Natural Cement

Michael P. Edison
Editor

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Michael P. Edison, editor

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Foreword

ASTM publications on hydraulic cement technology do not usually include treatises on American History, and historians do not often study the science and technology of hydraulic cements. Yet technology and history are inexorably interwoven, and that is nowhere more evident than it is in the field of historic restoration.

Historic restoration, by nature, is a multi-disciplinary undertaking, including both technical and historical components. Sound technical decision-making requires an understanding of historical practices, and sound historic preservation decision-making requires an understanding of the underlying materials science. Over the past 20 years, there has been a growing revival in the use of traditional materials for the restoration and maintenance of historic buildings and structures. Yet it is only recently that the pivotal role of natural cement in 19th and early 20th Century construction has been rediscovered.

Although there is a wealth of historical and technical documentation of past uses and practices for natural cement, some publications are rare, and not readily available to restoration practitioners. There are also technical challenges associated with incorporating traditional technology into contemporary work. New research is required to update our understanding of traditional materials and performance expectations must be redefined in terms of modern standards and testing protocols.

This STP is designed as a unique resource, providing historical and technical foundations in the original uses of natural cement, while disseminating current information on contemporary practices and results of recent research. The publication is divided into three sections:

1. Papers from the First American Natural Cement Conference, held in Rosendale, NY in March, 2005

2. Papers from the Second American Natural Cement Conference, held in Washington, DC in March, 2006

3. Supplemental Historical and Technical Resources

The conference papers are the first original material published on natural cement in more than 30 years. In joining them with the supplemental resources, this STP represents the most comprehensive work on the subject since the publication of American Cements by Uriah Cummings, more than a century ago. The supplemental resources were selected as follows:

ASTM C 10 - 06 Specification for Natural Cement
The current standard for natural cement, as of the time of this publication, was adopted on September 1, 2006. The reinstatement of one of ASTMs oldest standards was a critical step toward re-establishing natural cement within the mainstream of contemporary construction materials. While providing assurances that today's natural cement will meet the expected technical performance requirements, the standard maintains a strong historical connection to the traditional material.

Report of Committee C on Standard Specifications for Cement (1904)
In 1904, during the period predating establishment of the current system of standards numbering, Report of Committee C on Standard Specifications for Cement established comprehensive standards for natural and portland cements.

Excerpt: Internal Navigation, (1817)
The history of American natural cement began in the early 19th Century canal-building era. Young's 1817 compilation, Internal Navigation, provides a snapshot of the state of technology in canal construction and operation at the time just prior to the commencement of construction of the Erie Canal and the discovery of natural cement rock in Fayetteville, New York. The excerpt details the earlier uses of Dutch trass in lime-pozzolan mortars for canal construction, and predicts that the limestone materials required to produce hydraulic mortars will be found in New York State.

Excerpt: Essays on Hydraulic and Common Mortars and on Lime-Burning, (1838)
The adoption of natural cement technology for use in construction of seacoast fortifications can be largely attributed to the work of Colonel Joseph G. Totten of the Corps of Engineers. Working at West Point and at Fort Adams in Newport, Rhode Island, Totten experimented with various forms of lime and cement over the course of 13 years of construction. His conclusions, published in 1838, heavily favored the use of natural cement from Rosendale, NY. Totten also favored the use of lime hydrates over lime putty, for structural applications, based on its superior performance in his experiments.

Excerpt: Handbook of Railroad Construction; for the use of American Engineers, (1857)
The practices for use of natural cement in the mid-19th Century are concisely summarized in an excerpt from the1857 Handbook of Railroad Construction. It provides a formulary for natural cement mortars, concretes, stucco, grout and coatings, and includes a clear reference to the early practice of using hot-mixed hydrated lime in American engineering construction.

Excerpt: American Cements, Uriah Cummings, 1898
In the late 1890s, natural cement production was at its peak, with some 70 producers operating in 15 states. At the same time, American portland cement was rapidly gaining market share, and Cummings, a natural cement producer, sought to defend what he saw as the superior durability and performance of natural cement.

In his closing arguments, he cites the wonderful record of natural cement, listing several hundred prominent buildings and structures and identifying the sources of the natural cement with which they were built. This list is reproduced as a valuable reference, as many of these buildings and structures remain standing today, and some will undoubtedly endure for centuries to come. A number of these structures have been the subjects of recent maintenance efforts, and in each case the forensic evidence has confirmed Cummings representations.

Michael P. Edison
Edison Coatings
Plainville, CT

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Leya L. Edison[1]

Perspectives: The Reintroduction of Natural Cement

ABSTRACT: The development of natural cement technology was the culmination of thousands of years of research and development. Its rise to become the primary hydraulic binder used in buildings and structures in the United States occurred in the 19th century. Today, it is again finding a place in the restoration industry. Ultimately, it is the understanding of both the history of this technology and its redefinition in contemporary technical terms that will guide appropriate use of this traditional 19th century material in 21st century restoration work. The First and Second American Natural Cement Conferences brought together experts from a wide variety of disciplines in order to re-establish and augment the base of knowledge for this technology and our connection to it.

Mortar History

A brief overview of mortar history is required to understand the historic context of the natural cement era. Mortar history begins 4000 years ago in ancient Egypt where the oldest known durable mortars were produced using a gypsum plaster with low-fired lime impurities [1].

Over 2000 years ago, the Romans not only used lime, but also discovered the first methods for making hydraulic mortars for use in aqueducts and other structures that would be immersed in water. According to Vitruvius, who wrote a tome in the 1st century BCE about the technologies of his day, they used a mix of lime and volcanic ash [2]. In areas where ash was unavailable, they used ground-up tile or pottery fragments. As with a number of other things, it is likely the Romans appropriated some of this technology from the Greeks.

The Dark Ages which followed the fall of the Roman Empire marked the loss of scientific and technical knowledge. Included was the loss of the ancient formula for hydraulic mortar used during Roman times. The use of simple lime mortars resumed, and remained the primary technology for over 1000 years.

It was not until the mid-18th century that English engineer John Smeaton began to experiment using other materials with lime. In particular, he discovered that clay impurities in limestone produced hydraulic properties, allowing these mortars to set under water and to resist deterioration from water exposure. This represented an important difference from simple lime mortars and a pivotal point in mortar history. In the course of time it would have a great effect on construction practices both in Europe and the soon to be independent colonies of America.

The Rise of Natural Cement

Early American Colonial history depicts George Washington as a leader in military planning and democratic principles, but he was an astute businessman as well. Long before the Revolutionary War, Washington, a wealthy land owner and an innovative farmer, managed a small industrial village in Mount Vernon [3]. It was these interests, no doubt, that guided his activities after the war. George Washington was among the first to recognize the importance of infrastructure for the transporting of goods to the marketplace.

Following the independence of the colonies, a financially weak national government left our borders vulnerable. In addition, problems surfaced regarding interstate trading and transportation of goods. Confusion, local skirmishes, and even outright fighting were commonplace among the newly formed states. Washington focused his attention on areas around the Potomac, the James River in Virginia, and the

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[1] Conference Moderator, First/Second American Natural Cement Conference.

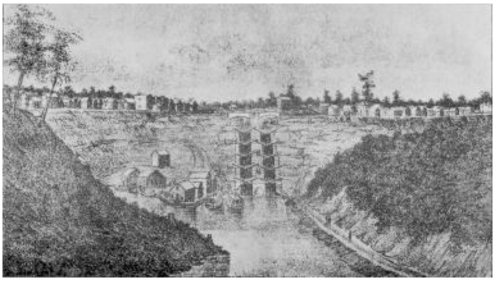

FIG. 1—*The "Flight of Five," five successive locks on the Erie Canal at Lockport, NY, was one of the most challenging structures built on the original Erie Canal (1825) [7].*

Mohawk River Valley region in upstate New York—the future route of the Erie Canal. In the 1780s, as the President of the newly formed Potowmack Company, he led the first attempt to construct a canal from Georgetown to Harper's Ferry, West Virginia. Though ultimately unsuccessful, his actions inspired others to continue the mission to construct the vast canal systems that began America's economic growth in the 19th century [4].

During the same period in Europe, the use of hydraulic materials had become commonplace. Dutch trass, a volcanic mud composed of clay and silica, was being used in combination with lime to build the Dutch system of dykes and levees. Some of this material was imported to America from the Dutch West Indies and was used in early canal construction [5].

In England, John Smeaton's work was published posthumously in 1791, and in 1796, the first commercial hydraulic cement was patented and produced under the name "Parker's Roman Cement." British canal systems widely used this hydraulic material. While it was considered costly to transport to America, it is known that some quantities of this material were imported and utilized during this period. Therefore, it is possible that from the late 1700s going forward, historic American mortars may have been based on materials other than just lime.

In the early 19th century, pivotal events helped speed the implementation of Washington's ideas regarding infrastructure for interstate commerce and securing our coastlines for national defense. In August of 1814, British troops landed on the Atlantic Coast, and after defeating a small American force at Bladensburg, Maryland, under the personal leadership of President James Madison, they invaded Washington and burned the White House, Capitol, and the Treasury building. Congress retreated to the mountains of Virginia, and Dolly Madison, the first lady, fled with as many White House treasures as she could carry. This was a low point in American history, and Congress was determined never to allow it again. The British continued on to Baltimore, where instead of finding an enemy demoralized by the destruction of its national symbols, they found a force of thousands of citizen-soldier volunteers prepared to fight. In the process they inspired Francis Scott Key to write a national anthem that continues to inspire us today.

Following the war, Congress mandated that the fledgling U.S. Army Corps of Engineers be charged with the construction of a system of seacoast fortifications to protect the Atlantic Coast, the Gulf Coast, the Great Lakes and the western port of San Francisco [6]. At the same time, plans were progressing for the construction of the Erie Canal. As canals built before the Erie using lime were performing poorly, the builders of the Erie Canal sought new materials and sent engineer Canvas White to England to study their canal construction methods. Upon his return, he recommended the use of Parker's Roman Cement. Due to the high cost of importing this material, they opted, in 1817, to proceed with construction using lime. By 1818, this lime work was already failing. White then sought and soon found a deposit of an impure limestone, similar to those studied by Smeaton and used by Parker, which, when burned, formed natural hydraulic cement.

The 365-mile canal, including hundreds of dams, locks (Fig. 1), retaining walls, and buildings of various types were constructed using this natural cement. From this point, over 150 other canal systems were built utilizing this material.

In the mid-1820s, the successful civilian use of natural cement and its increasing domestic production led the military to experiment with natural cement for construction of seacoast fortifications. During the

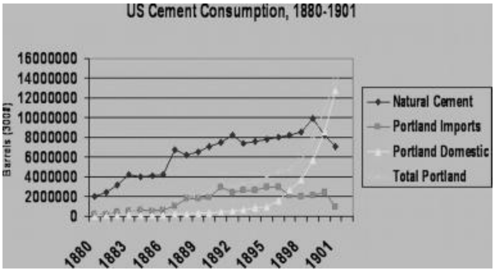

FIG. 2—*U.S. consumption of natural and portland cements, 1880–1901 [9].*

construction of Fort Adams in Newport, Rhode Island, extensive experiments were performed using various forms of lime and natural cement mixes. Following completion of the fort's construction in 1838, Colonel Joseph Totten published the results of his studies, including his conclusions that natural cement was the material of choice [8]. Totten was promoted to General and given command of the U.S. Army Corps of Engineers in Washington, DC. For the next 40 years, virtually all military construction utilized natural cement.

As America's economy began to grow, in part because of improved infrastructure, huge changes occurred in building practices. In the late 1830s the Industrial Revolution began to reach America. Large industrial structures had to be built, as well as the dams, power plants, roads, and bridges necessary to support them. By the mid-19th century, the nation's substantial system of canals began to be supplanted by a new, faster form of transportation for both goods and people—the railroads.

In the vast majority of these constructions, natural cement either solely, or in combination with lime, was used in masonry mortars, early concretes, and stuccos. Changes, however, were imminent.

Portland Cement

In Great Britain in the 1820s Roman cement resources were becoming less plentiful and more difficult to obtain. This reality encouraged the development and production of artificial cements that would match the characteristics of Roman cement. In 1825, James Aspdin patented the first portland cement. By the mid-19th century, this material was rapidly growing in usage in parts of Europe that had nearly depleted their Roman Cement sources.

In 1875, the first American portland cement plant began production. Quantities were small at first, and quality was initially considered inferior to English and German portland cements. It was not until 1897 that U.S. production of portland cement exceeded importation of all foreign cements. At this point in history, portland cement usage levels began to catch up to natural cement usage. Until that time, natural cement was the dominant material used in major construction in the 19th century in this country. Roman cement was dominant in Europe during the same period.

By the turn of the 20th century, portland cement was becoming the dominant technology in this country, and masonry mortars based on portland cement and lime became the most frequently used materials (Fig. 2). This was due, in part, to the higher strength that was achieved using portland cement, and the shorter time required to achieve it, compared with natural cement.

In 1970 the last of the original natural cement producers, The Century Cement Company in Rosendale, New York, closed its doors. Rosendale was the historic center of the natural cement industry and is now the birthplace of its revival.

The Natural Cement Revival

At the start of the 21st century, natural cement had not been used in great quantities for almost 100 years. In the 20th century it had been used only sporadically, and with the closing of the last remaining working natural cement mine in 1970, it had been out of production for over 30 years. Virtually all working knowledge of natural cement had been lost. Craftsmen had no experience working with it, architects and

FIG. 3—*Participants in the First American Natural Cement Conference gather at the ruins of the Binnewater Cement Mill in Rosendale, NY, in March 2005.*

engineers had never heard of it, even petrographers could not recognize it, and most historians had forgotten about it. The goal of the first American Natural Cement Conference was to begin the reversal of that predicament.

In March/April of 2005, the first American Natural Cement Conference was held in Rosendale, New York. Speakers represented a wide range of disciplines including history, geology, petrography, chemistry, engineering, restoration architecture, and the masonry trades. While thousands of buildings and structures, originally built with natural cement, remain in service, very few of today's restoration professionals and trades people have any experience in appropriately identifying and preserving these structures using the original natural cement materials.

First Conference Papers

The American Natural Cement Conferences were designed to be a complete experience, providing both technical knowledge and historical context, while allowing participants to connect with places that are deeply associated with the history of this material (Figs. 3 and 4).

The first paper of this publication, *The Natural Cement Revival,* appropriately begins with the story of the revival itself. Author Ken Uracius, a mason trained in traditional materials, relates his experiences in the course of his work on the restoration of Fort Adams in Newport, Rhode Island. He came to question the lime-based technology used for the restoration of this historic structure. So began his quest to rediscover the history, technology, materials, and processes used in the production of natural cement in the 19th

FIG. 4—*Nineteenth century illustration of Harpers Ferry, WV, site of a segment of the Second American Natural Cement Conference. Natural cement was used in the building of the C & O Canal along the river's far shore, the B & O Railroad, and many of the town's buildings.*

FIG. 5—*Remains of the Fort Scott Hydraulic Cement Co. kilns still stand in Fort Scott, KS, one of over 70 sites where natural cement was produced in the 19th and 20th centuries.*

century. Ultimately, this led to the reintroduction of natural cement as a contemporary restoration material [10].

The next paper is *An Overview of the History and Geology of the Natural Cement Industry at Rosendale, Ulster County, New York*, by Dietrich Werner and Kurtis C. Burmeister. Werner, President of the Century House Historical Society in Rosendale, New York, recaps the beginnings of mining and use of natural cement in the United States. Taking us back to the exploration of New York's Mohawk Valley, Werner writes of Erie Canal Engineer Canvas White. Werner's paper traced the development of the natural cement industry and its rise to prominence in the 19th century [11].

By the 1890s, natural cement was produced by more than 70 plants in 17 states employing thousands of workers in the production of up to three billion pounds per year (Fig. 5). It was the dominant technology for both engineering and large-scale architectural construction. Its uses included the construction of canals, dams, drinking water systems, sewer systems, lighthouses, military fortifications, bridges (Fig. 6), railroads, federal, state, and municipal buildings, industrial complexes, large commercial buildings, and others [12]. The building of America in the first century of our independence is reflected in these structures. Arguably, then, these structures are as much a part of our history as the struggle that compelled us to build them.

While history tells us of the use of this cement, geology sets the backdrop for its creation. Geologist Kurtis Burmeister detailed the geological processes that formed the natural cement deposits in Rosendale, NY, and the methods used by 19th century producers to extract and process this valuable resource [11].

Dr. Burmeister's presentation at the second conference compared and contrasted geological formations in New York State with those in the Potomac River Valley and elsewhere around the world. These

FIG. 6—*The Stone Arch Bridge in Minneapolis is one of the numerous surviving structures documented as having been built with natural cement. Photo by the author.*

differences have significant impact on the ultimate working properties of the cements made from these materials.

Understanding both the properties of natural cement and its utilization in 19th century mortars, stuccos, and concretes is basic to its successful use as a restoration material. In *Formulating with Rosendale Natural Cement,* Michael Edison, a chemical engineer and President of Edison Coatings, Inc., reviews 19th century formulation practices using natural cement in mortars, stuccos, concretes, grouts, and limewash. The expanded use of natural cement is currently possible due to the widening range of additives and the advancement of production technologies. The consistency of burning, process additions, and customization of grinding practices can produce higher quality materials without waste, and allows greater control in the final characteristics of the product—such as set time, color, workability, and flow. These elements were not available in the production practices of the 19th century [13,14].

A troubling issue encountered in the revival movement is that of identifying natural cement in existing structures. One means of natural cement identification is by review of existing documentation available in the form of numerous books and other works published over the course of more than one and one-half centuries. These writings may include lists of natural cement buildings and structures. But what of those uncounted thousands of natural cement structures that are undocumented? In addition to this, the practice of restoring these structures with materials other than natural cement mortars was and continues to be quite common. Therefore, the presence of substitute materials hampers efforts to identify the composition of the *original* materials. If historically correct and compatible restoration work is to be done, accurate identification of the original materials is essential.

At the First American Natural Cement Conference, John Walsh, a geologist and petrographer with Testwell Laboratories in Ossining, New York, illustrated how standard analytical procedures could be used to accurately identify natural cement and distinguish it from other historic binders. *Petrography: Distinguishing Natural Cement from Other Binders in Historical Masonry Construction Using Forensic Microscopy Techniques* deals with this critical issue [15]. Because petrographic analyses of historic binders are so often done incorrectly, and proper identification is such a basic prerequisite for historically accurate restoration work; Mr. Walsh was asked to present his laboratory methods at the second conference as well.

This information was instrumental in corroborating the identity of original natural cement materials at Fort Jefferson, off the Coast of Florida. The site became one of the first major restoration projects to utilize natural cement in this century. The initial identification of the mortar used in this structure incorrectly concluded that it was some form of lime. That conclusion was challenged based on historic documentation citing natural cement as the material used in Fort Jefferson. The final verification came in the form of a petrographic analysis by John Walsh.

The masonry at Fort Jefferson was found to be in remarkable condition, despite lack of maintenance since the beginning of its construction in 1840. It has endured extreme weather and marine exposures without significant masonry deterioration. The need for restoration was a result of the corrosion of cast iron shutters used to protect artillery crews from incoming fire. The evaluation process included a mock-up phase which comprised one of the first modern day uses of natural cement on a significant scale.

Second Conference Papers

The second Conference was held in Washington, DC and Harper's Ferry, WV (Fig. 7), in March/April of 2006.

Michael Edison's *Natural Cement in the Twenty-First Century* describes the work of ASTM Task Group C1.10.04 on natural cement. This group developed the current, reinstated standard for natural cement, designated as ASTM C 10. The paper also discusses techniques for color matching of natural cement formulations for use in historic restoration work.

The first significant modern use of natural cement in an historic restoration project was the restoration of Cheshire Mill #1 in Historic Harrisville, New Hampshire. In a paper presented at the second conference, titled *Masonry Repairs at Cheshire Mill #1, Harrisville, New Hampshire,* Linda Willett, Executive Director, and Fred O'Connor, an experienced mason, discussed the restoration of a portion of this 1840s industrial complex [16].

Our understanding of natural cement in the United States is enhanced by conversations with our colleagues abroad in various European Union countries. The European Union has funded a long-term

FIG. 7—*Natural cement stucco preparation and application was demonstrated by masons from the National Park Service Historic Preservation Training Center at the Harper's Ferry pulp mill ruins during the Second American Natural Cement Conference. Photo by the author.*

project to research historic European cements and to develop suitable replacements for use in historic restoration works. The Roman cement group ("ROCEM") is comprised of scientists and other interested parties throughout the European Union. The results of their recently completed project were reported in a series of three papers focused on history [17], calcination processes [18], and hydration mechanisms [19].

In the course of reporting the results of this work, the use of the terms "natural cement" and "Roman cement" had become the object of some considerable controversy. American and European "pre-portland" cements are two significantly different groups of materials, in spite of some common chemistry and terminology, and parallel histories of use. They are similar in that they were relatively low-fired cements produced from naturally occurring mixtures of carbonates and clay. There are important geological, chemical, and performance differences, however.

Geologically, the raw materials mined to produce these cements were, for the most part, different from each other in structure, age, and composition. American natural cements were generally derived from argillaceous limestones with high magnesium carbonate content, while European cements were generally produced from low magnesium source materials [20]. This had an important impact on their ultimate properties.

Chemically, the presence of high magnesium carbonate content in the vast majority of American cement rock necessitated firing at relatively low temperatures, and produced cements that were slower to set, softer, and lower in modulus of elasticity [21]. In terms of performance, this is significant, permitting the effective and durable use of American natural cements in masonry mortar and stucco, even without lime addition.

The low magnesium carbonate content of European raw materials permitted calcining at higher temperatures, and European cements have been characterized as brittle and hard. Higher strengths, comparable to portland cements, were reported.

Due to the differences in properties, primary uses of American and European cements differed somewhat. American cements were used extensively in masonry mortars, stuccos, and concretes, but rarely in precasting. European cements were used largely for precasting and for certain types of stucco.

The Second American Natural Cement Conference adopted a convention which defined natural cement in terms of the historic American standard ASTM C 10 (*Standard Specification for Natural Cement*). This standard was first adopted over a hundred years ago. European cements do not meet this standard due to excessively rapid time of setting, and in some cases, burning at temperatures reaching the sintering point.

