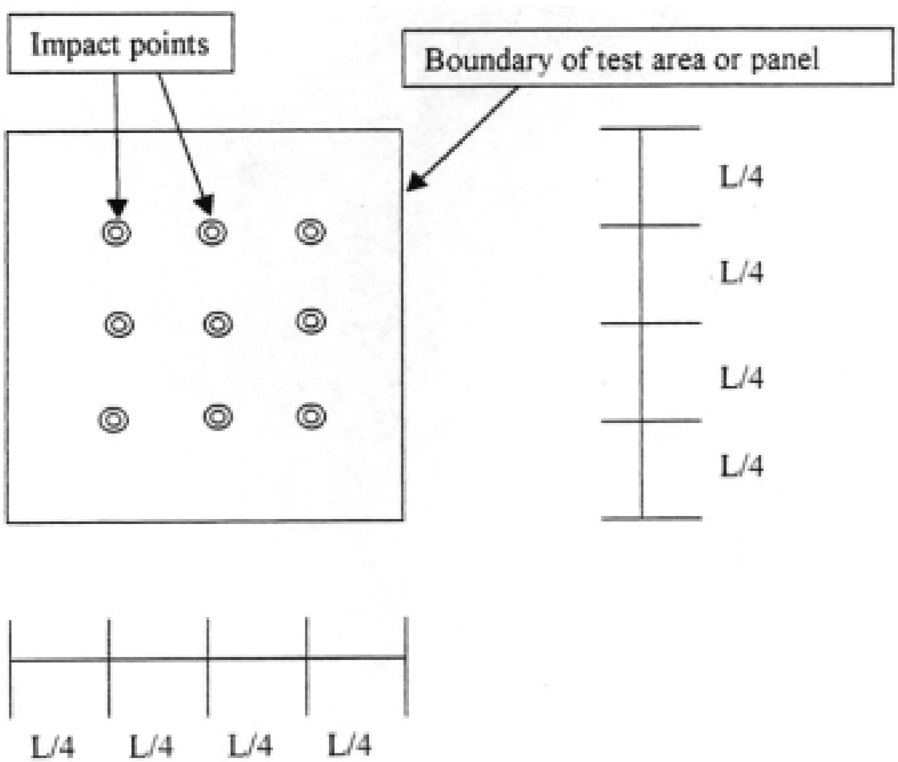



Figure 2.4 Example of the spacing of impact points for determining the rebound value in accordance with RILEM MS.D.7.

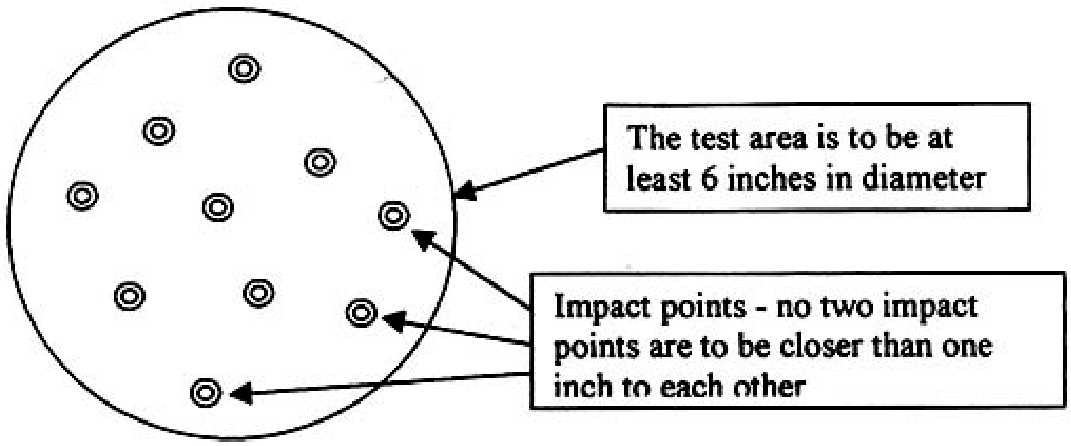



Figure 2.5. Example of the spacing of impact points for determining the rebound value in accordance with ASTM C 805.