The European Union group's own terminology was adopted as the standard for referring to European pre-portland era cements as "Roman cements." The use of the term "Roman cement," however, is not without its detractors as it has three different usages:

(1) A specific traditional material produced by calcining septaria, as patented by James Parker in 1796.
(2) The common current usage in the EU ROCEM group, which includes any sort of low to moderate temperature calcined argillaceous limestone.
(3) The traditional material used by the Romans, which bears no relation to the other two [22].

The use of the term "Roman cement" as an equivalent to European natural cement helps maintain the distinction between these two groups of cements. Though the terms themselves may remain controversial, their use, within the context of the American Natural Cement Conferences, clarifies the differences between the two.

Conclusion

In conclusion, these conferences are about a telling of a story: The story of American Natural Cement and our connection to it. The papers gathered herein for publication by ASTM are a portion of that narrative. The goal is to continue this discussion for the betterment of historic restoration here and in other parts of the world.

Beyond the technical data, research, practices, and historic documentation regarding natural cement, the presentations made at the American Natural Cement Conferences capture the passion of the authors, for which no excuses need be given. There is an unfaltering dedication among those who are working to restore natural cement to its rightful place in masonry and historic technology. It is our hope that the reader will become part of this movement.

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Ken Uracius[1]

The Natural Cement Revival

ABSTRACT: Although lime has long been an important component in masonry construction, experienced masons working on the restoration of historic buildings in the United States cannot help but notice that some American mortars are very different from the traditional lime mortars used in Europe. American mortars, as found in many 19th century commercial, industrial and government buildings, are clearly tougher and more tenacious than the typical lime mortars. While some claimed that this is due to the importation of hydraulic limes from Europe, study of the period's plentiful documentation reveals that natural cement was the most widely used hydraulic binder in its time. This paper retraces key steps in the search for the history of natural cement use in the United States, and in rediscovering its origins, production methods and use. Ultimately, these steps led to the commercial reintroduction of natural cement for use in historic restoration.

KEYWORDS: natural cement, lime, hydraulic lime, mortar, historic restoration, Fort Adams, Fort Jefferson

Introduction

Among the challenges faced by masons working on a wide variety of restoration and construction projects is trying to balance material flexibility and strength while maintaining good workability. The increasing number of training workshops in the use of traditional materials, in recent years, has attracted many masons seeking this balance. Some programs have involved travel to Europe for study of traditional masonry. Many of the workshops focus on lime-based materials, as lime has been a very important component of masonry binders.

In the course of working on the restoration of large 19th century American buildings, however, it becomes obvious that some American mortars are very different from the ones used in Europe. To the masons working on these structures, it seems clear that certain historic mortars are much tougher and more tenacious than the lime mortars used in the restoration training workshops. In at least one workshop, this difference was explained away as being due to the use of imported hydraulic lime, which seemed to be a reasonable explanation at the time.

Fort Adams

While working on the restoration of Fort Adams, in Newport, Rhode Island, in 2002, a demolition crew was assigned to remove an old concrete floor in one of the casemates. Fort Adams (Fig. 1) is one of the 51 third system seacoast fortifications, built after the War of 1812, during which the British captured and burned the nation's capitol. The forts were designed to protect against another such British invasion.

Demolition of the floor proved very difficult, however, and the drill bit became hot while the floor resisted its impact. The project's architect was called and it was decided to send core samples of the concrete to Scotland for analysis.

While awaiting results of the analysis, further research into the fort's history was undertaken. Simon Bernard, the French engineer engaged to plan and design the third system fortifications, is generally given credit for the fort's design. Day-to-day construction decisions, however, were made by Joseph Totten, an officer in the U.S. Corps of Engineers. From 1825 to 1838, Totten was in charge of the fort's ongoing construction, and he used the fort as a large-scale laboratory, along with a series of test walls constructed

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[1] Stone and Lime Imports, Inc., 303 Highland St., Holden, MA 01520.

FIG. 1—*Fort Adams.*

and blown up each year at the U.S. Military Academy at West Point. During that period he conducted numerous tests of limes and cements, the results of which were published in 1842 [1].

Among Totten's conclusions were findings that lime hydrated to a powder by sprinkling with carefully controlled amounts of water produced stronger mortar than lime made into a paste or putty by using excess water for slaking. He also concluded that New York cements were of the highest quality. This reference led to a search for the source of those cements, which were known to have come from the Town of Rosendale, in the Hudson Valley.

Rosendale, NY

Internet searches on this subject led to the web site of the Century House Historical Society in Rosendale, located on the grounds of the Snyder Estate, site of the last producer of American natural cement to close its doors, the Century Cement Company. At one time, the natural cement industry had employed thousands of workers in Rosendale, but most of the producers had gone out of business in the early 1900s, when Portland cement became the most widely used binder for concrete and masonry. Portland cement reaches higher strengths at an earlier age than natural cements, and this was seen as an advantage in the rapid construction of large buildings and structures. Century Cement continued to prosper until closing in 1970, its principals having reached an age where they could not continue to work. Century House curator Dietrich Werner was able to produce large quantities of original documentation on the history of use of natural cement. In particular, two books on the subject of natural cement production and use in America were found to be most informative: *Practical Treatise on Limes Hydraulic Cements and Mortars* by Quincy Gilmore [2] and *American Cements* by Uriah Cummings [3].

Gilmore's book explains that although stones to make hydraulic lime were found extensively in the United States, it was not manufactured. He comments on the reported successes of lime-pozzolan mortars in France, reporting that repeated inspections of French port facilities almost always led to observed failures. His view of the controversies surrounding the hydraulic limes used in France concluded: "The American engineer can congratulate himself that the supply of hydraulic cement in this country affords a more reliable source of hydraulic mortars than either natural or artificial pozzuolana."

American Cements contains the following data: 151 990 817 barrels of natural cement were produced from 1830 to 1896; there were 67 natural cement producers in 1895; over one-third of natural cement produced came from Rosendale, NY.

Werner was able to trace the beginning of the American natural cement industry to the canal-building period in the early 19th century. While many canals were constructed during this period, four provide a good perspective on their connection with the development of natural cement.

Canals

The Middlesex Canal was built 1794 to 1803. Running from Boston, MA to Lowell, MA, it was one of the first significant canals built in the United States. The records of construction were later used to prevent problems in building the Erie Canal. The failure of the wooden locks on the Middlesex Canal was one of

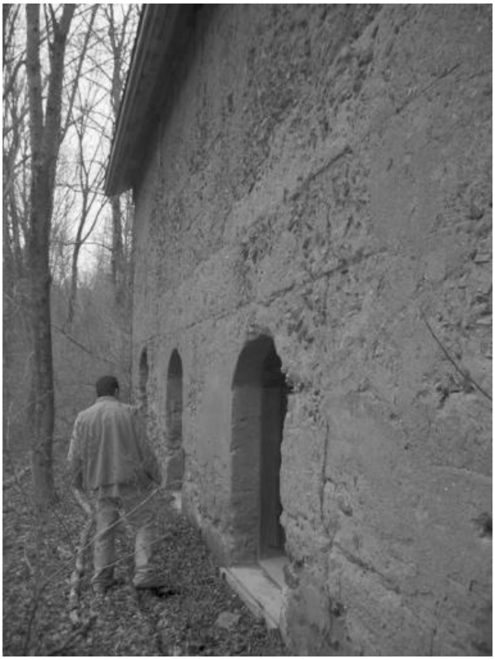

FIG. 2—*Hugh White's cooperage at Rosendale.*

the reasons for sending engineer Canvas White to Great Britain to study their canals.

The Erie Canal was built 1808 to 1825. Benjamin Wright and James Geddes were engaged to build the canal from the Hudson River to Lake Erie, and they sent Canvas White to England to learn how the British had managed to succeed in building their canals. While in England, White observed the cement material they were using on the locks, a natural cement made from a clayey limestone. White later recognized a similar limestone in Chittenango, NY, from which he was able to produce natural cement. He filed patents on the production of natural cement and set up his brother, Hugh, to run the factory producing the cement for the Erie Canal (Fig. 2).

The Delaware & Hudson Canal was built in 1825 to 1829. It ran from the Hudson River to Honesdale, PA. While digging the canal natural cement rock was discovered in Rosendale, NY. From this point, all cement works on the canal were made with Rosendale cement including John Roebling's first suspension aqueduct across the Allegheny River in 1845. Roebling went on to use natural cement in all of his later great suspension bridges, including the Niagara River Bridge, the Cincinnati-Covington Bridge, and the Brooklyn Bridge.

The Chesapeake and Delaware Canal was begun in 1804 and not completed until 1829 because of construction problems. Benjamin Wright, Joseph Totten, Simone Bernard, and Canvas White were called in to consult on the canal. This brings together the leading civilian canal engineers with the military fortification engineers.

Engineers

Additional engineering connections are found in the records of Rensselaer Polytechnic Institute in Troy, NY. Stephen Rensselaer was involved in the building of the Erie Canal, and after its completion he founded one of the nation's first engineering schools. Among RPI's graduates were the engineers for the major railroads and bridges of the era, including Washington Roebling, who went on to complete construction of his father's design for the Brooklyn Bridge. All of these engineers routinely used natural cement in their work.

Natural Cement Production

Once the historical connection between natural cement and American masonry and concrete construction was made, the next step was to visit the mines from which the natural cement rock came. The size and scope of the mines are at first overwhelming. At the end of a short trail overgrown with brush, and hidden beneath a forested hill is a 40-acre cement mine. The Lawrence Mine in Rosendale, NY, contains several different layers of cement rock, which were simultaneously mined and blended by the original cement producers.

Sample materials were removed for testing and burning trials. The texts written by Totten [4], Gilmore [5], and Cummings [6] all describe the original processes for producing natural cement. The original material was coal fired in a continuous burn vertical kiln, often built into a hillside. Alternating layers of coal and cement rock were fed into the top of the kiln, and burnt rock was drawn from the bottom and later ground into a powder. Attempts to burn the material in June 2003 were unsuccessful, and after four designs of homemade kilns natural cement could still not be produced. Eventually an electric batch kiln was purchased and modified to produce the burn cycle that was needed. It took approximately six months of trial and error to produce a properly burnt cement rock. The next challenge was grinding the rock to a powder that will pass through a No. 80 U.S. sieve. The first grinding attempts were done by mortar and pestle. It worked well but was very inefficient. Eventually, a series of trials allowed appropriate commercial grinding equipment to be selected.

While looking for books on natural cement on the Internet, I met architect Mary Catherine Martin who was also interested in natural cement. After exchange of a few choice e-mails it was decided to share information. Martin was working on a restoration project at Fort Jefferson in Florida and was scheduled to speak about the mortar she had found there at the 2003 APT International Conference in Portland, ME [7]. She was provided with samples of the prototype natural cement material from Rosendale, NY, and used them in her presentation. It became evident through laboratory analysis [8] that Fort Jefferson, like Fort Adams, was built with Rosendale cement. Mock-ups at Fort Jefferson were completed using Rosendale cement in January, 2005.

Commercial production of Rosendale natural cement was begun in November, 2004 by Edison Coatings, Inc., in Plainville, CT, and the first phase of major restoration began at Fort Jefferson several months later. This was the first commercial production and use of Rosendale cement in 35 years.

Conclusion

In conclusion I cannot say it better than Uriah Cummings:

> "…when all the evidence is heard it will be found and conceded, that for enduring qualities, for excellence in places of trial, for performance, and for worth, no artificially made cement can be found to compare with that mixed in the moulds of nature" [9].

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Dietrich Werner[1] *and Kurtis C. Burmeister*[2]

An Overview of the History and Economic Geology of the Natural Cement Industry at Rosendale, Ulster County, New York

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ABSTRACT: The Rosendale region of southeastern New York State is widely recognized as the source of the highest quality natural cement in North America. The North American natural cement industry was founded in 1819 by Canvass White in central New York, but soon shifted to Rosendale where it flourished for over 150 years. By the end of the 19th century, the superior quality of Rosendale cement was known worldwide and was actively used in the construction of some of America's most enduring landmarks. Rosendale natural cement's reputation stems from the unique composition of the clay-rich layers of dolostone in the Upper Silurian Rondout Formation from which it is manufactured. Miners utilized room-and-pillar techniques to extract this dolostone from strongly deformed strata in the Rosendale region, creating unique bedrock exposures in mines that are something of an engineering marvel. The exposures resulting from these mining activities have long attracted the attention of geologists for research and education. Production of natural cement transformed extracted dolostone into barrels of cement through a labor-intensive process involving calcination in kilns, cracking, and grinding. Barrels of cement produced were quickly shipped at competitive prices via the Delaware and Hudson Canal, which directly connected the Rosendale natural cement region to major shipping avenues.

KEYWORDS: natural cement, Canvass White, Delaware and Hudson canal, cement production, geology, education, Rosendale, Ulster County, New York

Introduction

The momentum of the North American Industrial Revolution in the opening years of the 19th century sparked a number of large-scale building projects, including the construction of regional canal networks. These canal projects required quantities of high-quality mortars unavailable in North America prior to the introduction of natural cement. Natural cement forms a surprisingly tenacious mortar and is made from clay-rich dolostone or limestone that is capable of hardening while submerged. Thus, natural cement was well suited for many applications including canal construction and quickly gained popularity. Commercial production of natural cement in North America began in 1819 near Chittenango, central New York, and quickly expanded to include factories in several states. However, the region near the town of Rosendale in the central Hudson Valley of southeastern New York State is most commonly associated with the American natural cement industry (Fig. 1).

The highest-quality natural cement in North America originates from the mines in the low northeast-trending hills of the Rosendale region [1]. In addition to various North American canal projects, natural cement produced at Rosendale was used in the construction of some of America's most enduring landmarks. Thousands of public works projects, including portions of the U.S. Capitol building, the Brooklyn Bridge, the Starrucca Viaduct, Roebling's Delaware Aqueduct, the pedestal of the Statue of Liberty, and the Croton Aqueduct Dam and High Bridge began underground in cement mines near Rosendale. Use of Rosendale natural cement was so widespread that Uriah Cummings remarked that both New York and Boston were likely built entirely from mortars using this cement [2].

The excellent bedrock exposures within the mines of the Rosendale region also attracted the attention of numerous geologists. Some of North America's first professional geologists, including Mather [3] and

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[1] Century House Historical Society, 668 Route 213, Rosendale, NY 12472, e-mail: rosendalebuff@aol.com

[2] University of the Pacific, Department of Geosciences, 3601 Pacific Avenue, Stockton, CA 95211. Corresponding author, e-mail: kburmeister@pacific.edu

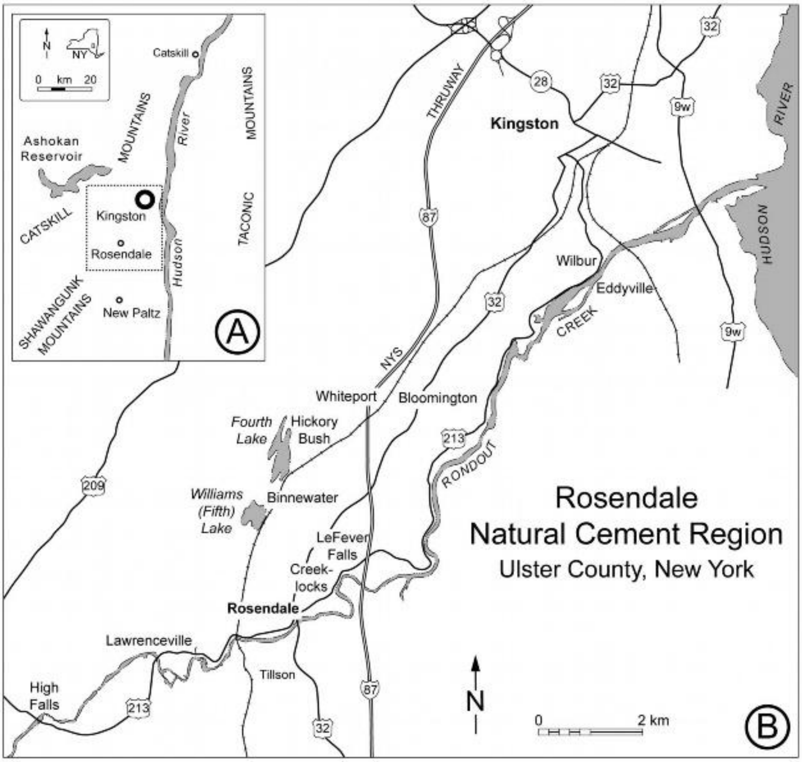

FIG. 1—*Map (A) showing the location of the Rosendale natural cement region in the central Hudson Valley of southeastern New York State. Dotted outline corresponds with area of larger map (B), which illustrates the relative locations of major natural cement producing locations within the Rosendale natural cement region. The trace of the Delaware and Hudson Canal in the Rosendale region follows State Route 213 and the Rondout Creek from High Falls to Eddyville.*

Davis [4] examined the exposures created during the earliest days of the cement industry at Rosendale. Large-scale bedrock exposures in the mountains of eastern North America are uncommon, and the Rosendale region quickly developed a reputation as a unique geologic classroom as mining activities continued to uncover new areas. Princeton University students regularly used the Rosendale region for field studies during the early 1900's. Princeton students compiled a remarkably detailed series of theses and reports, containing photographic archives of quarry and mine exposures taken prior to reforestation of the Rosendale region. These important photographs record historical and geologic relationships that have since been covered or destroyed. These historical records add a valuable perspective to ongoing research projects in the Rosendale natural cement region and provide a foundation for the field-based education of geologic principles.

Canvass White, Canals, and the Birth of the American Natural Cement Industry

Canal construction occurred at a frenzied pace during the first half of the 19th century. The rapidly growing network of canals integrated regions across the northeastern United States and provided a nexus for politics, trade, and technological advances. Engineers associated with these canal projects commonly sought local sources of building materials to minimize costs. Canvass White, an engineer on the Erie Canal project, discovered rocks suitable for manufacturing natural cement in 1818 in northcentral New York (Fig.

FIG. 2—*Canvass White (1790–1834) learned of natural cement while studying canal construction methods in England and later worked as an engineer on the Erie Canal project. White was the first individual to manufacture natural cement in North America (collections of the Century House Historical Society).*

2). White learned of natural cement while studying canal construction methods in England and knew this material was ideally suited for the construction of North American canal systems. The explosion of the North American natural cement industry quickly followed White's discovery. In less than 25 years following White's discovery, natural cement works were established in Illinois, Kentucky/Indiana, Maryland, New York, Pennsylvania, and Virginia.

Canvass White began the first North American commercial production of natural cement at Chittenango, in central New York, in 1819 and received a patent for his product the following year. With this patent, White expected to be the sole supplier of cement to the State of New York for the construction of the Erie Canal. However, competition developed rapidly as others along the proposed canal course began manufacturing natural cement and selling it to the State of New York. White sued several of these manufacturers for patent infringement and royalties. White's attempts to protect his patent rights drew widespread attention and were supported by such luminaries as Benjamin Wright, De Witt Clinton, Secretary of State John Quincy Adams, and Senator Henry Clay. Ultimately, in a move to end litigation, in 1825 the State of New York purchased the patent rights for natural cement from White for $10 000.

Following the completion of the Erie Canal, Canvass White and his younger brother, Hugh White, continued to manufacture natural cement at Chittenango. Canvass White soon accepted a position as engineer for the Union Canal Company, leaving Hugh White to manage the Chittenango cement works. In a partnership that proved extremely profitable for several years, the elder White specified amounts of cement necessary for projects on the Union Canal, which were in turn provided by the younger White. However, in a letter written to the Chittenango cement works in the spring of 1825 from Reading, Pennsylvania (terminus of the Union Canal), Canvass White remarked that a local brand, Bald Mountain Cement, was entering the market due to the limited availability of White's cement. This event marked the beginning of a protracted period of increased competition with other successful natural cement producers that beleaguered Canvass White until his death in 1834.

Natural Cement at Rosendale

Rocks suitable for the manufacture of natural cement were discovered in 1825 along the proposed course of the Delaware and Hudson Canal near Rosendale. Soon after the discovery of this resource, the first contract to supply natural cement to the Delaware and Hudson Canal Company was awarded to John Littlejohn. As with the Erie Canal project, fierce competition quickly developed as others joined Littlejohn in natural cement production. This competition sparked Rosendale's nascent natural cement industry, which was first mentioned in the Report of the Committee on Roads and Canals in 1828 [5]. Among the early competitors were Lucas Elmendorf and Watson E. Lawrence, who began manufacturing under the Rosendale Cement brand in the fall of 1827. Elmendorf obtained a charter to incorporate the Rosendale

FIG. 3—*Cement works (ca. 1872) along the Rondout Creek at Lawrenceville (Fig. 1) in the Rosendale natural cement region. This location was the site of Lucas Elmendorf's cement works in 1828 (photograph by D. J. Auchmoody, collections of the Century House Historical Society).*

Manufacturing Company from the New York State Legislature in 1827, which was subsequently acquired by Lawrence in 1831 (Fig. 3).

Canvass White sought to transport his products to the Hudson Valley from Chittenango via Albany in response to the growing market for natural cement in southeastern New York and competition he faced from new producers near Rosendale. However, White conceded in a series of letters in late 1827 that the White brothers were in a poor position to compete for business with the producers near Rosendale. This realization proved correct as the demand for natural cement produced at Rosendale continued to grow and quickly expanded beyond the Delaware and Hudson Canal project. For example, Rosendale cement companies secured a contract in 1829 for the construction of Fortress Monroe in Hampton, Virginia, with an initial shipment of 500 barrels of natural cement. In a final attempt to spur business and expand the market for White's cement, Peter Remsen, Canvass White's agent in New York City, began placing advertisements for White's cement in several major newspapers during the summer of 1829.

The White brothers' cement business suffered another setback later the same year. Benjamin Wright, the chief engineer of the Chesapeake and Ohio Canal Company, and Robert Leckie identified rocks suitable for the manufacture of natural cement near Shepherdstown, Virginia, in the spring of 1829 [6]. Leckie began commercial production of natural cement production in August 1829 and subsequently provided most of the cement used in the construction of the Chesapeake and Ohio Canal from local sources. As a result, the Chesapeake and Ohio Canal Company used only 1204 barrels of White's hydraulic cement between 1829 and 1832 [6]. Finally, in an attempt to end nearly ten years of difficult competition with better located cement producers, Hugh White relocated his cement works in 1836 from Chittenango to Whiteport, near Rosendale (Figs. 1 and 4).

FIG. 4—*Newark and Rosendale cement works at Whiteport (ca. 1880s). Located north of Rosendale and west of Bloomington (Fig. 1), this was the site of Hugh White's cement works between 1838 and 1848. White sold the property to the Newark and Rosendale Cement Company, who in turn sold the facilities to the Consolidated Rosendale Cement Company in 1902 (photograph courtesy of M. Pavlov, collections of the Century House Historical Society).*

FIG. 5—*The Century Cement Plant in Rosendale (ca. 1955) was the last cement works to manufacture natural cement in North America. This plant was operational between 1928 and 1970 (collections of the Century House Historical Society).*

Hugh White's move to Rosendale coincides with a time of considerable growth in the natural cement industry. W. W. Mather, a geologist working for the State of New York, noted during his first visit to the Rosendale region during the late 1830s that the only active cement works were located in Lawrenceville, approximately two kilometres west of the present village of Rosendale (Fig. 1) [3]. Mather returned to Rosendale in the early 1840s to find 13 companies operating 16 cement works collectively producing 600 000 barrels of cement annually [3]. Mather's description of the burgeoning Rosendale cement industry also notes a broad range of uses for cement produced in this region, including the construction of cisterns, wet cellars, the Croton Aqueduct system, and various other North American government projects [3].

The success of the Rosendale natural cement industry depended upon unobstructed access to the Delaware and Hudson Canal. The Delaware and Hudson Canal, the Rondout Creek, and the Hudson River connected Rosendale to markets and fuel, providing local companies with a significant cost advantage over cement factories in competing regions. Thus, Rosendale natural cement could generally be delivered at a significantly lower cost due to the proximity of water-borne conveyance systems. As a result, the market for the high quality and relatively inexpensive Rosendale cement continued to broaden and eventually included all of the major Atlantic ports and the West Indies [3].

American natural cement production reached its peak in 1899 with an estimated annual production of their 9 868 000 barrels of cement. The natural cement industry declined rapidly during the early 1900s, but lingered until 1970 when the Century Cement Manufacturing Company in Rosendale, the last natural cement works in North America, finally closed (Fig. 5). Annual reports of the United States Geological Survey suggest that the Rosendale cement region led the nation during most of the 151-year span of the natural cement industry, often accounting for nearly 50 % of all the natural cement manufactured in North America. Cummings [2] highlighted the quality of Rosendale natural cements in his comprehensive review of American cement, in which he ranked them among the foremost American cements in quality.

Applications of Rosendale Natural Cement

Debates over the application of natural cement mortars over other types of mortars were frequently addressed in publications written for 19th century agriculturalists and engineers. Some authors suggest that metallic cements (a historical term referring to natural cements like Roman and Parker's/English natural cements) are inferior to lightly hydraulic lime mortars [7]. Indeed, Canvass White overcame contemporary reluctance to employ natural cement mortar on the Erie Canal project instead of the relatively popular lime mortars commonly used in canal construction during the early 19th century. However, many advocated the use of natural cements for various construction applications. For example, Henry Heath used Rosendale natural cement in 1858 to construct the Allen House (later renamed Hotel Allen), the first concrete hotel in Pennsylvania [8]. Newspaper advertisements provide evidence for other early applications of natural cement. For example, the *Observer* of Salem, Massachusetts, featured advertisements for Knight's Patent Hydraulic Cement drain pipes, sewer pipes, and culverts and Down's Patent Concrete walks in 1870 (Fig. 6) [9].

Rosendale natural cement quickly became popular enough to compete for business in regions with

CEMENT
PIPE

Knight 's Patent Hydraulic Cement
PIPE,
FOR DRAINS, SEWERS, AND CULVERTS.

THIS PIPE is specially adapted for Distribution and Drainage in Cities, Towns, and Villages. It will stand the most severe tests of acids and frosts, and improves in strength with age, and is now extensively adopted by eminent Hydraulic Engineers.

The SEWER PIPES are in use in New York, Brooklyn, Albany, Hartford, Lowell, Boston, and numerous other places. Also used under heavy Rail Road Embankments.

3, 4, 5, 6, 8, 9, 12, 15, 18, and 24 inch Bore—Also, 30 inch Well Pipe—Manufactured and sold by

S. FLINT,
221 Derby Street, Salem, Mass.,

FIG. 6—*A newspaper advertisement for Knight's Patent Hydraulic Cement Pipe from the Salem (Massachusetts) Observer, February 1, 1873 (collections of the Century House Historical Society).*

well established, local natural cement works. For example, an interesting advertisement published by John Drucker of Chicago, Illinois, in 1878 lists the prices and relative qualities of three brands of cement: Bangs & Gaynor's, Ramsey's Hydraulic, and Rosendale [10]. Bangs & Gaynor's cement is noted as being of equal quality to brands from Akron, Buffalo, and Milwaukee and is listed for $1.00 per barrel. Ramsey's cement is listed at $1.25 per barrel and suggested to be of comparable quality to brands from Louisville. Rosendale cement is listed at $1.30, the highest price. No comparison of relative quality is provided for Rosendale natural cement. This omission is likely because Rosendale natural cement had a widespread reputation of being of superior quality to the other brands listed. Newspapers in major cities commonly listed the current price of Rosendale cement along with imported European portland cements and eventually with American portland cement in the financial pages. An example from the General Market Report for Building Materials in the *New York Daily Tribune* of 9 October 1889, lists Rosendale cement as the cheapest cement for mortar relative to American, English, and German portland cements. Thus, the popularity of Rosendale natural cement persisted long after the introduction of portland cements in the 1870s because of its reputation for quality at competitive prices.

Geology of Rosendale Natural Cement

The rock mined for the production of natural cement at Rosendale occurs within a stratified sequence of sedimentary rocks including limestone, dolostone, sandstone, shale, and conglomerate deposited during the Ordovician, Silurian, and Devonian periods approximately 450 to 375 million years ago (Fig. 7) [11–15]. The oldest geologic unit exposed near Rosendale is the Middle Ordovician Martinsburg Formation, a thick sequence of dark gray shale and sandstone. The Upper Silurian Shawangunk Formation, a thick sequence of silica-cemented quartz pebble conglomerate and sandstone, unconformably overlies the Martinsburg Formation. The Shawangunk Formation likely comprises the deposits of gravel-choked, braided streams that once flowed out of the ancient Taconic Mountains of present day eastern New York and western Massachusetts [16]. The Shawangunk Formation is overlain by the Upper Silurian High Falls Formation and Binnewater Formation. These strata record a gradual transition from continental to nearshore environments associated with the eastward advance of a broad, shallow, inland sea that at times extended from present day New York to Iowa. The Upper Silurian Rondout Formation, a thickly bedded sequence of dolostone and moderately fossiliferous limestone, unconformably overlies the Binnewater Formation. The Rondout Formation records a shift from nearshore to marine depositional environments. These Silurian strata are overlain by limestone, shale, and sandstone of the Lower Devonian Helderberg and Tristates Groups [12,13,17,18].

A series of tectonic collisions between the eastern margin of North America and other land masses during the Devonian and Carboniferous to Permian periods (approximately 400 and 300 million years ago, respectively) deformed the sequence of Silurian and Devonian rocks in the Rosendale region and uplifted the ancient Appalachian Mountains. Today, the deeply eroded western flank of the ancient Appalachian

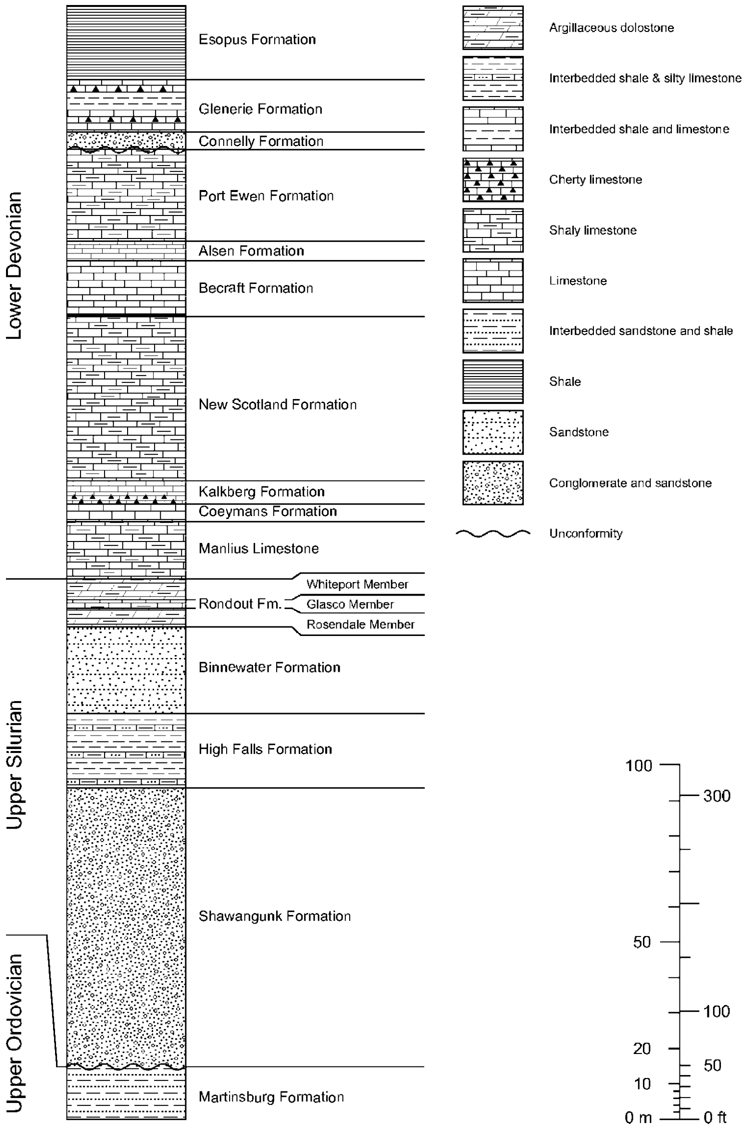

FIG. 7—*Simplified stratigraphic column of the Ordovician, Silurian, and Devonian rock units exposed in the Rosendale natural cement region. Dolostone from the Rosendale and Whiteport members of the Upper Silurian Rondout Formation was used in the production of natural cement. The Glasco Member of the Rondout Formation was not suitable for natural cement production. Stratigraphic thicknesses after Waines and Hoar [13] (please refer to discussion therein for information regarding geologic units not mentioned within this text).*

Mountains is exposed in a narrow belt of deformed strata near Rosendale and elsewhere along the western margin of the Hudson River Valley [19]. These complexly folded and faulted rocks presented both challenges and benefits to miners working in the Rosendale natural cement region. Brittle fractures associated with folding and faulting weakened rock layers, compromising the stability walls, pillars, and ceilings in quarries and mines. However, folding and faulting often duplicated the stratified sequence of rocks in imbricate stacks, which facilitated the extraction of certain rocks for cement production.

Rondout Formation

Rosendale natural cement was produced from dolostone mined from the Upper Silurian Rondout Formation (Fig. 7). The Rondout Formation comprises a highly variable sequence of clay-rich dolostone, silty limestone, and calcareous sandstone exposed along much of the western margin of the Hudson Valley [12,13,20,21]. The thickness of the Rondout Formation is variable in the Rosendale area, ranging from more than 15-m thick southwest of Rosendale to less than 9-m thick near Kingston [13,21]. Near Rosendale, the Rondout Formation is divisible into three stratigraphic members: Rosendale, Glasco, and Whiteport [22]. The composition of the clay-rich dolostone in the Rosendale and Whiteport members of the Rondout Formation are ideally suited for natural cement production and were extensively mined in the Rosendale region. The Glasco Member contains limestone, dolostone, and shale that are not suitable for natural cement production and is generally left untouched in mines near Rosendale [13].

The lowest of the members in the Rondout Formation locally is the Rosendale Member, which is a fine-grained, blue-gray, clay-rich dolostone that weathers rusty, light orange-brown. The Rosendale Member is approximately 8-m thick south of High Falls, but thins to less than 2-m thick north of Kingston. Fossils within the Rosendale Member are rare, but include fragments of brachiopods and echinoderms. The Glasco Member, a moderately fossiliferous, fine- to medium-grained, gray, silty dolostone and limestone with local coral-rich facies, overlies the Rosendale Member [23,24]. Silicified fossils of the chain coral *Cystihalysites sp.*, favositids, and stromatoporoids are abundant in the lowermost Glasco Member. Thickness of the Glasco Member varies near Rosendale, ranging between 4 and 0.2-m thick [25]. The Whiteport Member overlies the Glasco Member and is a very fine-grained, thinly bedded, light blue-gray, clay-rich dolostone that weathers light gray-brown. The Whiteport Member contains disarticulated fossil fragments of the ostracod *Leperditia sp.* and cup (solitary rugose) corals [25]. The Whiteport Member thins northward from approximately 4.8-m thick near Rosendale to 3-m thick near Kingston [25].

Complex Nomenclature of the Rondout Formation

The varied nomenclature used to discuss the rocks within the Rondout Formation is the source of much confusion regarding the age, distribution, and stratigraphy of this unit [12,25]. Hall [26] first named the unit by proposing the terms Rosendale “upper cement” and “lower cement” for the series of units quarried for cement rock in Ulster and adjacent counties. Darton [27] subsequently referred to these strata as the Salina Waterlimes. In a slight variation, Clark and Schuchert [20] referred to the Rondout Formation as the Rondout Waterlime. Hartnagel [22,28] was the first to recognize a “middle ledge” (the Glasco Member) separating the natural cement bearing rocks that he referred to as the Cobleskill and Salina units. Van Ingen and Clark [29] referred to strata within the Rondout Formation near Kingston as the Vlightberg sequence. Logie [23] assigned the geographically based name LeFever Limestone. Chadwick [24] reintroduced the designation Rondout, which was later supported and refined by Rickard [12] and Hoar and Bowen [25] into the presently accepted convention discussed above.

Natural Cement Production

Room-and-Pillar Mining

During much of the 19th century, miners utilized sledge hammers, star drills, black powder, and room-and-pillar mining techniques to extract dolostone from the Whiteport and Rosendale members of the Rondout Formation. Despite the eventual incorporation of technological advances such as pneumatic drills, the use of basic room-and-pillar mining techniques persisted throughout the entire course of the cement industry near Rosendale. Room-and-pillar mining is an effective technique for removing cement rock from stratified deposits by leaving a carefully arranged array of pillars to support the ceilings of excavated spaces (Fig. 8). Mines in the vicinity of Rosendale generally began with the quarrying of a series of 4 by 9-m shafts spaced at roughly 4-m intervals along an outcrop exposure in one of the dolostone-bearing members of the Rondout Formation [30]. These shafts were then connected by 16 m^2

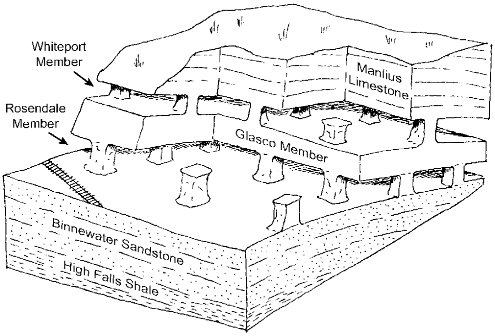

FIG. 8—*A three-dimensional sketch of the inner workings of a typical room-and-pillar mine in the Rosendale natural cement region. Cement rocks were extracted from the Rosendale and Whiteport members of the Rondout Formation (see also Fig. 7). Rocks in the Glasco Member of the Rondout Formation were unsuitable for cement production and were commonly not removed, resulting in a ledge that separated the two mined horizons. Mining of cement rocks began with the excavation of a series of rooms in the Rosendale or Whiteport members, or both along a surface exposure. Subsequent mining interconnected these rooms at depth, leaving pillars of cement rock to support the weight of overlying strata. The initial rooms were then extended with new shafts, which were later interconnected to form a new row of rooms and pillars.*

sized rooms, resulting in a honeycomb of main shafts separated by pillars of rock along the original surface. The mining process continued by extending the original main shafts deeper into the mine before connecting them with an additional row of rooms. Mining of dolostone generally continued in this fashion until the rock layers became friable, were truncated by faults, or until miners encountered property lines or claim boundaries. Extracted rock was collected laterally along rows of rooms using networks of narrow-gage rail cars before being hauled to the surface by steam-driven hoists along one of the main shafts [30].

In modern room-and-pillar mines, engineers carefully account for pillar height, overburden weight, rock creep, and structural defects in the rock when calculating room to pillar area ratios to maximize both safety and returns [31]. In general, only about 60 % of a rock layer can be safely extracted from a room-and-pillar mine, but it is possible to increase this percentage to upwards of 90 % if the pillars and roof rocks are competent enough support wide spans [31]. However, the load on pillars increases rapidly as the percent of extracted material increases. For example, pillars of rock in a mine with 40 % extraction experience 1.67 times the normal load, whereas pillars in a mine with 75 % extraction experience four times the normal load [31]. Pillars in strata that dip more than a few degrees from horizontal are subjected to additional hazards associated with shear stress. For this reason, engineers generally utilize room-and-pillar mining techniques only in horizontal or very shallowly dipping strata. Given these constraints to the application of room-and-pillar mining techniques, the mines of the Rosendale natural cement region are truly engineering wonders. These mines were successfully completed in highly fractured and faulted rocks, and the strata within many of these mines are steeply dipping. For example, strata in the mines near Hickory Bush dip upwards of 80 degrees from horizontal (Fig. 9).

Calcination, Cracking, Grinding, Packing, and Shipping

Elaborate tramways transferred cement rock extracted from mines in the Rosendale natural cement region to batteries of kilns to begin the refining process (Fig. 10). Round kilns constructed of brick and local rock fired the dolostone in a process called calcination, which uses heat to drive off carbonic acid and yields a soft yellow product [30]. Workers charged the kilns at their upper openings with alternating layers of fuel and dolostone. Initially, locally hewn wood was the preferred fuel. However, following deforestation of the region, pea coal shipped from Pennsylvania on the Delaware and Hudson Canal became the primary fuel. Workers carefully regulated the kilns, because if temperatures became too intense the dolostone recrystallized into a clinker that was unsuitable for the production of cement [32]. Workers drew the calcined

FIG. 9—*Photograph looking north into an abandoned cement mine in the Rosendale Member of the Rondout Formation (see also Fig. 7) in the west-dipping limb of the Hickory Bush anticline near the Fourth Binnewater Lake (Fig. 1). This mine was completed in strata that are dipping at roughly 80° from horizontal. Pillars are approximately 4-m (13-ft) tall.*

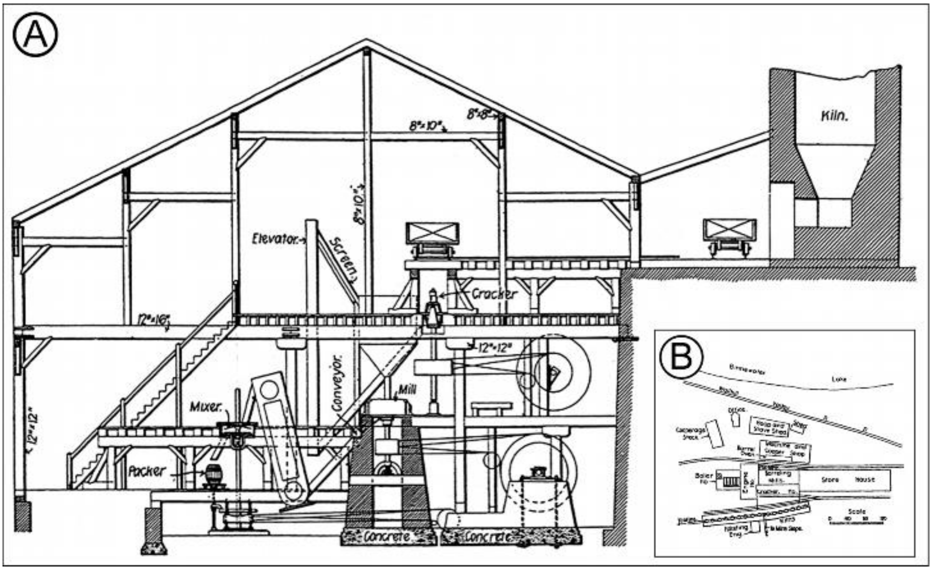

FIG. 10—*Cross-sectional elevation (A) of the kiln battery and mill structure of the Lawrence Cement Company at Binnewater (Fig. 1). Note the relative positions of the kiln battery, cracker, grinding mill, and packing areas. The tramways atop the kiln structure leading to the adjacent mines are not shown. The various buildings of the Lawrence Cement Company were located immediately east of Binnewater Lake (now known as Fifth or Williams Lake), along the Wallkill Valley Railroad (inset B). Figure after Lewis [30].*

FIG. 11—*Loading dock of the Consolidated Rosendale Cement Company along the Delaware and Hudson Canal at Binnewater Road in Rosendale. Notice the tramway directly above the canal barges. The cars on this tramway are loaded with barrels of natural cement produced from the Beech Mine along Binnewater Road. The structure built from dark iron girders at upper right is a footing for the Wallkill Valley Railroad Trestle over the Rondout Creek. This photograph was originally published by the Consolidated Rosendale Cement Company in a 57-page advertisement booklet in 1910 (collections of the Century House Historical Society).*

materials from the base of the kilns and removed the clinker before feeding the properly burned rocks into crackers. The gravity-fed, coffee-mill type cast iron crackers crushed the relatively soft burned rocks into smaller fragments. (Fig. 10). Mills containing large grindstones quarried from local exposures of the Shawangunk Formation ground the crushed burned rock fragments into a fine-grained powder. Workers discharged the resulting powder directly into paper-lined, 20 lb (9.07 kg) wooden barrels commonly manufactured in on-site cooper shops. Each finished barrel contained approximately 300 lb (136.1 kg) of powdered natural cement product.

Shipping

As discussed earlier, manufacturers in the Rosendale natural cement region used the Delaware and Hudson Canal, the Rondout Creek, and the Hudson River to transport their products to market. Factories along the Delaware and Hudson Canal (now State Route 213 and Creek Locks Road) generally loaded barrels of cement directly onto barges from company-owned docks (Fig. 11). Cement works located inland near the Binnewater Lakes, Hickory Bush, and Whiteport, with no direct access to the canal, utilized either the Wallkill Valley Railroad or other creative methods for transporting their goods to nearby docks. One such innovative solution was a horse-drawn railroad that connected remote cement works near Hickory Bush with docks on the Rondout Creek at Eddyville (Fig. 12).