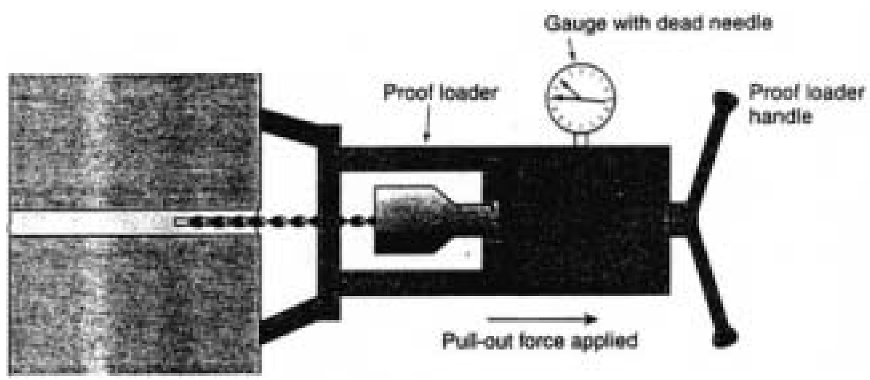



Figure 2.6. The screw pullout test (from BRE Digest 421).

Figure 2.8. Cross-section of a wall from the Pavia Tower.

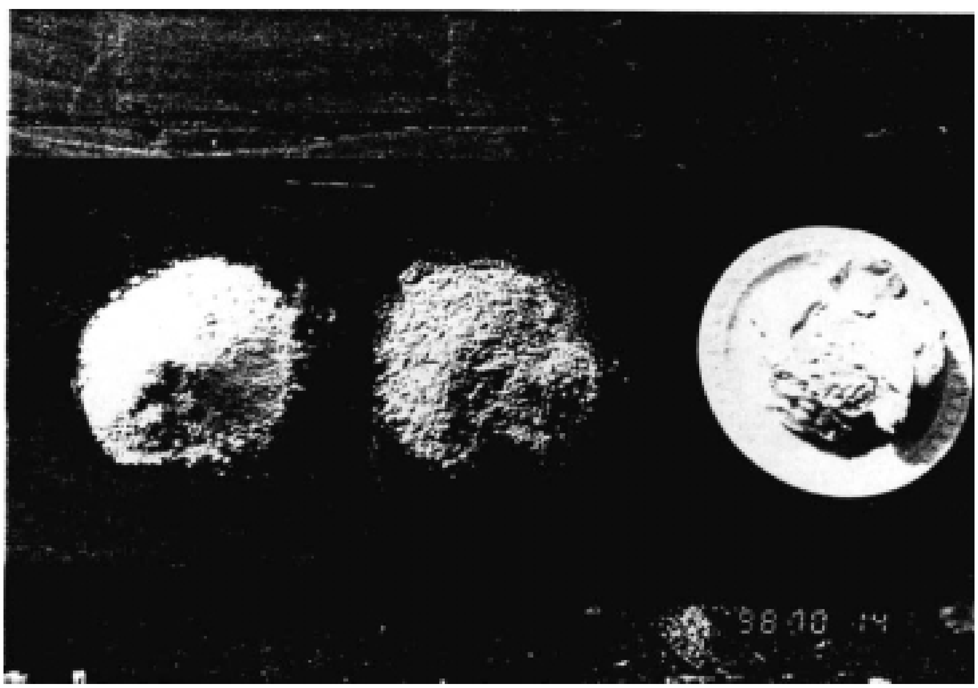


Figure 3.1. From left to right: type S hydrated lime, hydraulic lime, and lime putty.

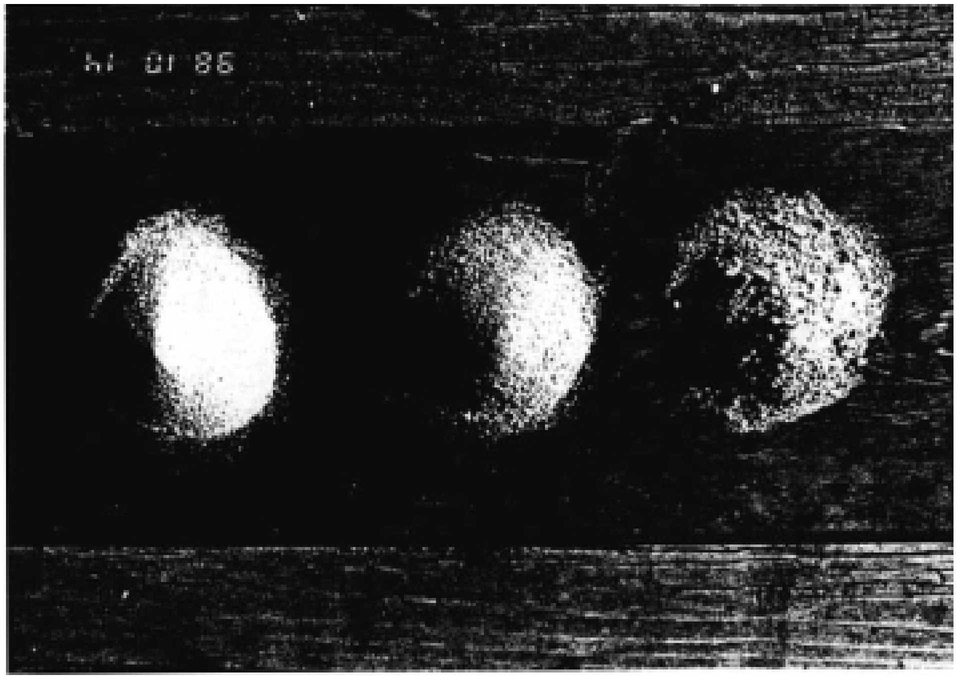


Figure 3.2. From left to right: fine sand, play sand, and coarse sand.


Figure 3.3. Hydraulically pressed molded bricks circa 1900.

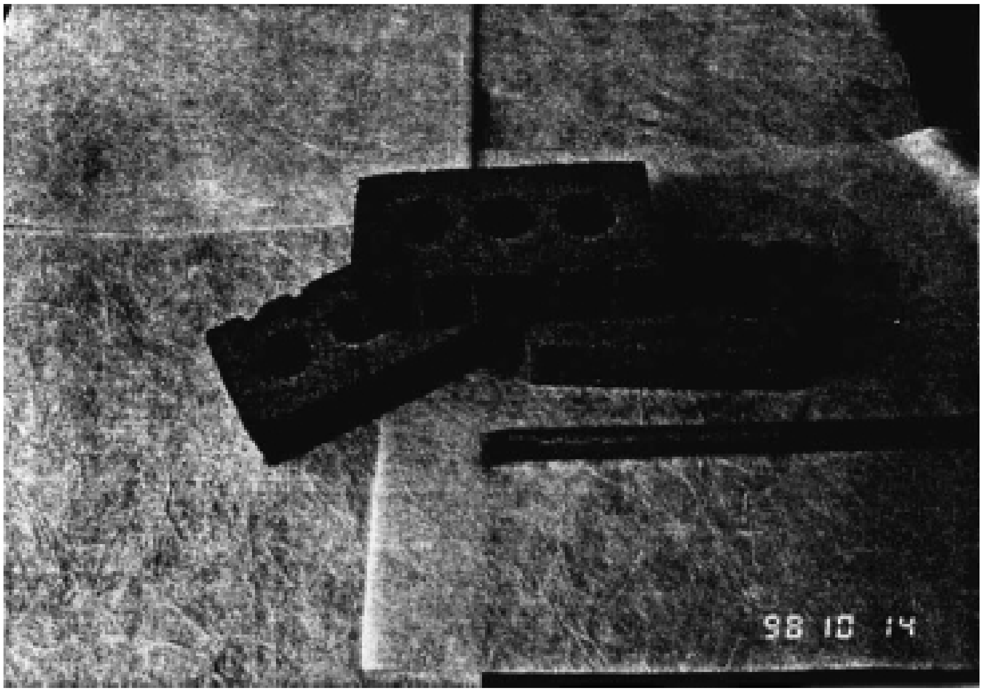


Figure 3.4. Modem extruded, cored, clay bricks.