FIG. 12—*Photograph of the horse-drawn railroad (ca. 1899?) that once transported natural cement manufactured at plants near Whiteport and Hickory Bush to docks at Eddyville along the Delaware and Hudson Canal (collections of the Century House Historical Society).*

Summary

The success of the Rosendale natural cement industry stems from both the quality of the available raw materials and the proximity to shipping avenues. Rosendale natural cement's reputation for superior quality is related to the unique composition of the clay-rich layers of dolostone within the Rondout Formation. The Rosendale region was directly connected to a distribution network via the Delaware and Hudson Canal that ensured the rapid delivery of natural cement products to various markets at competitive prices. After nearly 150 years of production, the legacy of Rosendale natural cement is preserved in some of our nation's most recognizable landmarks. The abandoned mines in the Rosendale region, excavated using room-and-pillar mining techniques, contain unparalleled exposures of strongly folded and faulted rocks. These mines provide a window into the deeply eroded remnants of the Appalachian Mountains that continually attract geologists for purposes of research and education.

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John J. Walsh[1]

Petrography: Distinguishing Natural Cement from Other Binders in Historical Masonry Construction Using Forensic Microscopy Techniques

ABSTRACT: Petrography is a microscopy method providing a revealing view of inorganic materials. Hydraulic cements rarely react completely and telltale residuals are detected by the petrographer. Combined with accurate chemical analysis, the petrographic examination not only identifies the original components but often allows for a quantitative assessment of material proportions. Such data are crucial for the proper conservation and rehabilitation of historic masonry structures. Portland cement, lime, and natural cement in any combination may be present in historic American masonry construction. A comprehensive petrographic examination serves as the basis for the successful creation and implementation of an historically accurate project specification. This paper provides insight into how various binders are properly distinguished. While technical data will be offered, the goal is to provide the architect or conservator with a general understanding of the methods employed by the petrographer and to demystify the often complicated mortar analysis report.

KEYWORDS: mortar analysis, natural cement, petrography, Rosendale, historic binders, masonry conservation

Introduction

Materials analysis is often perceived by the construction industry as the proverbial black box; a randomly chosen sample is placed in one end and a perfectly unequivocal result appears at the other. It is the workings inside this mythical contraption that are usually misunderstood. The scientific language accompanying materials examination reports may give the false impression that the sample has undergone an invariable procedure that would produce identical results no matter which black box was chosen. Fortunately, the preservation industry has a sympathetic appreciation for the forensic materials scientist's task. All preservation projects have a forensic component and all involved are familiar with the detective work that is usually required. As with criminal investigations, a great part of the investigation's success relies on the intuition, experience, and approach of the detective. Nevertheless, the particular skills and experience the materials analyst possesses are rarely understood by others in the preservation industry and blind faith is too often the governing criterion for choosing a laboratory.

As the volume in which this paper appears is a special issue dedicated to the American natural cement industry, a portion must focus on identifying that particular binder in historical construction. The binder in cementitious construction materials is the most dynamic of the system, expected to chemically react and convert to a new material and as such the most difficult to identify in older construction. Most conservators and preservation professionals would be surprised to learn of the paucity of modern technical literature regarding the properties and identification of natural cement. The primary goal of this paper is to share with other analysts the criteria and approaches this investigator has learned to utilize in examinations of historical masonry construction. This summary contribution aims to add something to the practitioner's toolbox and encourage further research into this resurgent industry. However, an additional goal is to give some insight to those not privy to the methods of the materials scientist and hopefully allow for more effective and educated partnerships between the preservationist and the materials analyst.

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[1] Senior Petrographer/Geologist, Testwell Laboratories, Inc., 47 Hudson Street, Ossining, New York 10562.

TABLE 1—*Typical chemical analyses of two mortars.*

Chemical Data	Sample A[a]	Sample B[b]
SiO_2	3.05	3.06
CaO	11.86	10.64
MgO	2.03	2.09
Al_2O_3	0.77	1.76
Fe_2O_3	0.58	0.82
Insoluble residue	74.27	69.65
Loss on ignition	6.68	11.26
Total	99.24	99.28
Proportions	1:1:6	1:0.7:5.6
Type (ASTM C 270)	N	N

[a] Sample A is a fictitious Type N portland cement-lime mortar.

[b] Sample B is an actual analysis from a natural cement mortar sampled from a stone masonry pier at High Bridge over the Harlem River in New York City constructed circa 1848.

Chemical Analysis

In the United States, mortar analysis methods are provided for in ASTM C 1324 [1]. This relatively new document calls for both the analytical skills of the chemist and the observational techniques of the microscopist or petrographer. What seems to go unnoticed is how this collaboration must result in a set of observationally based assumptions used to interpret the hard numbers of the chemical analysis. The required forensic skills are explicit in the document and the standard reads as a set of guidelines and suggestions for interpretation rather than an algorithmic methodology. While a great deal of interpretative freedom is left to the analyst, the rules of the chemical analysis may seem to represent the comfortable and infallible black box. When blind adherence to the chemical rules are applied by a laboratory and these are provided to a restoration contractor insensitive to historical materials, predictable but potentially disastrous results are likely.

The chemical procedures require an acid digestion to separate the sand from the binder matrix. Ideally, the sand is recovered as a wholly insoluble component while the binder matrix goes into solution. The solution containing the dissolved binder is then analyzed to determine elemental concentrations. Water and carbon dioxide are measured separately by igniting the sample in a furnace and determining weight losses at specific temperatures. In most cases, these procedures isolate and partition the components reasonably well. A presentation of typical chemical analyses is given in Table 1. What is important to note is that the results comprise elemental percentages rather than mortar component percentages. In order to come up with raw material ratios a number of assumptions must be made. The interpreted mortar design is only as good as the assumptions made about the original components even if the chemical analysis is highly accurate.

When considering binder components, the first assumption involves the partitioning of the measured elements into the original raw materials. Consider the chemical analysis of Sample A shown in Table 1. Let us assume the mortar is identified as a contemporary cement-lime mortar. While an oversimplification, the important measurements to consider here are silica (SiO_2) and calcium oxide (CaO). Modern portland cement contains both silica and calcium oxide at approximately 21 and 63 %, respectively. Hydrated lime contributes only calcium to the analysis. If these assumptions are valid, one can divide the measured silica weight by 21 % and determine the original cement weight. This would result in 14.5 % cement by weight for Sample A. Given this portland cement proportion, we would need to deduct 9.2 % of the measured calcium oxide to partition into the cement. The remaining calcium oxide must then belong to the hydrated lime. Similar calculations may be made for magnesium oxide which is present in dolomitic limes. With some simple manipulation based on molecular weights, these oxides are then mathematically converted resulting in 6.2 % hydrated lime by weight. Of course, masons do not mix mortar by weight so we must make some more assumptions to convert these weights to volumes. If we assume that cement and lime have densities of 94 and 40 lb per cubic foot, respectively, it is a simple matter to divide the weight percentages by density resulting in a one to one volume proportion. Similar manipulations for the aggregate result in a classic Type N cement-lime mortar at a 1 : 1 : 6 cement to lime to sand proportion. It should be clear that there is some error built into these conversions. For instance, if the original cement contained 2 % more silica as might be typical in a white portland cement, there could be a 10 % error in the calculated cement weight.

FIG. 1—*High Bridge over the Harlem River in New York City. The photograph was taken before 1927 when masonry piers over the river were removed to accommodate a steel span to allow for larger naval ships to pass. The picturesque New York landmark was constructed using Rosendale cement manufactured several tens of miles north along the Hudson River.*

Though the chemistry assumptions alone may produce a significant error, these pale in comparison to those produced by misidentifying the original cementitious components. The analysis given for Sample A is admittedly fictitious and represents an idealized Type N portland cement-lime mortar completely manufactured by the author. The data presented for Sample B are an actual chemical analysis using the same techniques described above. Interestingly, the data are very similar to that of Sample A with some very minor differences. In fact, if we were to go through the same mathematical procedures we would find the mortar to be a 1:0.7:5.6 proportion by volume also characterized as a Type N cement-lime mortar. In actuality, the mortar was sampled from a stone masonry pier at High Bridge over the Harlem River in New York City constructed circa 1848 as part of the city's aqueduct system (Fig. 1). Original records show that the bridge was constructed using Rosendale natural cement produced in upstate New York [2] and petrographic examinations performed by the author are consistent with historical data. Clearly, there is nothing in the chemical analysis that would uniquely characterize the material as a natural cement mortar. Other methods are required to place the chemical data into a proper context and allow for an accurate design estimate.

Mineralogical Methodology

When requesting a mortar analysis on an historic property, the conservator should ensure that some method will be used that identifies the actual binder components in addition to producing chemical data. This is particularly important for structures built in the mid- to late 19th and early 20th centuries where any combination of binders may be present. Regardless of the method chosen, it must at the very least be capable of identifying mineral species and ideally should also be able to discern microstructural evidence that aids in distinguishing the various binders. X-ray diffraction is an excellent method for determining mineral phases but it cannot image the binder residuals that are almost always present within the mortar matrix. Scanning electron microscopy is a perfect tool for imaging microstructure and when properly calibrated may also quantify mineral compositions. However, the analysis may be prohibitively expensive for routine examinations. Both tools provide excellent supplementary data where other methods fail but the workhorse for mineral identification is the polarized light microscope. Petrographic methods using polarized light microscopy are over a century old and are adopted from the geological sciences [3]. Advantages of the technique include its ability to image binder residuals and determine mineralogy, and its relatively low expense as a laboratory tool.

Polarized light microscopy relies on the principle that plane polarized light passing through a crystalline material will usually split into two perpendicular rays traveling at different velocities. The velocity difference is a function of the crystallography and orientation of the mineral. As the light rays reach a second polarizing film, they are resolved back into the same plane. Due to the difference in the wave speeds these two rays will interfere with one another producing light of a particular color. The color

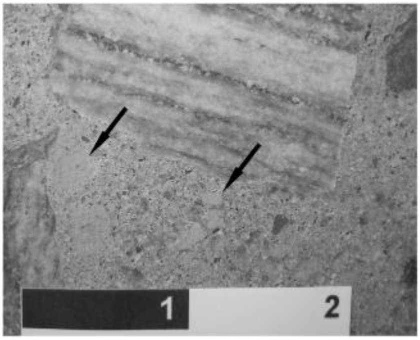

FIG. 2—*Close-up photograph of a polished cross section of concrete produced with Rosendale natural cement. The arrows indicate visible tan colored lumps of residual cement. Large unreacted or partially grains such as these are relatively common in historic construction materials and greatly aid the forensic petrographer in identifying the binder. The included scale is in inches. (See color insert for color version of this figure).*

differences are used by the petrographer to glean quantitative information about the mineral species being viewed. Petrography is a methodology defined by many scales of analysis one of the most important being that of the polarized light microscope and its etymology is “rock pictures.” The “picture” part of the root represents an important feature of the microscope. With adequate sample preparation, the microstructural relationships of the binders and aggregates are readily viewed by the petrographer to a resolution measured in the thousandths of a millimetre. Combined with the quantitative crystal data, a tremendous amount of information is available to the analyst in an intuitive pictorial manner that does not present itself in many other analytical techniques.

There are several ways of preparing a mortar specimen for microscopic examination. The most commonly employed in petrographic laboratories is the powder mount. The procedure costs pennies and preparation time is measured in tens of seconds. The sample is crushed and sieved and a fraction of a milligram is placed on a glass slide in an oil immersion. When looking for residual binders, the petrographer must hunt these mortar crumbs for any evidence of unhydrated or uncarbonated binder minerals. The method is perfectly acceptable for routine analyses of contemporary mortars where all that needs to be determined is whether the portland cement is white or gray and whether or not crushed limestone is present as the lime addition. However, residual lime grains and natural cement residues in historic materials are exceptionally difficult to detect using this method.

Thin sectioning is the preferred method for examining historical materials microscopically. The material is slabbed and wafered and impregnated in a low viscosity epoxy. The mounting surface which may represent as much as 3 in^2 is sequentially ground, rough polished, and epoxy-mounted to a glass slide. The mounted wafer is then trimmed and milled until the surface to be examined is one-thousandth of an inch in thickness and essentially transparent. The material may now be examined in an unadulterated state with every microscopic particle in its original position. Components that represent a trace fraction may be easily detected with their boundaries intact and abundances readily estimated. The disadvantage of the method is the increased cost and turnaround time. Considering the schedule and budget of conservancy projects where replacement-in-kind is a high priority; these disadvantages hardly seem significant when weighed against the quality of the obtained results.

Detecting Binders Petrographically

The key to binder identification lies in the unreacted residuals. One would think that older mortars should not contain unreacted binders. In fact, many older materials exhibit more residual cement or lime than even contemporary materials of several years age. The coarser grinds of older binders combined with the generally lower quality control in production results in grains large enough to survive decades and even centuries in most service environments. It is not uncommon to find unreacted grains visible to the naked eye (Fig. 2). These coarser grains, even when microscopic, provide abundant evidence for the petrographer

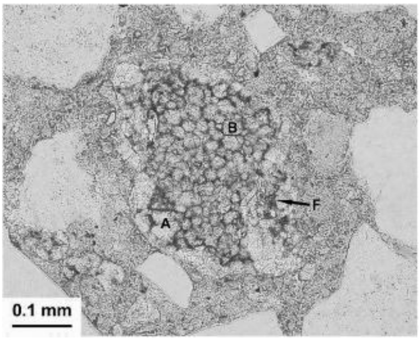

FIG. 3—*Plane polarized light photomicrograph of a residual portland cement particle typical of those detected in early 20th century materials. Petrographers refer to these relicts as having the "bunch of grapes" texture. The texture is produced by agglomerates of the calcium silicate mineral belite (B). Large groupings of small belite crystals are typical of older portland cements. Alite (A) is another calcium silicate and occurs only when clinkering temperatures are obtained. Its presence positively identifies a clinkered cement as opposed to natural cement or lime. The brown-colored ferrite phase (F) is common in portland cement but may be present in any binder containing calcium, aluminum, and iron. (See color insert for color version of this figure).*

to sort through. The various cementitious materials have sufficient differences in their raw feeds, burning temperatures, mineral phases, and microstructure that a well trained petrographer should have a reasonably good chance of distinguishing them in thin section.

Portland Cement

Portland cement is a distinctly different product than either lime or natural cement and this difference is easily detected petrographically. Portland cement is manufactured from ground limestone and shale and is formed through a process known as clinkering. This means the raw feed is brought to temperatures in excess of 1400°C, sufficient to cause a virtually complete reaction to hydraulic mineral species. The phases that are important in the investigation of historic materials include two types of calcium silicate known as alite and belite and an iron-bearing species known as ferrite. Portland cement manufactured in the late 19th and early 20th centuries was typically less finely ground than in the later 20th century with individual particles often approaching a large fraction of a millimetre in size. So while all the constituents are reactive in the presence of water, it is very common to find an abundance of relatively large, partially unreacted cement grains. In older cements, the belite phase is most obviously abundant forming clusters of small subrounded crystals often described by petrographers as the "bunch of grapes" texture (Fig. 3). The crystals themselves are clearly defined and the crystallographic properties under polarized light are well known to concrete petrographers [4]. Small clusters of belite may be detected in trace quantities in hydraulic limes but the difference in abundance should preclude any misidentification. With the exception of white portland cements, the belite phases are surrounded by a brown-colored crystallographically indistinct ferrite phase. Ferrite is not a mineral with a strict proportion of elemental constituents and is a phase that will likely form if any iron is present in burned materials containing calcium and aluminum. As such, it is almost sure to be present in a cement of any hydraulicity and should not be used to distinguish between the various binders. What clearly distinguishes portland cement from other historical binders is the presence of alite (Fig. 4). Alite is not a thermodynamically stable phase at temperatures below approximately 1300°C [5]. Nevertheless, the phase may be difficult to detect in older portland cements due both to its lower original abundance and its higher reactivity than belite. The particular structure of the well defined belite clusters should be sufficient to identify the cement but the identification of alite ensures the petrographer that a clinkered cement is the binder present.

If a fresh sample can be extracted sufficiently away from environmental exposure, additional information may be gleaned from the hydration products rather than the unhydrated residual particles. Portland cement reacts to form a combination of hydrates including calcium hydroxide. While the hydroxide is the

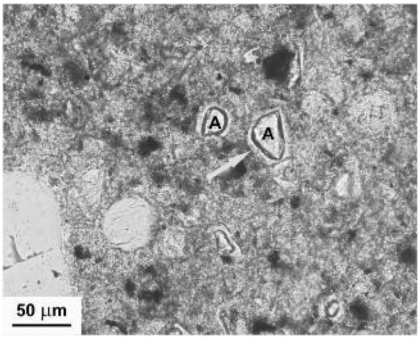

FIG. 4—*The mineral alite (A) is found exclusively in clinkered cement products. Note how the relict grains appear to stand out above the surrounding matrix. This is a function of the slower light velocity through the mineral as opposed to surrounding materials. This "relief" helps identify alite. The arrow indicates a colorless halo around the grain that represents a hydration rim produced during the reaction of alite with added mix water. (See color insert for color version of this figure).*

primary constituent of unreacted lime, its form is distinctly different when a product of portland cement hydration. Crystals are orders of magnitude larger than in hydrated lime. The size difference is easily distinguished under the petrographic microscope in contrast to instrumental methods such as X-ray diffractometry where the mineral is detected but not imaged.

Limes

Lime mortars of any type are quite different in both composition and structure. In fact, there is little danger of mistaking a lime for a portland cement when appropriate petrographic techniques are applied. Whether a hot-mixed lump lime, fat lime putty, or eminently hydraulic lime, the principal component of the raw material is calcium hydroxide. Manufacturing processes are quite different than for portland cement. A limestone of variable purity is "calcined" or brought to a temperature just high enough to drive off the carbon dioxide present in the original limestone. This temperature is much lower than the clinkering point and is typically less than 1000°C. The primary product is calcium oxide or free lime. However, this is a highly unstable compound and an additional step called slaking is required. There are a variety of slaking methods but simply put, it involves the addition of water to convert the oxide to calcium hydroxide. With some exceptions, the lime curing process does not involve hydration but rather carbonation. Over longer time periods than required for cement hydration, the lime begins to absorb carbon dioxide from the atmosphere, finally converting the binder back to calcium carbonate. The process is essentially one that produces an artificial limestone returning the product back to its approximate original form.

As with portland cement, residual lime grains are usually apparent even in lime mortars many centuries old. These rounded white lumps are distinctive and a simple powder scraping placed under the microscope may be sufficient for a tentative identification if the grain is macroscopically visible. But thin section examination is required to positively identify residual grains smaller than one millimetre. The difficulty in using simple powder mount techniques for lime identification is that the relict grains and the carbonated matrix are all composed of very fine-grained calcium carbonate as are the carbonated portions of hydraulic cement pastes. The presence of lime is revealed in the microstructural relationship between the residual grains and the surrounding matrix. Even though compositionally identical, the relict grains often have a fairly distinct boundary and a slightly denser character than the surrounding matrix (Fig. 5). Differential shrinkage between the two components often causes differing microscopic crack structures betraying the location of the relict grain. Additionally, the higher porosity and characteristic microscopic shrinkage cracking of lime mortars are blatantly obvious in thin section when no cementitious binders are present. Once these are detected, the chemical analysis may be used to estimate the original mix design where lime is present with another binder.

Further complicating the lime story are the more hydraulic varieties. These begin as "dirtier" limestones containing clay, quartz, and other minerals in smaller proportion. At the calcining temperature, the

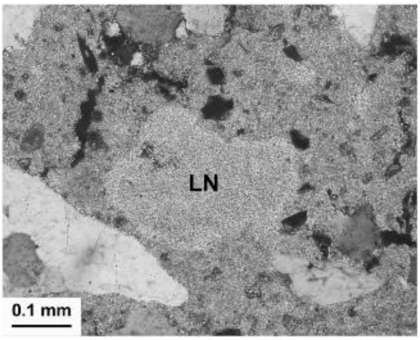

FIG. 5—*A residual lime nodule (LN) is depicted in this cross polarized light photomicrograph. The cream coloration of the grain identifies the carbonate that is a function of the curing process. The surrounding matrix is also carbonated but appears more blue-colored due to the blue-dyed epoxy impregnation that highlights the more porous areas. In powder mount, this grain would not be distinguished from any other carbonated cementitious material. Thin section preparation allows the petrographer to detect the subtle boundary between the lime grain and the otherwise carbonated matrix. (See color insert for color version of this figure).*

aluminum and silicon present in these other mineral phases will begin to combine with the free lime to form hydraulic calcium aluminates and calcium silicates. These minerals may be identical to those present in true hydraulic cements. In many cases, the original silicate minerals may not fully react and it is not unusual for the petrographer to observe what appears to be normal geological quartz. However, these grains usually contain expansive crack structures and a rim of either higher temperature varieties of quartz or hydraulic calcium silicate. Nevertheless, their appearance within the boundary of a petrographically identified lime grain precludes the possibility that they derive from either a cement component or the aggregate (Fig. 6).

Natural Cement

All of the binder products discussed so far are familiar to most petrographers. On the other hand, natural cements have received much less attention in previous decades and many examples go unrecognized or misidentified as a result. The situation is complicated by the fact that natural cements may be highly

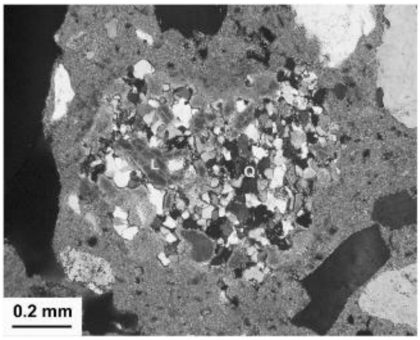

FIG. 6—*This cross polarized light photomicrograph illustrates a lime nodule representing a more hydraulic type of lime. The original limestone portion of the rock has been calcined and converted to the tan-colored lime (L) that has since carbonated. However, gray-colored grains of quartz (Q) are nearly unaffected by the burning process and retain their geologic character. The higher silica (or quartz) content of the lime identifies it as having some potential degree of hydraulicity. (See color insert for color version of this figure).*

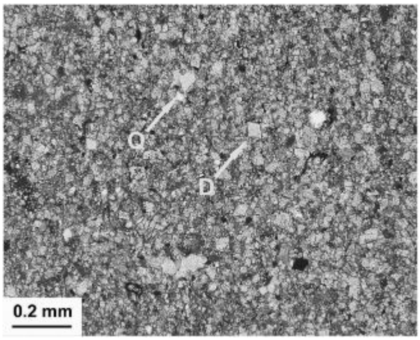

FIG. 7—*This cross polarized light photomicrograph illustrates the mineralogy and texture of the lower member of the Rondout Formation used in the production of Rosendale cement. Rhombic-shaped grains of dolomite (D) constitute a large portion of the rock. Gray-colored grains of quartz silt (Q) are evenly dispersed throughout the carbonated matrix. The overall darker brown coloration to the matrix is produced by clay minerals. The silica present in the quartz and the alumina contributed by the clays are responsible for the hydraulic properties of natural cement and distinguish it from other calcined limes. (See color insert for color version of this figure).*

variable in microstructure. Fortunately, there are several distinctive microtextures that allow for a positive identification and petrographic techniques remain one of the best tools for distinguishing these features. Before describing these textures, it helps to have an understanding of the raw materials and burning processes involved in natural cement manufacture.