Figure 4.1. Steel plate with mortar base prepared for pier construction.

Figure 4.2. Checking for horizontal level during pier construction.

Figure 4.3. A pier in construction with a solid collar joint.

Figure 4.4. The tooled joints of a pier.

Figure 4.5. Completed piers in the laboratory.

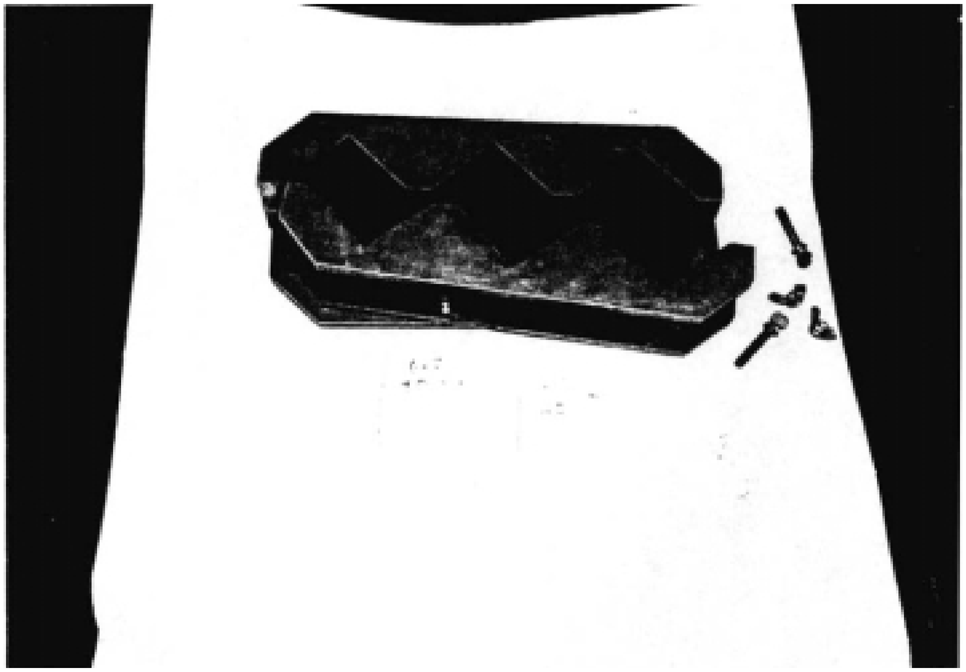


Figure 4.6. Mortar cubes and a brass mold.

Figure 5.1. Mortar is tamped in the brass mold on the flow table.

Figure *5.2*. Excess mortar is scraped from the top of the mold to leave a level surface.

Figure 5.3. The brass mold has been removed from the mortar on the flow table.

Figure 5.4. The diameter of the mortar pancake is measured with calipers.