While admittedly an oversimplification, natural cement may be thought of as residing within the continuum between portland cement and hydraulic lime. The composition of the raw materials are more similar to those of portland cement containing higher proportions of silica and aluminum. These are the elements that when combined with calcium will form the hydraulic minerals. However, the burning temperatures for natural cements were closer to the calcining temperatures of limes and were never clinkered unless accidentally overburned. The Rosendale district cements manufactured in New York State between the 1820s and 1970s deserve special attention, as these represent a majority of American-made natural cements. These were produced from carbonate rocks of the Rondout Formation along the Hudson Valley. The raw materials used in their manufacture include two layers of dolostone rock between which a thin unproductive limestone is found [6]. Dolostone is composed of a magnesian carbonate as opposed to the calcium carbonate found in raw materials for fat lime. The combination of relatively low burning temperatures with the distinctive mineralogy allows for a distinctive set of microstructural features unique to natural cements such as the Rosendale. Historical literature suggests that a large majority of American natural cements were mined from dolomitic sources thus distinguishing them from all portland cements as well as European Roman cements [7]. Rosendale cements are therefore considered representative of the majority of 19th century American hydraulic masonry cements. Preliminary research into other materials such as those produced in Shepherdstown, WV appears to support this generalization.

Figure 7 illustrates the typical microstructure of the lower member of the Rondout Formation in its raw state. The bulk of the rock comprises carbonate material including rhombic-shaped dolomite crystals. In addition, dispersed grains of quartz and finely divided clays are relatively evenly distributed throughout the rock. Were this fine-grained rock to have been clinkered, much of the original texture would have been destroyed and replaced with relatively coarse-grained hydraulic species similar to those observed in portland cements and calcium aluminate cements. Instead, the rock was burned at temperatures closer to calcining temperatures. While this was sufficient to form hydraulic species, the obtaining time and temperature were not sufficient to completely rearrange the original microtexture of the rock. Reactions occurred across grain contacts without complete decomposition of the original constituent minerals.

Even before the individual binder grains are detected, the distinctive matrix produced by natural cement curing may be apparent. Portland cement pastes are homogeneously isotropic or dark-colored where cementitious gels have formed, broken only by thin dispersed grains of calcium hydroxide which

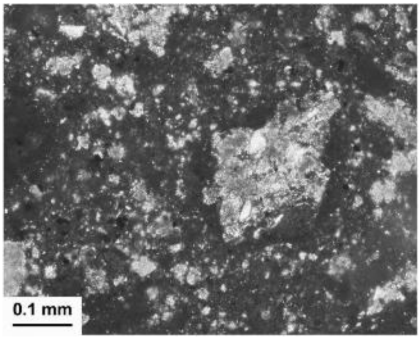

FIG. 8—*Natural cements may be thought of as containing both hydraulic as well as lime-type species. The mineralogy and texture shown in this cross polarized light photomicrograph is typical of natural cements. Portions of the rock were calcined during the burning process and essentially behave as lime. Carbonated material appears as bright-colored areas and represents calcined dolomite that has carbonated during the curing process. Dark areas of isotropic material represent hydraulic areas that have undergone hydration. This petrographic character is diagnostic of natural cement where fresh areas that have not been exposed to the environment are examined. This sample derives from a partially hydrated cement barrel found in the Widow Jane Mine in Rosendale, NY [8] believed to represent material produced during the early 20th century. (See color insert for color version of this figure).*

appear bright-colored. Lime matrices are homogeneously carbonated appearing very bright in polarized light. Microscopic shrinkage cracking as well as higher porosity are also hallmarks. Natural cement matrices are distinctively different. Both hydraulic as well as lime-type species are present in raw natural cement and these are heterogeneously distributed at the micron scale of observation. Under polarized light, the matrix of natural cements often appears spotted with dark isotropic areas broken by bright but dense carbonated regions. While these textures may be highly varied, there will usually be areas in thin section that have overall features that are not easily attributed to either portland cement pastes or lime matrices (Fig. 8).

The residual binder grains are where the most unambiguous evidence exists. Our laboratory obtained samples of both the lower and upper members of the Rondout Formation from Rosendale, NY and fired the samples in a furnace for 24 h at a variety of temperatures. Figure 9 illustrates one of the distinguishing features when viewed petrographically. At temperatures as low as 600°C, iron contained within the individual dolomite crystals begins to migrate out, lining the crystals with an iron-bearing phase. By the time calcining temperatures are reached, the dolomite has completely decomposed leaving behind calcium oxide and magnesium oxide. Even though the original mineralogy can no longer be identified, the original rock texture is largely preserved. This is one of the diagnostic features of natural cements observed in actual historical construction. In many cases, after a century or so of exposure, the calcined dolomite may carbonate again. However, the iron-rich outline is preserved betraying the texture of the original raw feed (Fig. 10). The cement residuals may appear to the petrographer as an odd carbonate rock but the lack of crystallinity within the dolomite structure in combination with the iron-rich lining should signal the analyst that the grains are not part of the aggregate fraction.

The dispersed quartz grains and other sand-sized silicate minerals also aid in distinguishing natural cements. These tend to retain most of their original texture when burned at calcining temperatures (Fig. 11). As temperature is increased, quartz begins to transition through a number of different structural forms. At temperatures below the calcining temperature a slight adjustment of the silicate bonds produce a more open structure which results in a bulk volume expansion. This may cause the quartz to develop internal cracks that are microscopically visible. These are best observed in cements produced from the upper member of the Rondout Formation which contains coarser grained quartz than the lower member. At temperatures approaching the calcining temperature, quartz will convert over to a different crystallographic form known as tridymite. At this point, the petrographic properties are significantly different than those of the original quartz grains. Tridymite rims around original quartz grains may be detected by their

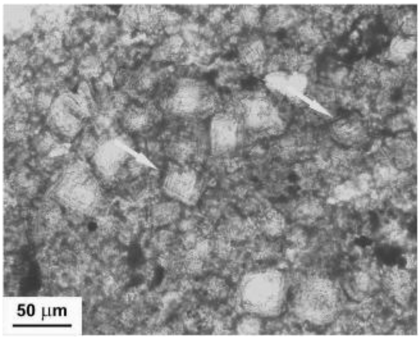

FIG. 9—*Our laboratory obtained samples of the Rondout Formation from Rosendale, NY and burned them at various temperatures for 24 h in a laboratory furnace. This plane polarized light photomicrograph illustrates lower member rocks burned at 600°C. The original rhombic-shaped dolomite crystals are still detected in their original positions and the rock fabric is not altered. However, iron contained within the dolomite crystals has migrated out to form a new iron-bearing species. The arrows indicate the reddish colored iron-bearing minerals that outline the original carbonate minerals. (See color insert for color version of this figure).*

crystallographic properties in both natural cements as well as limes especially when underburned. Finally, as the surrounding carbonate minerals calcine and convert to oxide forms their composite elements become available for combination with the silicate and hydraulic calcium silicates may form. Belite is the most likely phase to form and this is the same mineral comprising the bulk of historical portland cements. However, the microtexture is so significantly different that when viewed using polarized light microscopy, there should be no mistaking these silicates for clinkered forms. In clinkered cements, the belite phase will be well developed and display the "bunch of grapes" morphology (Fig. 3). Belites in natural cements will be much less well developed and surround a core of petrographically identifiable quartz.

These partially reacted grains may pose a problem for petrographers when the rims have reacted as the grains have a nearly identical morphology to that of alite. This is especially problematic in cements manufactured from the lower member of the Rondout Formation in Rosendale as well as some Round Top natural cements produced in Maryland where quartz silt is present in the size range of typical portland cement minerals (Fig. 12). This is where careful use of the polarized light microscope comes into play. Due to the very different velocities of light through quartz and alite, the optical properties should betray

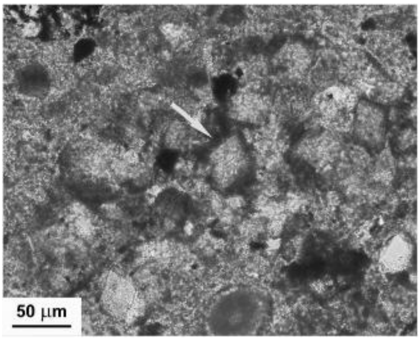

FIG. 10—*This plane polarized photomicrograph illustrates a residual grain of Rosendale natural cement circa 1850. Rhombic-shaped crystals of calcined dolomite are surrounded by reddish rims of an iron-bearing mineral phase (arrow). Note the similarity to the laboratory produced cement depicted in Fig. 9. This microtexture is diagnostic of natural cements produced from dolomitic raw materials and is never observed in portland cements or limes. (See color insert for color version of this figure).*

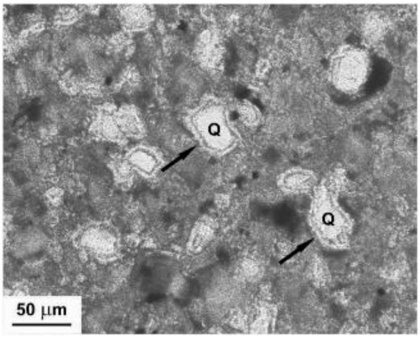

FIG. 11—*The cement shown in this plane polarized light photomicrograph was created in the laboratory by burning the lower member of the Rondout Formation rocks at 1000°C for 24 h. The original quartz grains (Q) have begun to react either forming trydimite (a different structural form of quartz) or have combined with the surrounding carbonates to form a calcium silicate. Even at this temperature, a large degree of the original raw feed texture is preserved. The arrows indicate the thin rims formed around the quartz grains as a result of the burning process. (See color insert for color version of this figure).*

the superficial similarities. Alite with its high refractive index will appear to stand out above the plane of the thin section while quartz will appear "flat" against its surroundings. The colors produced by the polarized light interference are subtly different but significant enough to detect by the trained eye. Alite will appear a dull gray while quartz may appear gray to white. When accurate optical properties are collected there should be no mistaking the difference. Even so, the preservationist should be wary if alite is identified in a report generated for a structure built before approximately 1880. While European portland cements were available, natural cement is the much more likely cementitious component.

Discussion

Good forensic laboratory practices can go a long way toward revealing the materials comprising historical construction. Petrographic techniques that are often as old as the materials being studied can play a lead role in the analysis. Reasonably accurate reverse engineering of cementitious materials is quite possible when microscopy techniques are combined with chemical analysis. For the sake of clarity, the most

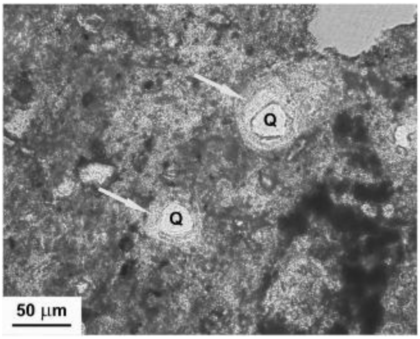

FIG. 12—*Depicted here in this plane polarized light photmicrograph is a mortar produced with natural cement. The arrows indicate reaction rims that formed around quartz grains (Q) during the burning process. These textures may be confused with hydration rims surrounding alite in portland cement (see Fig. 5). However, the optical properties are distinctly different and careful petrographic examination should preclude any confusion. (See color insert for color version of this figure).*

distinctive petrographic features are described in this article. It should be understood that when multiple binders are present or when significant deterioration has occurred, the analysis may become substantially more complicated.

If nothing else, the article should have dispelled the black box myth. The results of a mortar analysis report are only as good as the sample provided, the techniques applied by the analyst, and the investigator's experience. If material identification and replacement-in-kind are of importance then the laboratory analysis should be given high consideration.

Only a small portion of a typical mortar analysis has been discussed. Completely neglected is the aggregate analysis performed by a complete dissolution of the binder matrix and petrographic description of the intact residues. Chemical analysis and the several accompanying destructive procedures have only been summarily addressed. Consider the search for large binder residuals and the preparation of large area thin sections for petrography and the need for significant sample becomes obvious. Powder scrapings from the mortar joint will reveal little to nothing. Consider providing a full bed joint for brick construction or a significant portion thereof for stone masonry. Samples collected away from atmospheric or environmental exposure better represent the original material.

The laboratory should be considered an important member of the preservation team. Retaining a laboratory that performs only routine examinations and has no real experience in historical materials analysis is equivalent to hiring a masonry contractor that only repoints Type N portland-lime mortars and has no experience in placing restoration materials. A brief discussion of the project with the laboratory manager will often reveal volumes about the skill of that laboratory in reverse engineering historical materials. When an experienced laboratory is found, the forensic work should be performed as early as possible as the analyses described above will require several weeks for completion.

It is refreshing that a momentum is gathering toward an appreciation for authentic American masonry materials and practices. Many decades of inappropriate restorations have been suffered with the application of portland cement-based repair materials "softened" with hydrated lime. The recent interest in hydraulic limes as a restoration alternative represents a quantum leap in sophistication. Where natural cement beds are present, limes are much more physically compatible than portland cement mortars and further deterioration will likely be avoided through their application. However, where true replacement-in-kind is desired, limes are as inaccurate as portland cement when natural cements are present in the construction. Foremost in a determination of an appropriate repair material is an identification of the original binders and their proportions. It is hoped this paper will spark further interest in the forensic aspects of American masonry construction and that the scientific data will keep pace with the increasing desire among preservation professionals for accurate analysis of existing materials.

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Michael P. Edison[1]

Formulating with Rosendale Natural Cement

ABSTRACT: Understanding the guiding formulation principles behind the use of natural cement in the 19th and early 20th centuries allows better interpretation of the results of laboratory analyses and more accurate reproduction of historic masonry and concrete materials. This paper reviews traditional formulation practices for natural cement mortars, grouts, stuccos, concretes, and lime-washes, including ingredient selection, technical and economic criteria affecting formulation, and how the materials and formulations changed over time. Effects on performance of typical formula variations are reviewed, and potential effects on performance of modern admixtures are considered.

KEYWORDS: natural cement, Rosendale, historic mortars, historic concrete, historic stucco, mortar formulation, lime mortars

Introduction

The restoration of traditional masonry mortars, stuccos, lime-washes, grouts, and concretes will generally be best performed by duplicating original formulations, when they have performed well. The goal of faithful reproduction of historic materials is more likely to be achieved if results of forensic investigations are combined with knowledge of traditional formulation practices. If the guiding formulation principles behind the use of natural cement in the 19th and early 20th centuries are understood, the results of laboratory analyses can be better interpreted.

Common formulation practices for masonry and concrete materials of the 19th and 20th centuries variably utilized natural cement as the sole binder, primary binder, co-binder, or as an additive. These formulations were not static, but rather were manipulated in response to changing technical and economic realities.

Understanding the past is also the first step in moving forward, as natural cement may have some compelling potential nontraditional uses today.

The goal of understanding the past is complicated by the wide diversity of historical applications for natural cement. The prolific uses of natural cement technology ranged from post-war of 1812 coastal fortifications and canals, to railroad bridges and depots from the earliest days of transcontinental transportation, to Industrial Revolution-era manufacturing complexes, to late 19th century commercial, institutional, and governmental buildings, to the nation's first municipal subway systems, water systems, dams, bridges, monuments, and lighthouses, to mid-20th century interstate highways and seaways.

The diversity of the formulations used for combining natural cement with other materials fully reflects all of these differences. In addition, thriving technologies are subject to ongoing process developments, changes in cost structures and a growing body of experience-based knowledge, all of which will lead to changes over time.

It may be most instructive to begin with a review of the major traditional uses of natural cement, and of the other ingredients with which it was most commonly combined.

Ingredients Used in Natural Cement Formulations

Natural Cement

Historical formulations in North America began with one of the many commercial brands of natural cement produced from 1818 to 1970. Natural cements were produced in over 70 locations in the United

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[1] Edison Coatings, Inc., 3 Nothwest Drive, Plainville, CT 06062.

States and Canada at various times during that period, and composition was highly variable. More than half of all of the more than 35 million tons of natural cement produced in the United States originated with cement rock mined in Ulster County, New York, in and around the Town of Rosendale in the Hudson River Valley. Major secondary centers of production were located along the Potomac, James, and Ohio Rivers.

The first formulation variable, therefore, is the cement rock itself, and one of the key variables traditionally used to control natural cement performance stems from its geological deposition in multiple layers of varying composition. Cement producers learned to use these differences to balance such properties as strength and setting time, which were controlled by blending rock from different layers, usually before calcining.

The calcining process itself also has a significant effect on performance. The ideal burning cycle leaves the rock slightly underburnt, and cement producers managed to produce viable cements in spite of the almost complete lack of temperature controls. Properly calcined rock had to be separated from underburnt and overburnt materials, however, resulting in rejection of perhaps 25 % or more of all production.

The fineness to which natural cement powder is ground also has a dramatic effect on performance, and over time, the standards evolved to require finer and finer grinding. Early cements were ground using stone mills, and in 1872, General Q. A. Gillmore of the U.S. Corps of Engineers reported that “cements sent to market are, as a general thing, imperfectly ground” [1]. He further suggests: “Not more than 8 per cent of a cement should be rejected by a sieve of 6400 meshes to the square inch” [2] (US No. 80). Federal specifications referenced by Cummings, writing in 1898, however, include a standard of 90 % passing a No. 50 sieve [3], considerably coarser than Gillmore’s suggestion. In Cummings’ discussion of production methods, he refers to grinding mills of the time being capable of routinely producing cements with 95 % of particles passing a US No. 100 Sieve [4]. The ASTM Committee C report of its proceedings in 1904 established the first broad, comprehensive consensual standards for both natural and portland cements. The fineness requirement stated: “It shall leave by weight a residue of not more than 10 % on a No. 100, and 30 % on a No. 200 sieve” [5]. ASTM C10-76 Standard Specification for Natural Cement, the most recent published standard prior to the current reinstatement effort, included a fineness requirement of 6000 cm^2/g of specific surface [6].

Fineness of grind not only influences cement strength, but also directly affects time of setting. As cement is ground finer, its surface area in proportion to its volume is increased, resulting in greater area of contact with water and faster reaction and setting. Excessively rapid time of setting was recognized as a significant potential problem, as Gillmore writes: “… a quick-setting cement is always difficult to be used; it often requires special workmen, and, at all events, a very active supervision.” [7]. A workable balance between rapid hardening and reasonable working times was of great importance. Some natural cements produced from argillaceous limestone were recognized as being too rapid in their time of setting for the intended uses, and the earliest American specifications required a minimum of 10 minutes for time of initial setting, 30 minutes for time of final setting. A minimum of 30 minutes for time of initial setting was used in every revision of ASTM C 10 after 1952. Some revisions also included a maximum of three to six hours. [8].

Water

The ingredients typically used with natural cement obviously must include water. Neither water quality nor quantity can be taken for granted in formulating natural cement materials.

Figure 1 is a recent photograph of Fort Jefferson, located on Dry Tortugas, 70 miles west of Key West, Florida, in the Gulf of Mexico. Military engineers of the 19th century, faced with the task of building what was perhaps the largest brick masonry structure in the western hemisphere in its time, and having to do it on an island without its own source of fresh water, made the most obvious and expedient choice. They used was what was at hand, which, of course, was seawater. Some 150 years later this choice does not appear to have had any obvious detrimental effect, although results would clearly have been quite different had the technology of the time included steel reinforcement. That is not to suggest, however, that 19th century military engineers were oblivious to the potential negative effects of seawater on mortar and concrete.

In 1860, during the construction of Forts Richmond and Tompkins in New York Harbor, experiments were undertaken by the Corps of Engineers involving the injecting of a thin paste of Rosendale natural

FIG. 1—*Fort Jefferson, Dry Tortugas, Florida, offered 19th century engineers no fresh water for mixing of mortar and concrete. Seawater was used to no apparent detrimental effect. (Photograph courtesy of Michael Edison, 2004.)*

cement without sand into prepositioned boxes of coarse gravel and pebbles, submerged in seawater. In some cases the cement was mixed with fresh water, in others it was mixed with seawater. The concrete blocks were later examined, producing the following observations:

Blocks made from the cement mixed with seawater cracked and disintegrated. Blocks made from cement mixed with fresh water performed very well, however, even when placed and cured in seawater [9]. While natural cement mortars mixed with seawater have not displayed this same tendency to disintegrate rapidly, these results did guide later concrete work.

A second water-related issue, the importance of minimizing the amount of water used, was also recognized early on. In most cases natural cement was mixed with such little water as to never form the sort of plastic mass we are accustomed to working with when using portland cement mixes today. The historical references speak repeatedly of using incoherent mixes and of the importance of securing the services of a "faithful workman, one who will not spare his strength, or lay any mortar too loosely…" [10].

Sand

Sand is far less simple an ingredient than might be presumed. Its purpose and function were well understood, and that impacted its manipulation in various formulations. Returning to challenges of building Fort Jefferson (Fig. 2), a massive brick masonry structure on a small dry island in the Gulf of Mexico, 19th century engineers had little choice with regard to sand selection. While no doubts are expressed about shipping natural cement 1500 miles, all the way from Rosendale, New York (and in other cases, to sites much farther from the Hudson Valley than this) when it came to sand, they opted again to use what was at hand.

Still, 19th century engineers were not unclear in their thinking when it came to the purposes and effects of adding various types of sand to natural cement, and the subject was discussed in great detail.

They understood, for example, that the test cubes made with neat cement paste were substantially harder than the ones made from mixtures with sand. They understood that in return for giving up some of this strength they gained a benefit of reducing shrinkage and just as importantly, it reduced cost. Gillmore also discussed the effect of increasing permeability, although this may not have been viewed as a positive effect at the time.

Most importantly, the effect of using sand with an appropriate particle size distribution was properly appreciated. Sands that combine acceptable proportions of fine, medium, and coarser particles will achieve a higher density than sands of uniform particle size, and higher density leads directly to higher strength and better resistance to water infiltration.

It was also recognized that particle size distribution affects workability.

Figure 3 is taken from Gillmore's work, showing the breakdown of particle sizes of the sands from

FIG. 2—*Fort Jefferson's remote location left 19th century engineers little choice but to make use of the excessively coarse calcareous beach sand that was at hand. (Photograph courtesy of Kenneth Uracius, 2004.)*

various sources. The 1/12 in., 1/18 in., and 1/24 in. grain sizes he is reporting correspond with the proportions of the sand which were retained on a #12 sieve, a #18 sieve, a #24 sieve, etc. His primary interest was density.

It is interesting to note that sand No. 1, the calcareous sand from Key West, Florida, is relatively coarse, with almost all of the particles in the 18–60 mesh range. Gillmore reports that when the masons building Fort Taylor in Key West attempted to use this sand simply by hand mixing it with cement, it was described as "woolly," and required a much larger dose of cement or lime to work properly under the trowel. He also noted that when the coarse sand was used, brick mortar joints tended to be laid wider, resulting in higher cost of construction. This latter issue was undoubtedly what justified the building of a motor-driven mortar mill, as shown in Fig. 4, at the enormous sum (for 1860) of $5000.

The mortar mill both mixed the sand and cement and ground the coarse sand to a finer particle size, with the effect of making it more workable. An identical set of observations was reported during the work

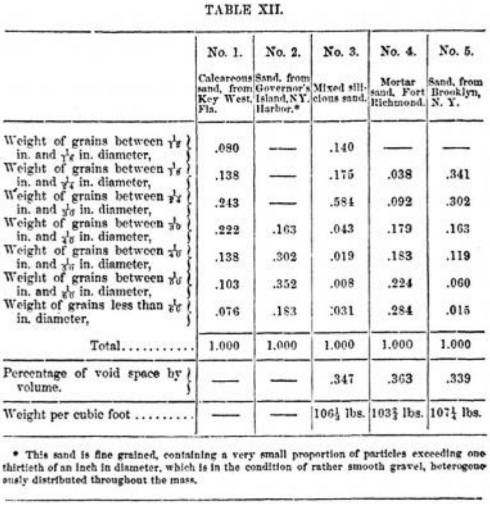

TABLE XII.

	No. 1. Calcareous sand, from Key West, Fla.	No. 2. Sand, from Governor's Island, N.Y. Harbor.*	No. 3. Mixed silicious sand.	No. 4. Mortar sand, Fort Richmond.	No. 5. Sand, from Brooklyn, N. Y.
Weight of grains between $\frac{1}{12}$ in. and $\frac{1}{18}$ in. diameter,	.080	—	.140	—	—
Weight of grains between $\frac{1}{18}$ in. and $\frac{1}{24}$ in. diameter,	.138	—	.175	.038	.341
Weight of grains between $\frac{1}{24}$ in. and $\frac{1}{30}$ in. diameter,	.243	—	.584	.092	.302
Weight of grains between $\frac{1}{30}$ in. and $\frac{1}{40}$ in. diameter,	.222	.163	.043	.179	.163
Weight of grains between $\frac{1}{40}$ in. and $\frac{1}{50}$ in. diameter,	.138	.302	.019	.183	.119
Weight of grains between $\frac{1}{50}$ in. and $\frac{1}{60}$ in. diameter,	.103	.352	.008	.224	.060
Weight of grains less than $\frac{1}{60}$ in. diameter,	.076	.183	.031	.284	.015
Total..........	1.000	1.000	1.000	1.000	1.000
Percentage of void space by volume.	—	—	.347	.363	.339
Weight per cubic foot	—	—	106⅓ lbs.	103⅔ lbs.	107¼ lbs.

* This sand is fine grained, containing a very small proportion of particles exceeding one thirtieth of an inch in diameter, which is in the condition of rather smooth gravel, heterogeneously distributed throughout the mass.

FIG. 3—*Sand particle size distribution data for sands used in the construction of various seacoast fortifications [11].*

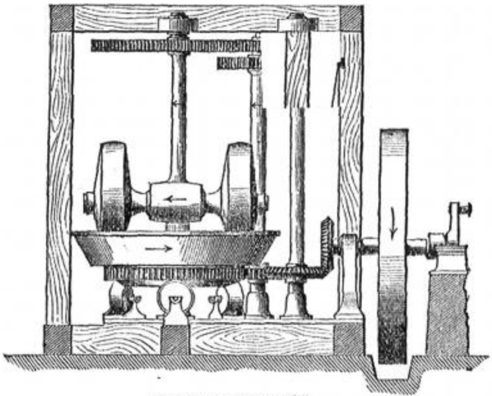

FIG. 4—*Steam-powered mortar mill, used in the construction of Fort Taylor in Key West in 1857 [12].*

at Fort Jefferson in the summer of 2004. Sieve analyses of the local sand at Dry Tortugas National Park showed a similar deficiency in fines, and a motorized roller pan mixer was employed to produce a workable mortar that was an excellent match for the original materials.

Lime

Lime was often used in combination with natural cement. The lime used by the Corps of Engineers in the 19th century was almost invariably quicklime, packed in sealed barrels in a lump condition. This material would be slaked on site, as the economic penalty for shipping lime as a paste or putty with excess water would have been out of the question. The primary objective of slaking is described as lump reduction, allowing the lime to be distributed uniformly in the mortar and to achieve a smoother, more workable consistency.

The issue of whether slaking to lime paste (putty) was preferable to the use of powdered hydrate was also considered 160 years ago. In General Totten's experiments at Fort Adams, in Newport Harbor, he compared the performance of mortars using lime paste (putty) to those made using dry lime hydrate.

The dry hydrate was prepared by spreading quicklime on the ground and carefully sprinkling just enough water onto it to cause it to crumble to a powder. The alternative method, preparing lime in a paste consistency using excess water, was aptly referred to as "drowning." Totten's conclusions were that the dry hydrate produced a stronger mortar, and that drowning weakens performance of the lime paste [13].

The process of slaking by sprinkling to produce a dry lime hydrate was not Totten's innovation. It is described by Young, writing in 1817, as a common practice, used by the Dutch in the 18th century for slaking of the lime used in the building of their system of dikes [14].

Gillmore reported, nonetheless, that drowning was the most commonly used method of slaking, primarily because it required less attention and effort by the workmen, whom he generally perceived as inclined to abuse the process in order to make the work easier. This being the principal reason for preference of paste given by Gillmore, one may speculate that dry hydrate would have been preferred had it been commercially available in 1860.

Extended aging of lime pastes was not routinely employed. They were often incorporated and used as soon as lump reduction was achieved. Gillmore specifies waiting at least two days after slaking. Although high calcium lime would have been available in some regions, even the high calcium lime produced in the United States is typically higher in magnesium content than European limes, and much of it would be classified as dolomitic.

While the historic texts do not directly address this issue, some 19th century specifications called specifically for lime produced in Rosendale, known to be high in magnesium content. American lime producers have maintained that dolomitic lime tends to more readily meet the requirements for plasticity and water retention specified for Type S lime in ASTM Standard C 207. This is claimed to be related to the microstructure of magnesium hydroxide crystals, which consists of a series of microscopic hexagonal

TABLE 1—*Tensile bond strengths at several intervals obtained from various combinations of natural cement and lime. All values are in pounds per square inch. Data is from a University of Illinois study, 1891.*

Natural Cement	Lime	7 Days	28 Days	56 Days	147 Days
100 %	0 %	8.4	27.1	33.3	47.3
90 %	10 %	16.9	24.4	31.2	51.3
80 %	20 %	5.2	23.6	35.1	36.8
60 %	40 %	7.1	15.2	24.8	25.0
40 %	60 %	7.0	8.7	13.4	15.7
20 %	80 %	3.6	8.9	9.0	10.4
10 %	90 %	3.1	6.9	10.8	11.7
0 %	100 %	2.3	7.3	15.2	12.2

platelets. The plates readily slip against each other when subjected to the shear of troweling, and also block the evaporation of water [15]. The same structures are only achieved in high calcium lime when made into putty and aged, perhaps accounting for differences in American and European practices, as high calcium lime is more prevalent in Europe.

Lime was used extensively in combination with natural cement, and its effects were well considered on several different levels. These include effects on performance properties, workability, and cost.

Table 1 lists the results of an 1891 study conducted at the University of Illinois, measuring the effects of mixing lime and natural cement together in proportions ranging from 10 % lime and 90 % natural cement to 10 % natural cement and 90 % lime. The blends used in these studies reflected common practice.

Gillmore reported that for structures not subject to immersion, or at least those not subject to immediate immersion, lime could be added at levels of 50 % of the cement or more without loss of mortar performance quality. He also noted that 10 % lime addition improves adhesion and workability, and in Table 1 the tensile bond strength is in fact generally higher for this 90/10 mix than it is for any of the other proportions.

On the other end of the scale there was a benefit recognized in gaging lime mortar with 10 to 20 % natural cement to provide faster set and to improve early strength and weather resistance characteristics. This simple practice may account for the absence of any significant historical production of hydraulic limes in the United States. Inexpensive, locally-produced ordinary lime could be rendered hydraulic by the addition of relatively small quantities of natural cement, providing the benefits of hydraulic limes without the expense associated with its transportation.

Economic Considerations

Effects of ingredient selection and proportioning on cost were primary considerations in 19th century construction. Table 2 lists the costs of mortar used for stone masonry in the construction of Fort Warren in Boston harbor.

The stone masonry mortar mixture illustrated in Table 2 is calculated to have a cost per cubic yard (27 ft^3) of $3.93. Table 3 illustrates the cost impact of using alternative mixes composed entirely of natural cement binder and lime binder, respectively.

Given the significant impact on cost of natural cement use, one may conclude that the mixtures actually used represented a considered balance of cost versus performance benefits. In a variety of applications from the 1850s to the early 1900s, it can be seen that while structures subject to immersion in

TABLE 2—*Costs of mortar for stone masonry during the construction of Fort Warren, Boston Harbor.*

Ingredient	Price per Unit	Cost per Mix
1 Cask Natural Cement, 308 lb	$1.625percask	$1.625
$\frac{1}{2}$ Cask Lump Quicklime	$0.70 percask	$0.350
14.67 ft^3 Sand	$0.50 per ton	$0.496
Labor of Men	$0.91 per day	$0.245
Labor of Horse	$0.40 per day	$0.028
TOTAL: 18.5 ft^3 of Mortar		$2.744

TABLE 3—*Cost impact in the 1850s of using natural cement, lime, and natural cement-lime binders in masonry mortars.*

Binder	Cost per Cubic Yard	Cost Penalty/(Savings)
1 Natural Cement: 1/2 Lime	\$3.93	…
All Natural Cement	\$5.96	+50.9 %
All Lime	\$2.53	(−35.6 %)

water were often built with mortars based entirely on natural cement, nonimmersion architectural applications typically used up to 50 % or more lime as a means of reducing cost without significantly compromising performance.

Miscellaneous Additions

Coarse aggregates were routinely added to natural cement mortars to produce early concretes. These were often simply whatever materials were readily available, and included brick and tile fragments, stone fragments, pebbles, gravel, or oyster shells. Fractured stone aggregates were also sometimes incorporated, and the use of a machine for fracturing stone is described in the construction of New York City's Central Park.

Early concretes did not generally incorporate coarse aggregates into fluid cement paste-sand mortars, as is the modern practice. Gillmore offers us this report from a Lieutenant Wright, charged with concrete construction at Fort Warren:

> As reported by Lieutenant Wright:
>
> The concrete was prepared by first spreading out the gravel on a platform of rough boards, in a layer from 8 to 12 inches thick, the smaller pebbles at the bottom and the larger at the top, and afterwards spreading the mortar over it as uniformly as possible.
>
> The materials were then mixed by 4 men, 2 with shovels and 2 with hoes, the former facing each other and always working from the outside of the heap to the center, then stepping back; and recommencing in the same way, and thus continuing the operation until the whole mass was turned.
>
> The men with hoes worked, each in conjunction with a shoveller, and were required to rub well into the mortar each shovelful, as it was turned and spread, or rather scattered on the platform by a jerking motion.
>
> The heap was turned over a second time in the same manner, but in the opposite direction, and the ingredients were thus thoroughly incorporated, the surface of every pebble being well covered with mortar.
>
> Wright comments further, that "the success of the operation, however, depends entirely upon the proper management of the hoe and shovel, and though this may easily be learned by the laborer, yet he seldom acquires it without the particular attention of the overseer" [16].

Gillmore follows this description with a note that "in Europe, machinery is sometimes employed for incorporating the ingredients of concrete, when large quantities are required" [17].

20th Century Natural Cement Additions

When the use of portland cement began in earnest in this country in the late 19th and early 20th centuries, the use of natural cement was not completely abandoned. Over the course of a long period ending in 1970, portland and natural cements were often used together. This combination is evident in major construction projects including New York's Rockefeller Center in the late 1930s, the New York State Thruway in the 1950s, and the St. Lawrence Seaway in the late 1950s and early 1960s. In the final years of its operation, the Century Cement Company of Rosendale, New York (Fig. 5), the last of the 20th century natural cement producers in the United States, focused on production of masonry cements based on natural and portland cement combinations. The most recent publication of ASTM C 10 in 1976 specifically references the intended use of natural cement as an addition for portland cement, and provides for a Type NA natural cement incorporating air-entraining admixtures [18].

FIG. 5—*Remains of the former Century Cement Company plant in Rosendale, NY, last of the original natural cement producers in the United States, closed in 1970. Natural cement mining in Rosendale was restarted in 2004 for production of natural cement for use in historic restoration. (Photograph Courtesy of Michael Edison, 2004.)*

Formulating Historic Mixes with Rosendale Natural Cement

With the reintroduction of natural cement in 2004, conservators now have the option to repair or replace historic natural cement materials in-kind. Often the formulation of restoration mixes is based on the results of analyses of the existing materials. As few petrographers have worked with natural cement and possess appropriate reference standards, and as many conservation laboratories rely on digestion methods that are incapable of distinguishing between a variety of hydraulic binders, misidentification has been a significant issue. Reference standards of stone, clinker, and ground cement are being made available to petrographers by the current producers, however, and coupled with educational efforts, this should result in the reduction of cases of such misidentification. Petrography remains something less than an exact science, however, and some background of common formulation practices may aid petrographers in making more accurate assumptions when analyzing historic masonry and concrete binders.

Masonry Mortar Formulations

As previously discussed, the wide range of formulations for natural cement masonry mortars corresponded with the wide range of applications, exposures, locally available ingredients, and economic constraints. As a general rule, however, natural cement masonry mortar mix proportions tended to be somewhat richer in binder than modern masonry mortars. Binder-sand proportions of $1:2$ to $1:2\frac{3}{4}$ were most common, though some applications requiring higher strength or greater resistance to water, or both, may have utilized mortars as low as $1:1\frac{1}{2}$ or even $1:1$.

Table 4 is a listing of several recipes used in mid-19th century seacoast fortification construction, illustrating some of the typical variability in these formulations.

Pointing Mortar

Common 19th century masonry mortars were perceived as being deficient in their resistance to water and weathering. To overcome these perceived shortcomings, the practice of applying a harder pointing mortar on the joint surface became common. This process was undertaken at the time of original construction, and involved the raking back of new mortar to a depth of $\frac{1}{2}$ in. from the surface.

Pointing mortar formulations (Table 5) were generally prepared in the following proportions:

The mixture was prepared at very low levels of water addition to minimize porosity, and was hammered into the joints to the point where a thin film of water developed on the surface. The pointing mortar was then damp-cured for several days.

TABLE 4—*Masonry mortar recipes from the mid-19th century for three seacoast fortification applications.*

Stone Masonry at Fort Warren	Brick Masonry at Fort Warren	Brick and Stone Masonry at Forts Richmond and Tompkins
1 Cask/300 lb Natural Cement=3.7 ft^3	1 Cask/300 lb Natural Cement=3.7 ft^3	1 Cask/300 lb Natural Cement=3.7 ft^3
$\frac{1}{2}$ Cask Lime	$\frac{1}{2}$ Cask Lime	…
14.67 ft^3 Sand	12 ft^3 Sand	9.75 ft^3 Sand
$1:\frac{1}{2}:4$ Cement-Lime-Sand	$1:\frac{1}{2}:3\frac{1}{4}$ Cement-Lime-Sand	$1:2\frac{1}{2}$ Cement-Sand
1:2.67 Binder-Aggregate	1:2.2 Binder-Aggregate	$1:2\frac{1}{2}$ Binder-Aggregate
Yield: 18.5 ft^3 Mortar	Yield: 16 ft^3 Mortar	Yield: 11.75 ft^3 Mortar

This common practice may lead the inexperienced conservator or petrographer to incorrectly conclude that a harder repointing mortar had been placed at some later time, as was common in many inappropriate 20th century repointing efforts. Alternatively, if the pointing mortar has substantially eroded, an analysis may incorrectly conclude that the building or structure was originally constructed entirely with lime mortar, or with mortars with relatively high lime content. Evidence of residual, original pointing mortars should be sought in 19th century buildings and structures, in the interest of historical accuracy.

Stucco

The use of natural cement for producing stucco finishes and decorative castings over brick construction was the most common application for natural cement in northern Europe. The London Building Act of 1774 led to tremendous demand for stucco coverings and natural cement was widely used for this purpose [19]. This practice is reported to have been spread to the southeastern United States by an English immigrant to Charleston, and spread throughout the southeast as far west as New Orleans. Natural cement remained a basic ingredient in southeastern stuccos well into the 20th century.

The U.S. Corps of Engineers employed stucco as a covering for brick in the construction of Fort Adams in Newport Harbor in the mid-19th century, and some examples of 1850s stucco remain visible and in good condition after 150 years. Gillmore describes the practice of formulating and applying stucco in terms of a series of procedural steps.

The process begins with raking of the masonry mortar joints to a depth of $\frac{1}{2}$ in.. Dust and debris were then washed away and the walls were predampened. Contaminated surfaces were to be scored with an axe. Stucco was then prepared in a fluid, workable consistency, and was applied in two lifts. The first lift was intended to fill the raked masonry joints and to provide a thin base-coat over the masonry surface. The second coat was installed over the soft base coat to a depth of $\frac{1}{2}$ in. and was immediately finished. The stucco was then cured for several days. The stucco recipe in Table 6 is cited:

When color was desired to be added to stucco, iron oxide pigments were incorporated at appropriate proportions. When lighter colors were desired than could be achieved with natural cement binders alone, lime was blended with the natural cement to produce lighter-colored matrices.

TABLE 5—*Pointing mortar formulation.*

Ingredient	Proportions
Natural Cement	1
Sharp Silica Sand	$2\frac{1}{4}-2\frac{3}{4}$
Water	Very Low Levels; No Plasticity

TABLE 6—*Mid-19th century stucco formulation.*

Ingredient	Proportions
Natural Cement	1
Sand, Damp and Compacted	1.66
or Loose and Dry	2
Water	To Workable Consistency

Limewash

Historic U.S. Government specifications include reference to use of natural cement as a durable whitewash or limewash. In such applications where color was not of importance, the natural cement was simply mixed with water to a fluid consistency. Colors could be produced by addition of iron oxide colorants. Where lighter colors were desired, natural cement was first blended with lime.

Concrete

One particularly labor-intensive procedure for preparation of concrete, as used at Fort Warren, was described earlier. In general, early concrete practices involved use of relatively dry cement-sand mortars into which coarser aggregates were scrubbed or rammed. The use of concrete expanded significantly in the second half of the 19th century and among the best known uses of this material was the construction of the Brooklyn Bridge from 1870 to 1883. By this time, concrete mix designs were beginning to more closely resemble modern concrete and the use of more fluid, pourable mixes had become the prevailing practice.

Natural cement concrete was used in the filling of the caissons on which the bridge is supported. The caissons were similar to large, flat, inverted boat hulls that were launched from a shipyard, floated into place, and then sunk by the gradual addition of the weight of the bridge's granite superstructure to the caisson's thick wooden roof. Workers excavated the river bottom from within the caissons in a compressed air environment, until such time as they reached a stable footing. At that point the caissons were filled with concrete. The formula for the concrete used in the bridge's construction is described in Table 7.

Grout

Historic references to grout are few, but grouts based on natural cement were used in the 19th century. One such use was, again, in the construction of the Brooklyn Bridge.

During the early phases of construction, the caissons which were to eventually support the bridge's superstructure were, as previously described, an inverted boat of sorts with steel walls and a 25-ft thick wooden roof. This compressed air-filled work chamber was pinned to the floor of the East River by the weight of the rising granite superstructure. On December 1, 1870, fire broke out beneath the river's surface in the Brooklyn caisson, when a worker inadvertently ignited some exposed oakum sealant with a candle. As the fire spread through the wooden roof, the rush of compressed air through leaks which subsequently developed had the effect of fanning the flames. A fluid grout mixture consisting only of Rosendale cement and water was used to seal the air leaks, aiding in bringing the fire under control. Later, several hundred test borings were drilled into the roof to assess the extent of the fire damage, and these, too, were sealed with natural cement grout. All told, some 600 ft^3 of grout was pumped into the caisson roof [21].

The use of fluid cement grouts was later criticized by engineers. Writing in 1903, Baker states that "grout should never be used when it can be avoided. If made thin it is porous and weak; and if made thick, it fills only the upper portion of the wall" [22].

Nonetheless, simple fluid cement grouts were used for specific purposes during this period, and in the case of the Brooklyn Bridge, it played an important role in the project's ability to move past the near

TABLE 7—*Mix design for Brooklyn Bridge concrete [20].*

Ingredient	Proportions
Rosendale Natural Cement	1
Sand	2
Fine Long Island Beach Gravel	4

FIG. 6—*In a recent photo from the nearby Woolworth Building, the Brooklyn Bridge continues to carry traffic across the East River. (Photograph Courtesy of Michael Edison, 2005.)*

disaster of December, 1870. The bridge is one of the most recognized structures in the world, and is certainly the most recognized natural cement structure. Today, the bridge (Fig. 6) remains in full traffic-bearing service, carrying heavy vehicular traffic at a rate of over 50 million vehicle crossings per year [23].