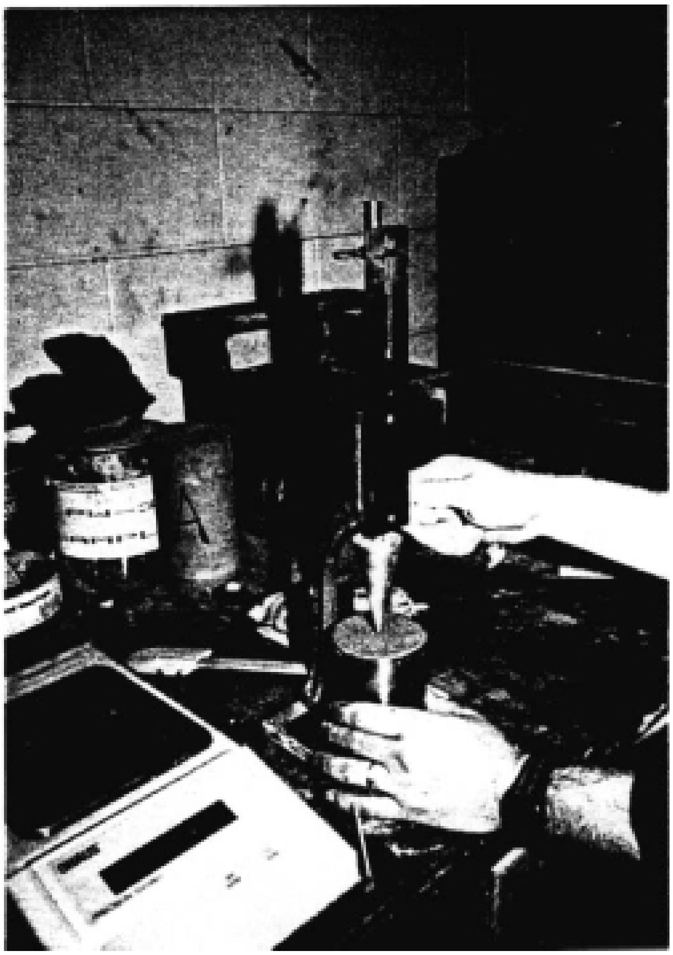


Figure 5.5. Modified Vicat cone penetration apparatus.

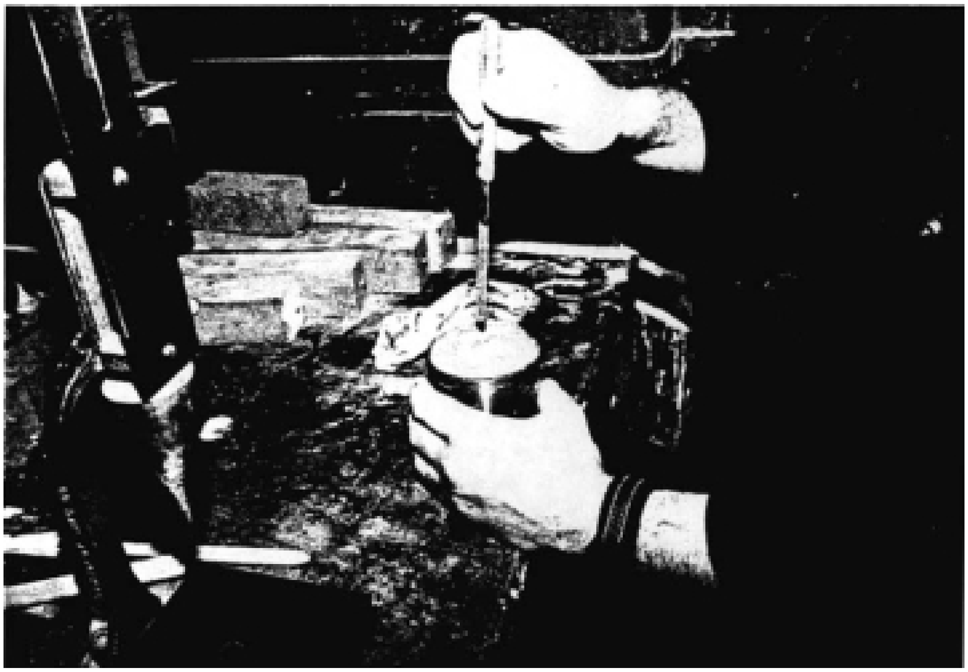


Figure 5.6. The last of three lifts of mortar is tamped with the steel spatula.

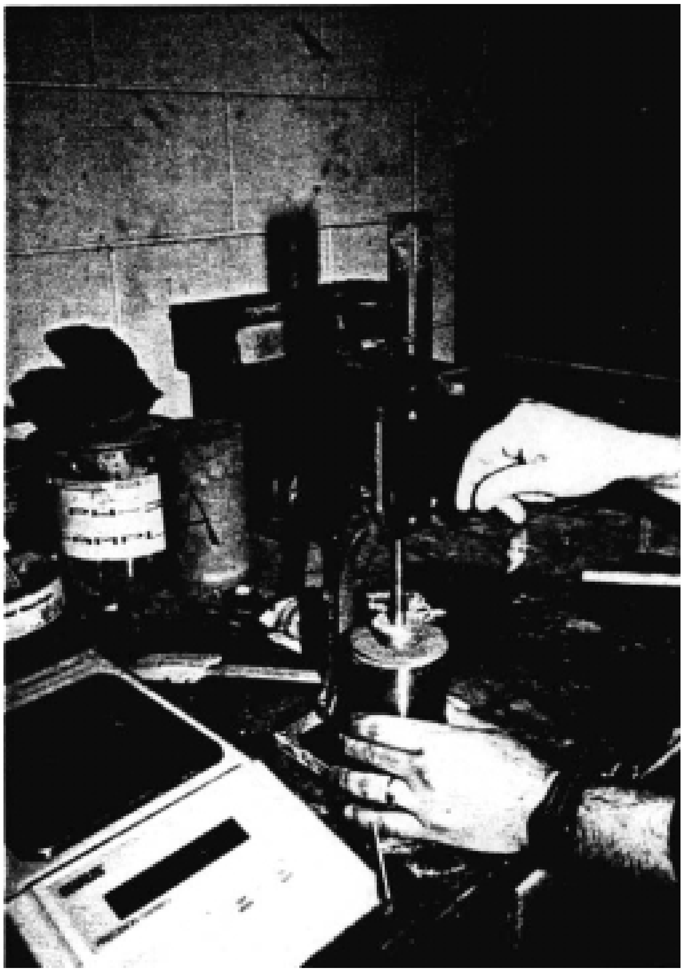


Figure 5.7. The Vicat cone has been released and has fallen into the cup of mortar.