Beyond Tradition

The use of portland cement came to dominate concrete and masonry construction as building technology pushed toward faster construction of less massive buildings and structures requiring higher-strength materials. Ultimately, portland cement permitted more cost effective construction, even though its price remained higher than that of natural cement.

In restoration work, however, a different set of criteria apply. Stronger is not necessarily better, more compatible or more appropriate, and the opposite is often taken to be true. With the benefit of 180 years of hindsight, natural cement can now be appreciated for having been a very durable, compatible and effective building material. As consideration is given to sustaining our historic buildings and structures over the long term, the reintroduction of natural cement provides a new series of options for their long-term maintenance and repair.

Although natural cement was used as a restoration material as early as 1820, when Thomas Jefferson replaced leaking lime mortars on the Monticello cisterns with natural cement, its true potential can only now begin to be imagined. Applications such as microinjection grouting and composite patching were never envisioned by the canal and fortification builders. The developments of the past 35 years in cement admixture technology have been widely applied to concrete construction and restoration, but have never been used in conjunction with natural cement.

There may be due cause for debating the appropriateness of using modern admixtures with traditional materials in any given historic restoration application, and those debates will undoubtedly occur. On the other hand, given the great lengths to which 19th century engineers went to try to control water-cement ratios, can there be any doubt that they would have enthusiastically embraced high range water-reducing admixtures (superplasticizers) if they had been available?

Beyond the traditional uses and the recently renewed capacity to repair natural cement buildings and structures in kind, natural cement holds great promise as a specialty material for use in a variety of restoration and preservation applications. They promise to be a resource that will remain in good supply, as well. Unlike the exhausted or inaccessible sources elsewhere, the mines in Rosendale, New York, still hold countless accessible tons of the highest quality natural cement rock, capable of supplying long-term future needs.

Understanding the past and rediscovering traditional means and methods have been the first steps toward moving forward. Looking back at the remarkable performance history of natural cement, one can't help but wonder whether the technology wasn't abandoned prematurely in the 20^{th} century, and what remarkable things may yet be accomplished with its reintroduction in the 21st.

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SECOND AMERICAN NATURAL CEMENT CONFERENCE

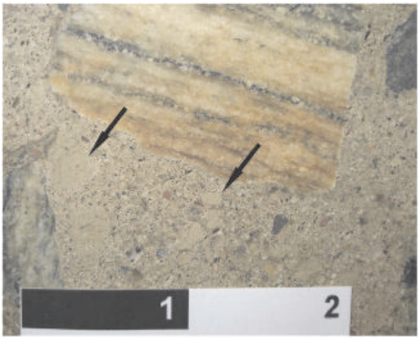


FIG. 2—*Close-up photograph of a polished cross section of concrete produced with Rosendale natural cement. The arrows indicate visible tan colored lumps of residual cement. Large unreacted or partially grains such as these are relatively common in historic construction materials and greatly aid the forensic petrographer in identifying the binder. The included scale is in inches.*

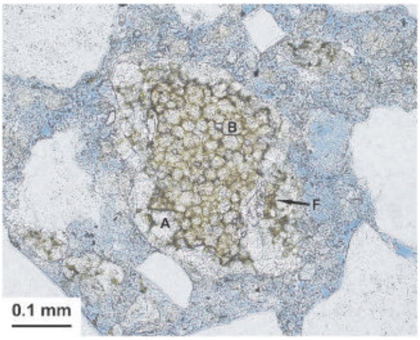


FIG. 3—*Plane polarized light photomicrograph of a residual portland cement particle typical of those detected in early 20th century materials. Petrographers refer to these relicts as having the "bunch of grapes" texture. The texture is produced by agglomerates of the calcium silicate mineral belite (B). Large groupings of small belite crystals are typical of older portland cements. Alite (A) is another calcium silicate and occurs only when clinkering temperatures are obtained. Its presence positively identifies a clinkered cement as opposed to natural cement or lime. The brown-colored ferrite phase (F) is common in portland cement but may be present in any binder containing calcium, aluminum, and iron.*

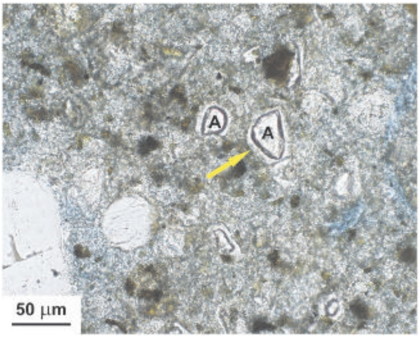


FIG. 4—*The mineral alite (A) is found exclusively in clinkered cement products. Note how the relict grains appear to stand out above the surrounding matrix. This is a function of the slower light velocity through the mineral as opposed to surrounding materials. This "relief" helps identify alite. The arrow indicates a colorless halo around the grain that represents a hydration rim produced during the reaction of alite with added mix water.*

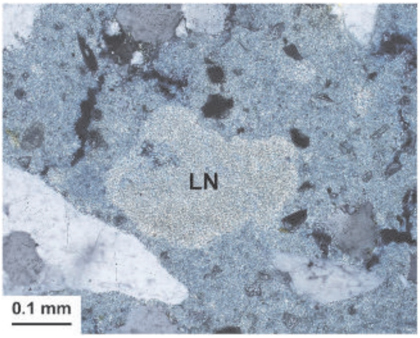


FIG. 5—*A residual lime nodule (LN) is depicted in this cross polarized light photomicrograph. The cream coloration of the grain identifies the carbonate that is a function of the curing process. The surrounding matrix is also carbonated but appears more blue-colored due to the blue-dyed epoxy impregnation that highlights the more porous areas. In powder mount, this grain would not be distinguished from any other carbonated cementitious material. Thin section preparation allows the petrographer to detect the subtle boundary between the lime grain and the otherwise carbonated matrix.*

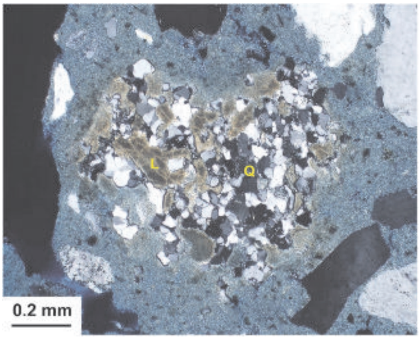


FIG. 6—*This cross polarized light photomicrograph illustrates a lime nodule representing a more hydraulic type of lime. The original limestone portion of the rock has been calcined and converted to the tan-colored lime (L) that has since carbonated. However, gray-colored grains of quartz (Q) are nearly unaffected by the burning process and retain their geologic character. The higher silica (or quartz) content of the lime identifies it as having some potential degree of hydraulicity.*

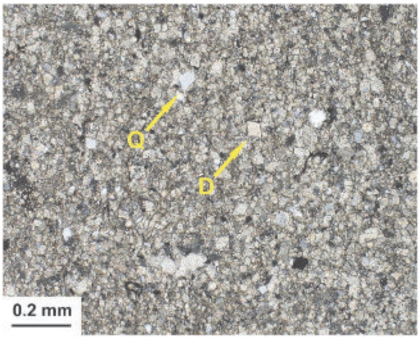


FIG. 7—*This cross polarized light photomicrograph illustrates the mineralogy and texture of the lower member of the Rondout Formation used in the production of Rosendale cement. Rhombic-shaped grains of dolomite (D) constitute a large portion of the rock. Gray-colored grains of quartz silt (Q) are evenly dispersed throughout the carbonated matrix. The overall darker brown coloration to the matrix is produced by clay minerals. The silica present in the quartz and the alumina contributed by the clays are responsible for the hydraulic properties of natural cement and distinguish it from other calcined limes.*

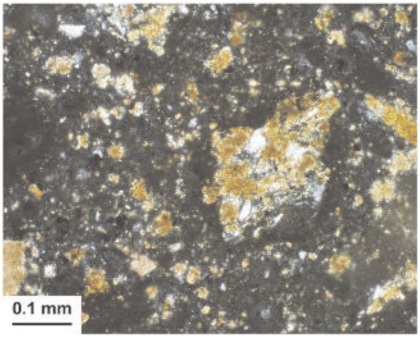


FIG. 8—*Natural cements may be thought of as containing both hydraulic as well as lime-type species. The mineralogy and texture shown in this cross polarized light photomicrograph is typical of natural cements. Portions of the rock were calcined during the burning process and essentially behave as lime. Carbonated material appears as bright-colored areas and represents calcined dolomite that has carbonated during the curing process. Dark areas of isotropic material represent hydraulic areas that have undergone hydration. This petrographic character is diagnostic of natural cement where fresh areas that have not been exposed to the environment are examined. This sample derives from a partially hydrated cement barrel found in the Widow Jane Mine in Rosendale, NY [8] believed to represent material produced during the early 20th century.*

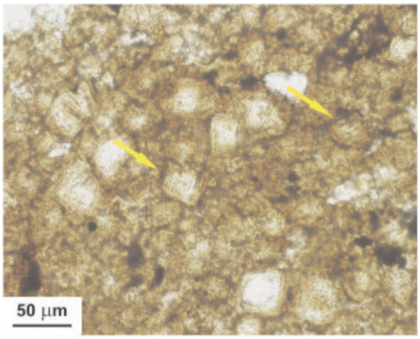


FIG. 9—*Our laboratory obtained samples of the Rondout Formation from Rosendale, NY and burned them at various temperatures for 24 h in a laboratory furnace. This plane polarized light photomicrograph illustrates lower member rocks burned at 600°C. The original rhombic-shaped dolomite crystals are still detected in their original positions and the rock fabric is not altered. However, iron contained within the dolomite crystals has migrated out to form a new iron-bearing species. The arrows indicate the reddish colored iron-bearing minerals that outline the original carbonate minerals.*

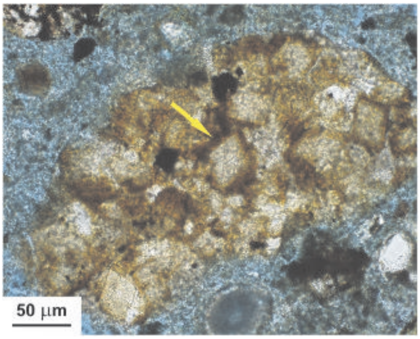


FIG. 10—*This plane polarized photomicrograph illustrates a residual grain of Rosendale natural cement circa 1850. Rhombic-shaped crystals of calcined dolomite are surrounded by reddish rims of an iron-bearing mineral phase (arrow). Note the similarity to the laboratory produced cement depicted in Fig. 9. This microtexture is diagnostic of natural cements produced from dolomitic raw materials and is never observed in portland cements or limes.*

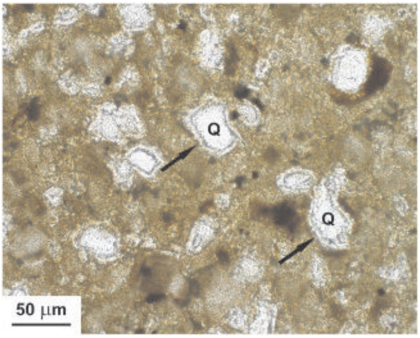


FIG. 11—*The cement shown in this plane polarized light photomicrograph was created in the laboratory by burning the lower member of the Rondout Formation rocks at 1000°C for 24 h. The original quartz grains (Q) have begun to react either forming trydimite (a different structural form of quartz) or have combined with the surrounding carbonates to form a calcium silicate. Even at this temperature, a large degree of the original raw feed texture is preserved. The arrows indicate the thin rims formed around the quartz grains as a result of the burning process.*

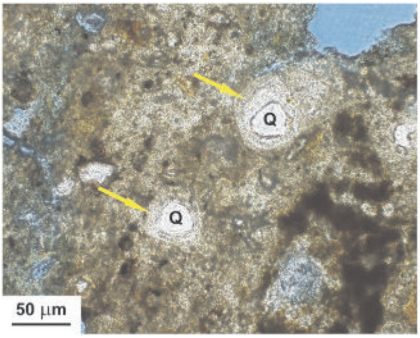


FIG. 12—*Depicted here in this plane polarized light photmicrograph is a mortar produced with natural cement. The arrows indicate reaction rims that formed around quartz grains (Q) during the burning process. These textures may be confused with hydration rims surrounding alite in portland cement (see Fig. 5). However, the optical properties are distinctly different and careful petrographic examination should preclude any confusion.*

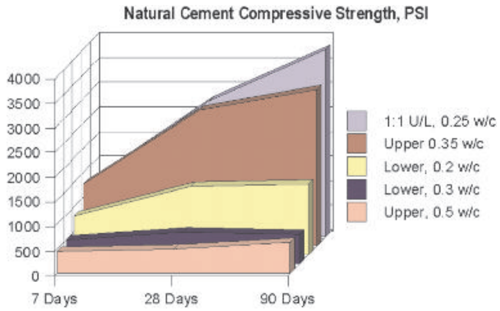


FIG. 4—*Effect of water-cement ratio on natural cement compressive strength [8].*

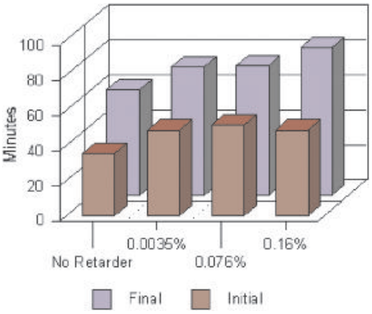
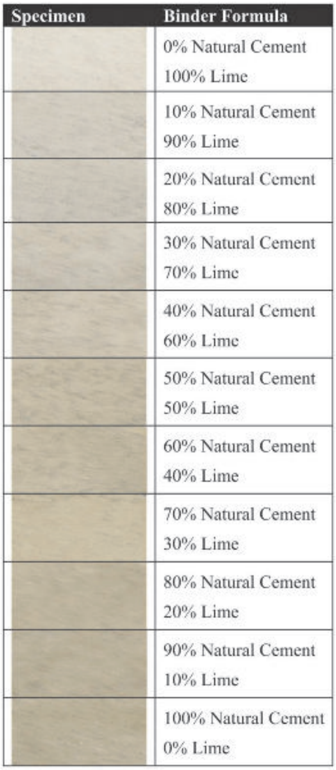


FIG. 6—*Effect of sodium citrate retarder on natural cement time of setting, ASTM C 191.*



Specimen	Binder Formula
	0% Natural Cement 100% Lime
	10% Natural Cement 90% Lime
	20% Natural Cement 80% Lime
	30% Natural Cement 70% Lime
	40% Natural Cement 60% Lime
	50% Natural Cement 50% Lime
	60% Natural Cement 40% Lime
	70% Natural Cement 30% Lime
	80% Natural Cement 20% Lime
	90% Natural Cement 10% Lime
	100% Natural Cement 0% Lime

FIG. 7—*Mortars utilizing varying blends of natural cement and lime illustrate the typical range of colors that can be produced without the use of additional colorants.*

FIG. 8—*Typical natural cement mortar and stucco colors; yellow, red, brown, and black mortar colors are achieved by addition of moderate quantities of iron oxide pigments. Buff to off-white colors are unpigmented mortars made from mixtures of natural cement with lime, as per Fig. 7.*

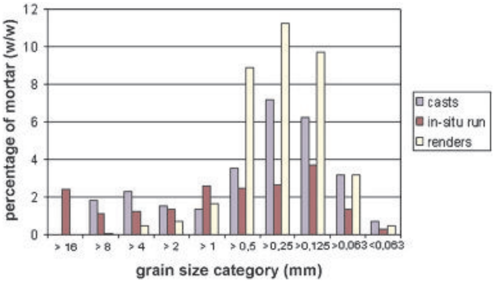


FIG. 8—*Grain size distribution of aggregates found in historic Roman cement mortars from casts, in situ run elements and renders; mean values of a total of 39 samples measured by sieve-fractioning.*

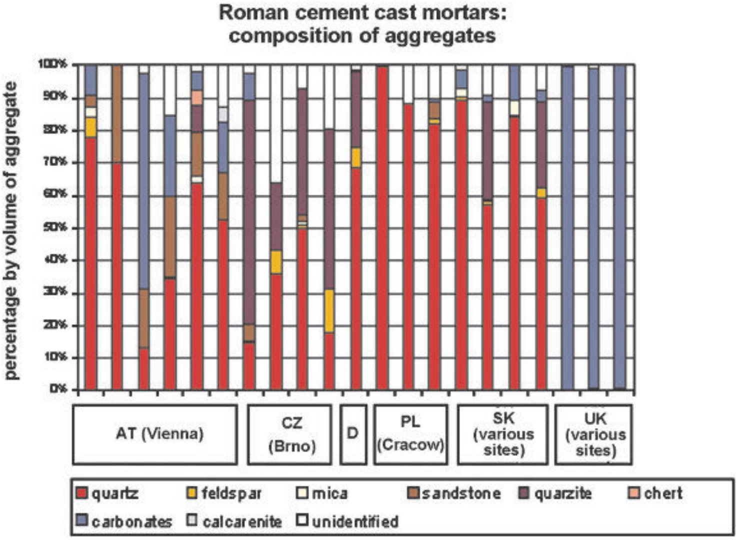


FIG. 9—*Mineral composition of aggregates in Roman cement cast mortars, showing regionally different types; similar holds for in situ run mortars and renders.*

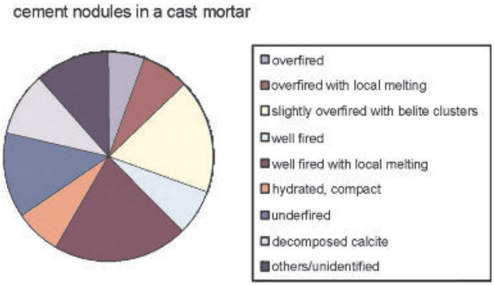


FIG. 11—*Relative amount of the various types of cement relicts in the binder of a single sample from a typical historic Roman cement cast mortar, analyzed by thin-section microscopy combined with SEM/EDX; total amount of phenograins: 69. All types of phenograins are represented in the mortar at nearly equal proportions.*

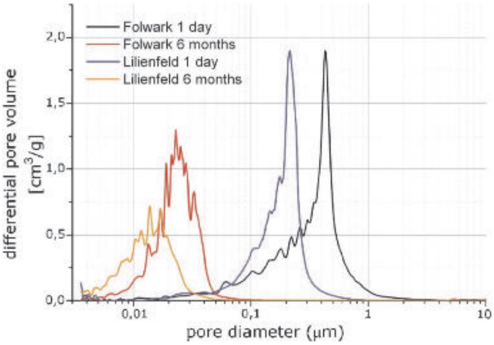


FIG. 6—*Pore size distribution of the pastes of two Roman cements at two ages—four hours and six months.*

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Michael P. Edison[1]

Natural Cement in the 21st Century

ABSTRACT: Natural cement, the predominant hydraulic binder of the 19th century, has re-emerged in the 21st century as a restoration material. Engineers, architects, conservators, and owners must be able to rely upon modern natural cements to meet the same performance criteria as historic cement materials. In addition to the performance criteria, natural cement must provide the working characteristics demanded by contemporary tradespeople and the aesthetic results expected in high-quality historic restoration work. Historic standards for natural cement are reviewed and criteria used in developing the recently reinstated ASTM C 10 Standard Specification for Natural Cement are discussed. Recent research into the effectiveness of set and flow modifying admixtures with natural cement is presented, as well as an overview of producing color matches for natural cement mortars and stuccos.

KEYWORDS: natural cement, historic cement, standardization, time of setting, color matching

Introduction

Two hundred and fifty years ago, when English engineer John Smeaton set out to rediscover and apply the secrets of the hydraulic mortars used by the Romans, nobody asked him whether it was going to comply with an ASTM standard. In the late 19th century, when natural cement was used for maintenance and modifications to the Erie Canal, nobody asked for a color match to the original natural cement produced in the 1820s.

Today natural cement is re-emerging as a 21st century restoration material. The benefits of contemporary use of natural cement are both philosophical and technical. At the most basic technical level, repair in-kind to buildings and structures originally built with natural cement is the most certain way of assuring compatibility between new and original materials. Philosophically, in-kind repair maintains historic integrity. From both perspectives it is clearly important that the natural cement produced today be the same as the traditional, historic material.

While Smeaton was separated from the Romans by scarce documentation, 1000 years of the Dark Ages and then some three or four centuries more, we have the benefit of a rich historical and technical record of 19th century natural cement practices. Standard specifications for natural cement have been in use for more than a century, and they connect the past and the future uses of this distinct class of concrete and masonry binders. By retracing the evolution of natural cement standards, we gain a better understanding of natural cement performance expectations at any given point in time. We can then define critical characteristics that assure the natural cement produced today will meet the same requirements as historic natural cements.

Formulation advances are a second focal point. In reintroducing a traditional material like natural cement, it must be recognized that there are additional expectations to be fulfilled in the context of contemporary restoration work that never had to be met by 19th century producers. There is an expectation that restoration materials should be reasonably easy to use by contemporary tradespeople, and should be usable under a wide range of seasonal conditions. These objectives are advanced when the modern formulator overcomes some of the traditional challenges in natural cement applications through the use of flow and set modifying cement admixtures.

Aesthetic match to original materials is also a common priority in American restoration work, so the ability to obtain and retain good visual color compatibility is expected. Color-matching procedures for natural cement mortars and stuccos must therefore be established.

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[1] Edison Coatings, Inc., 3 Northwest Drive, Plainville, CT 06062.

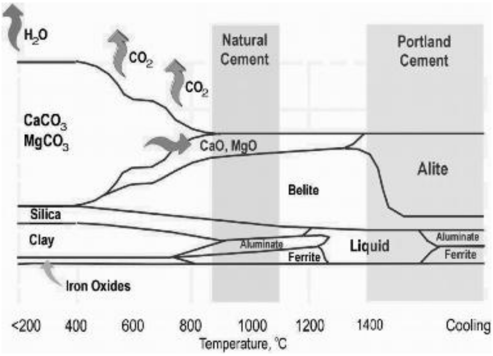


FIG. 1—*Chemical changes during calcination.*

Defining Natural Cement

Standard specifications for various materials are a cornerstone of modern construction practice. They assure that specific classes of materials are clearly defined and they establish minimum performance requirements for those materials. This serves the dual purposes of providing an objective basis on which manufacturers of these materials can compete, while protecting the purchaser and the general public from the potentially disastrous effects of compromises in performance and quality.

Perhaps the best place to start the discussion of cement standards is with a definition. Natural cement is currently defined in ASTM C 219 as a hydraulic cement produced by calcining a naturally occurring argillaceous [clayey] limestone at a temperature below the sintering point and then grinding to a fine powder [1].