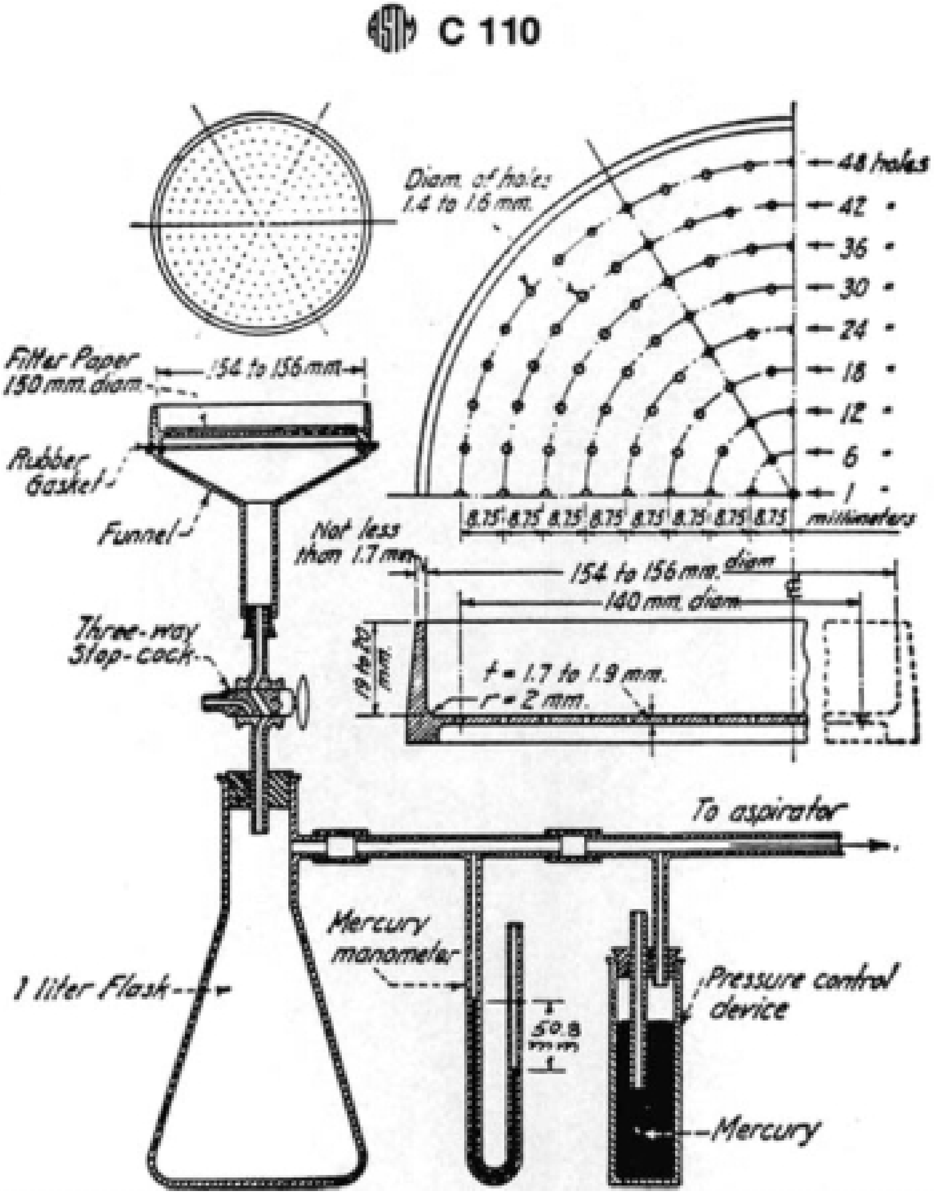



Figure 5.8. Apparatus Assembly for the Water Retention Test (figure taken from ASTM C 110).

Figure 7.1. Pendulum hammer testing in the undercroft of the Basilica of the Assumption.

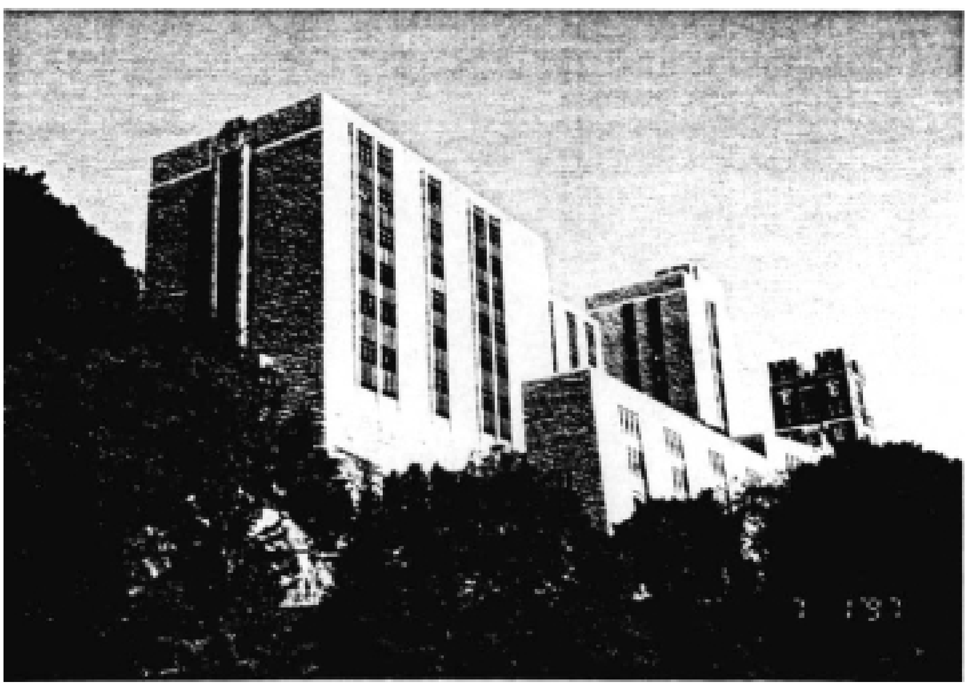


Figure 7.2. South elevation of Mahan Hall, West Point Military Academy.

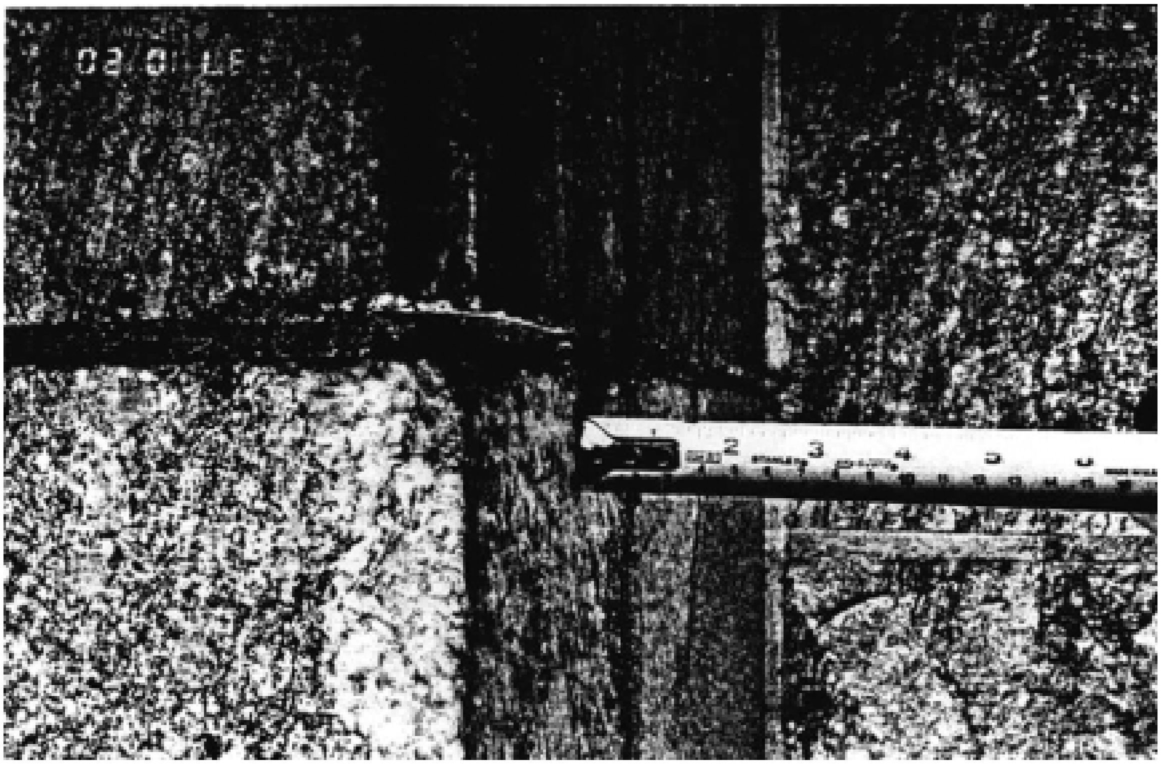


Figure 7.3. Poorly bonded pointing mortar at Mahan Hall.

Figure 7.4. South elevation of the Chamberlin Observatory.

Figure 7.5. Southwest elevation of the Graham Bible House Carriage House.

## APPENDIX C - REFERENCED ASTM STANDARDS

ASTM C 109, *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (using 2-in, or [50 mm] Cube Specimens*
ASTM C 110, *Test Methods for Physical Testing of Quicklime, Hydrated Lime, and Limestone*
ASTM C 136, *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*
ASTM C 150, *Standard Specification for Portland Cement*
ASTM C 207, *Standard Specification for Hydrated Lime for Masonry Purposes*
ASTM C 230, *Specifications for Flow Table for Use in Tests of Hydraulic Cement*
ASTM C 270, *Standard Specification for Mortar for Unit Masonry*
ASTM C 780, *Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry, Annex Al, Consistency by Cone Penetration Method*
ASTM C *805, Test Method for Rebound Number of Hardened Concrete*
ASTM C 1072, *Test Method for Measurement of Masonry Flexural Bond Strength*
ASTM C 1324, *Standard Test Method for Examination and Analysis of Hardened Masonry Mortar*
ASTM E96, *Standard Test Methods for Water Vapor Transmission of Materials*
ASTM E 122, *Standard Practice for Choice of Sample Size to Estimate a Measure of Quality for a Lot or a Process*