Portland cement, by comparison, is produced by blending and firing mixtures of limestone and clay at higher temperatures.

Figure 1 is a simplified diagram of the chemical changes that occur in the course of calcination. The left side of the diagram represents raw materials entering the calciner. These generally consist of calcium carbonate ($CaCO_3$), silica (SiO_2), clay minerals (hydrated aluminosilicates, e.g., Kaolinite, $2SiO_2.Al_2O_3.2H_2O$) and iron oxides. The calcium carbonate typically used in cement production is in the form of limestone, which often also contains some level of magnesium carbonate ($MgCO_3$). In natural cement production this initial mixture is naturally-occurring in the argillaceous limestone (“natural cement rock”). It should be noted that American natural cement rocks generally contained much higher levels of magnesium carbonate than are permissible in portland cements. In portland cement production, mixtures are carefully manipulated artificial blends of various different materials, used to provide the desired proportions of the various active constituents.

As the feed is heated, the first major change is dissociation of the magnesium carbonate, releasing carbon dioxide, beginning at around 400°C. This is followed by similar dissociation of calcium carbonate, beginning at approximately 600°C in some mixtures. These reactions form quicklime (CaO and MgO), which then begins to react with the clay and silica. At the relatively low firing temperatures used for production of natural cement, the principal reaction product is dicalcium silicate ($2CaO.SiO_2$, Belite, C_2S), typically burned in the 900–1100°C range. As temperature is raised past 1200°C, as in portland cement production, liquification or sintering occurs, beginning the formation of new compounds, either at the elevated temperature or during the cooling period that follows. These include tricalcium silicate ($3CaO.SiO_2$) and tricalcium aluminate ($3CaO.Al_2O_3$), typically found in portland cement [2].

Due to their respective firing temperatures, natural cement’s hydraulic species is primarily dicalcium silicate (C_2S), formed below the sintering point. The tricalcium silicate and tricalcium aluminate (C_3S, C_3A) typically formed above the sintering point in portland cement production are absent.

The practical explanation of these different classes of cements is that like portland cement, natural cement is a true hydraulic material. It sets when mixed with water and can set under water. Natural cement calcination is performed at the same temperatures as those used in lime burning, but after burning it is not

FIG. 2—*Fort Adams, Newport, RI, was constructed from 1825–1838 using natural cement mortar, concrete, and stucco. Despite the lack of expansion joints and annual temperature ranges of over 55°C (100° Fahrenheit), the structure exhibits no pattern of thermal expansion-related cracking or distress.*

slaked by adding water, as in lime processing. Instead, it is simply ground to a fine powder which can then be used as cement.

As a result of these compositional differences, natural cement develops lower compressive strength than portland cements, and although it sets faster, it achieves ultimate strength more slowly. These were key factors leading to the eventual market dominance of portland cement.

Natural cement is significantly lower in modulus of elasticity than portland, however, allowing its successful use in large concrete and masonry structures without expansion joints. The Third System seacoast fortifications such as Fort Adams (Fig. 2), exemplify this characteristic.

Like lime mortar, natural cement mortars deform as masonry units expand and contract with changes in temperature and moisture levels, relieving stress. In historic restoration work, avoidance of stress to the original building materials is important, as they constitute *historic fabric*, the key components of historic buildings that are the objects of preservation efforts.

More Than a Century of Standards

Prior to the adoption of the first ASTM Standards in 1904, the American Society of Civil Engineers had begun developing cement standards, and in 1885, an ASCE Committee published recommended minimum and maximum tensile strength values for natural and portland cements. These recommendations fell short of the influence realized by the more comprehensive eventual ASTM standards, however.

A more detailed picture of the state of specification practices in the pre-ASTM era is provided by Ira Baker, in his 1903 book *A Treatise on Masonry Construction*. In the table in Fig. 3, Baker provides averages of values found in specifications of the day for cement fineness and tensile strength. What is perhaps most interesting about this table, is not necessarily the values themselves, but the fact that the values are different based on who is writing the specifications and for what purpose.

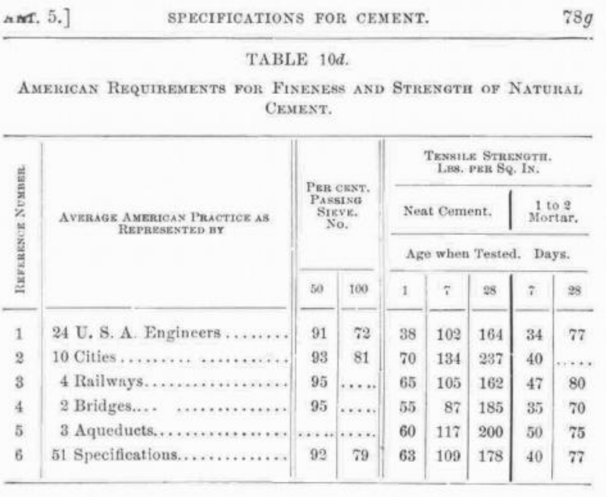
Given the inconsistency of cement specifications, it is not hard to understand the frustration it caused cement manufacturers. Writing in his 1898 book, *American Cements*, natural cement producer and proponent Uriah Cummings tells us that:

> Each engineer or architect is a law unto himself, and United States engineers…do not seem to be governed by any one standard…[4].

Further, he writes,

> …it would be difficult to find a brand of cement which could fulfill all the requirements of the various specifications which are from time to time given out to the manufacturers [5].

These problems were addressed by adoption in 1904 of the "Report of Committee C on Standard Specifications for Cement," including standards for both portland and natural cements. It became the eventual basis of ASTM C 10 Standard Specification for Natural Cement, one of ASTM's oldest standards.



ART. 5.] SPECIFICATIONS FOR CEMENT. 78g

TABLE 10d.

AMERICAN REQUIREMENTS FOR FINENESS AND STRENGTH OF NATURAL CEMENT.

Reference Number.	Average American Practice as Represented by	Per cent. Passing Sieve. No.		Tensile Strength. Lbs. per Sq. In.				
				Neat Cement.			1 to 2 Mortar.	
				Age when Tested. Days.				
		50	100	1	7	28	7	28
1	24 U. S. A. Engineers	91	72	38	102	164	34	77
2	10 Cities	93	81	70	134	237	40	.....
3	4 Railways..................	95	.....	65	105	162	47	80
4	2 Bridges....	95	.....	55	87	185	35	70
5	3 Aqueducts.................	.....	.....	60	117	200	50	75
6	51 Specifications.............	92	79	63	109	178	40	77

FIG. 3—*Table of Strength and Fineness Requirements for Natural Cement in 1903, just prior to the adoption of the first ASTM Standards [3].*

Ironically, natural cement use was already declining by the time these first standards were written. Portland cement became the dominant technology, of course, and has remained so to this day.

The standard was changed somewhat over its 75-year history, reflecting, to some extent, the changing market position of natural cement. The key requirements at several different revision points are summarized in Table 1.

In 1904, natural cement stood on separate but equal footing with portland cement as an important material of construction. In the 1950s the standard was revised to reflect the fact that natural cement's primary use at that time was as an addition to portland cement.

The combination of three bags portland cement and one bag Rosendale was common in engineering specifications in the 1940s, 50s, and early 60s, and was used in such massive engineering projects as the building of the New York State Thruway and the St. Lawrence Seaway. This is also the first version in which Type N- Normal and Type NA air entraining types are specified. This revision also adopts more stringent fineness standards, suggesting, perhaps, that natural cement may still be trying to compete in a portland cement world.

As modern admixtures for portland cement entered the marketplace in the 1960s, demand for natural cement in concrete construction waned, and what was left of the industry refocused its efforts on the masonry cement market. The final, or more accurately, the last 20th century revision of ASTM C 10 does not reflect this change, as by 1970 the last of the original natural cement producers had closed its doors. In 1979, the standard was withdrawn due to disuse.

In 2004, commercial production of Rosendale natural cement was restarted as a means of providing the restoration industry with compatible repair and maintenance materials for historic buildings and structures. With this reintroduction came an effort to reinstate and update ASTM C 10.

The lack of a current ASTM Standard Specification for Natural Cement, until recently, was an obstacle to the full realization of historically accurate and appropriate restoration work. Natural cement was used historically as a structural material, and is required to fulfill structural performance requirements in the course of some of its applications in historic repair and rebuilding. To protect the public, it is essential that materials marketed today as natural cement meet the same requirements that governed performance historically. In addition, ASTM task group C12.03.03, working to develop a new standard for historic mortars, must be able to reference an ASTM standard specification for natural cement if they are to include it in an eventual standard. To exclude natural cement from any eventual ASTM standard for historic mortars would be to forsake history.

ASTM Task Group C1.10.4 on natural cement worked to refocus the proposed new ASTM C 10

TABLE 1—*ASTM Standard specifications for natural cement, 1904–1970 [6].*

Property	1904	1937	1952	1970
Specific Gravity	2.8 minimum	No Requirement	No Requirement	No Requirement
Fineness	10 % max. retained on No. 100 sieve 30 % max. retained on No. 200 sieve	15 % max. retained on No. 200 sieve	Specific surface, sq. cm. per gram, ASTM C 204 Avg. 6000 Min. Value, any one sample: 5500	Specific surface, sq. cm. per gram ASTM C 204 Avg. 6000 Min. Value, any one sample: 5500
Time of Setting	Initial Set: 10 minutes minimum Final Set: 30 minutes min., 3 hours max.	Initial Set: 10 minutes minimum (Vicat) or 20 minutes (Gillmore) Final Set: 30 minutes min., 10 hours max.	ASTM C 191 30 minutes, min. 6 hours, max.	ASTM C 191 30 minutes, min.
Tensile Strength	Neat Cement 24 hours, moist air: 50–100 psi minimum 7 days (1 day in moist air, 6 days in water): 100–200 psi min. 28 days (1 day in moist air, 27 days in water): 200–300 psi minimum One Part Cement, Three Parts Sand 7 days (1 day in moist air, 6 days in water): 25–75 psi minimum 28 days (1 day in moist air, 27 days in water): 75–100 psi minimum	One Part Cement, Two Parts Sand 7 days (1 day in moist air, 6 days in water): 75 psi min. 28 days (1 day in moist air, 27 days water): 150 psi min.	No Requirement	No Requirement
Compressive Strength	No Requirement	No Requirement	ASTM C 190 One Part Natural Cement, 1 Part Standard Sand: 1 day in moist air, 6 days in water: 500 psi min. 1 day in moist air, 27 days water: 1000 psi, min.	ASTM C 190 One Part Natural Cement, 1 Part Standard Sand: 1 day in moist air, 6 days in water: 500 psi min. 1 day in moist air, 27 days water: 1000 psi, min.
Air Content	No Requirement	No Requirement	ASTM C 185 Type N: No Requirement Type NA: 18±3	ASTM C 185 Type N: 12 % max. Type NA: 19±3
Constancy of Volume/ Soundness	"Pat" test; Mortar discs immersed in water and stored in air for 28 days must "remain and hard and show no signs of distortion, checking, cracking or disintegrating."	"Pat" test; Mortar discs stored inmoist air for 48 hours and steam for 5 hours "shall show no signs of distortion, cracking, checking or disintegrating."	ASTM C151 Autoclave expansion, 25 % natural cement w/ 75 % portland 0.50 % max.	ASTM C151 Autoclave expansion, 75 % natural cement w/ 25 % portland 0.80 % max.
Chemical Requirements	No Requirement	No Requirement	ASTM C 114 Loss on Ignition ≤12 % Insoluble Residue ≥2 %	ASTM C 114 Loss on Ignition ≤12 % Insoluble Residue ≥2 %

standard away from the "portland cement addition" version of the 1950s and 60s, back to an earlier concept of natural cement as a multi-purpose hydraulic binder. The new standard makes reference to historical uses of natural cement in masonry mortar, concrete, stucco, limewash and grout, and has been rewritten with preservation guidelines in mind, as natural cement today is most likely to be used as a restoration material. The new ASTM C 10 standard was adopted on September 1, 2006.

The ASTM C12.03.03 historic mortars task group had previously accepted inclusion of natural cement in its testing phase work, pending the adoption of a new ASTM C 10 standard. Now that the new C 10

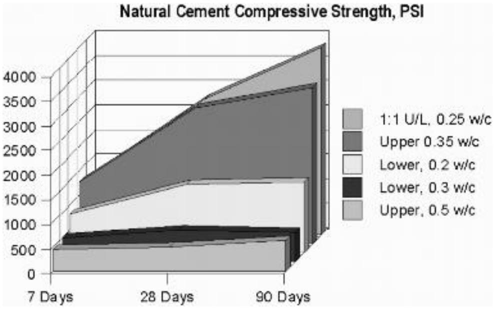


FIG. 4—*Effect of water-cement ratio on natural cement compressive strength [8]. (See color insert for color version of this figure).*

standard has been adopted, the mortars task group faces the challenge of fully integrating natural cement technology into the evolving historic mortars standard.

As the restoration industry rediscovers natural cement technology and its importance in our engineering and architectural heritage, there is also a danger that inauthentic materials will be promoted and labeled as natural cement. This has already occurred on a limited basis. In 2003, one such product was promoted as "New Rosendale Natural Cement B." While advertising proclaimed that it "CONTAINS NO PORTLAND CEMENT," it neglected to disclose that it also contained no natural cement. This offering was withdrawn when authentic natural cement was reintroduced in 2004.

Another product purporting to be natural cement was actually a rapid-setting, high-strength portland cement-calcium aluminate cement mixture. This type of material is inappropriate for restoring historic masonry and concrete, as it is likely to distress relatively soft historic masonry substrates.

Neither of these materials qualify as natural cement under any current or previous version of ASTM C 10 and they do not meet the ASTM C 219 definition. Now that specifiers can again require that natural cement meet the requirements of ASTM C 10, promotion and use of inauthentic substitutes can be restricted.

Formulating with Natural Cement in the 21st Century

Having established that today's natural cement will be properly defined and will meet the same requirements as the traditional material, we can focus on the challenges of formulating with natural cement in the 21st century. While natural cement is not particularly complicated or difficult to formulate or apply, two characteristics can easily be addressed by the formulator to improve convenience to the tradesperson.

Water-Cement Ratio

An important parameter in natural cement concrete and stucco work is the minimization of the amount of water used. This was recognized early on, and in most cases natural cement concretes and stuccos were mixed with such little water as to never form the sort of plastic mass we are accustomed to working with when using portland cement mixtures today. The historical references speak repeatedly of using incoherent mixes and of the importance of securing the services of a "*faithful workman, one who will not spare his strength, or lay any mortar too loosely*." [7]

The effects of water-cement ratio on natural cement strength are the subject of ongoing laboratory investigations. The data in Fig. 4 show the impact on compressive strength of using different amounts of water with cements made from each of the two geological strata being mined in Rosendale, NY. A particular grind of upper layer cement has an optimum water cement ratio of 0.35, and its strength development over the course of 90 days of curing is as indicated. The same cement, mixed at an excessively high 0.5 water-cement ratio exhibits a dramatic drop in strength at all ages. Similar results are obtained with a particular grind of lower layer cement, as indicated. The work also shows that blends of the two layers produce even better strengths, as long as the proper amount of water is used.

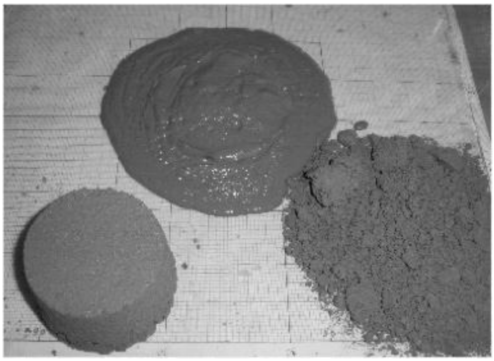


FIG. 5—*Natural cement at 0.3 water-cement ratio. The incoherent mix (lower right) is readily compacted (lower left), but addition of a commercial superplasticizer results in high fluidity (center), facilitating use for stucco and poured-in-place concrete without altering water-cement ratio or reducing strength.*

In all cases, the optimum water-cement ratio produces mixes that are nearly incoherent. Although they compact well under impact or trowel pressure, they are relatively dry as compared with typical portland cement mixes, and more fluid consistency would be a desired convenience, particularly for work involving forming and pouring of concrete or application of stucco.

This objective is readily achieved with any of a number of natural or synthetic superplasticizers. The three samples pictured in Fig. 5 represent the same natural cement, mixed at 0.3 water-cement ratio. The incoherent, damp mortar at the right is typical of the consistency of natural cement mixed at optimum water-cement ratio. Under compaction or when troweled, the same mix becomes slightly plastic and can readily be formed into monolithic elements, as shown at the left. The center sample incorporates the same cement and water proportions with an addition of 0.5 % by cement weight of a melamine sulfonate superplasticizer. A fluid, pourable consistency is obtained. Similar results are obtained using natural plasticizers, such as casein.

Time of Setting

Minimum requirements for time of setting have always been an integral part of natural cement standards in the United States. Excessively-rapid setting cement is not only inconvenient, it is likely to induce the tradesperson to retemper mixes that have begun to set and have lost plasticity, upsetting control of the desired water-cement ratio. There is also a risk of poor performance if installation is attempted utilizing material which has already substantially set.

Under the original natural cement standards, minimum final set times of 30 minutes were required for neat natural cements. Past ASTM C 10 revisions required a minimum initial time of setting of 30 minutes, and it remains so in the current standard. Once these cements are blended with the proper proportions of sand, and particularly if lime is added to the mix as an extender, working times will increase somewhat. It is nonetheless desirable, in some situations, to further increase the working time of natural cement mixes, particularly in hot weather. This is accomplished through the use of retarders.

Figure 6 illustrates the effects on time of setting of neat natural cement incorporating various levels of sodium citrate.

Color Matching with Natural Cement

In historic restoration work, aesthetic matching of new mortar, stucco, or concrete to original materials is often an important objective. With natural cement materials, this work is complicated by the wide variations in composition of the cements used in the 19th century, and by the wide variety of formulating practices employed.

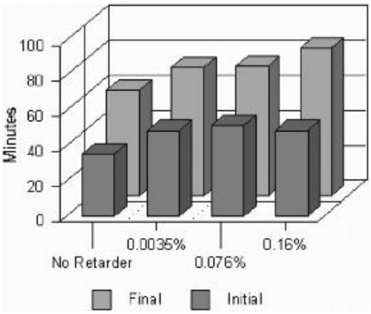


FIG. 6—*Effect of sodium citrate retarder on natural cement time of setting, ASTM C 191. (See color insert for color version of this figure).*

Natural cement colors tend to be distinct from portland cement colors, typically ranging from yellow to olive green to brown at full strength, and from warm buffs, to grays and off-whites when blended with lime. The colors can be difficult to match accurately by simply adding iron oxide colorants to other binders.

The process of color matching historic natural cement mortars, stuccos, and concretes begins with matching of aggregates. Once closely matching aggregates have been identified and selected, the binder proportions are determined. Sand to binder ratio is generally a function of the void volume of the sand. Lime to natural cement ratio is often determined on the basis of a petrographic analysis of the original mortar, though matrix color is sometimes a useful guide. Figure 7 illustrates the typical range of colors achieved simply by blending natural cement with hydrated lime, without addition of pigments.

Addition of Pigments

The use of colorants such as iron oxide was a common practice in the 19th century and natural cement mortars were sometimes tinted red, black, yellow, or brown through the addition of integral pigments. Addition of brick dust to red and brown mortars was also a common practice. While brick dust was commonly used as a pozzolanic admixture for lime mortar, the reactivity of brick dust is low, compared with natural cement, and its effect on hydraulicity of natural cement-lime mortars was probably inconsequential.

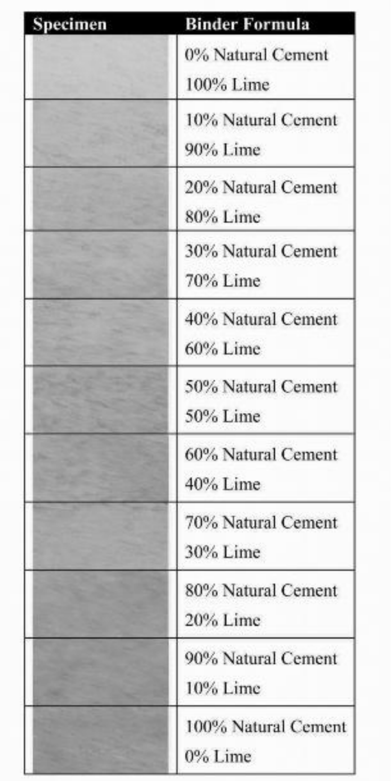
As with portland cement mortars, there is a potential detrimental effect of incorporating finely ground pigments at excessive levels. While there are no specific guidelines for maximum pigment addition levels to natural cement mortars, their proper historic levels of use were described by Gillmore as “moderate.” Current ASTM C 979 restrictions of <2 % carbon black and <10 % iron oxide on cement weight (for portland cement colorants) probably represent prudent limits.

Figure 8 illustrates a range of natural cement mortar and stucco colors, matched to samples taken from various 19th century American buildings. Some of the lighter colors are only achieved when lime is added to the natural cement.

Perspectives on Natural Cement in the 21st Century

In the hiatus between 1970 and 2004, during which commercial sources of natural cement were absent, the importance of its technical and historical role was temporarily obscured. The use of lime and hydraulic lime-based materials enjoyed a revival, but they do not accurately represent the major portion of mainstream, large-scale, 19th century building practices in the United States. Indeed, many of the advances achieved during that period were only made possible by the replacement of lime-based technology with natural cement.

There are uncounted thousands of buildings, bridges, monuments, dams, lighthouses, aqueducts, military installations, harbor systems, canals, transportation systems, and other assorted structures built with



Specimen	Binder Formula
	0% Natural Cement 100% Lime
	10% Natural Cement 90% Lime
	20% Natural Cement 80% Lime
	30% Natural Cement 70% Lime
	40% Natural Cement 60% Lime
	50% Natural Cement 50% Lime
	60% Natural Cement 40% Lime
	70% Natural Cement 30% Lime
	80% Natural Cement 20% Lime
	90% Natural Cement 10% Lime
	100% Natural Cement 0% Lime

FIG. 7—*Mortars utilizing varying blends of natural cement and lime illustrate the typical range of colors that can be produced without the use of additional colorants. (See color insert for color version of this figure).*

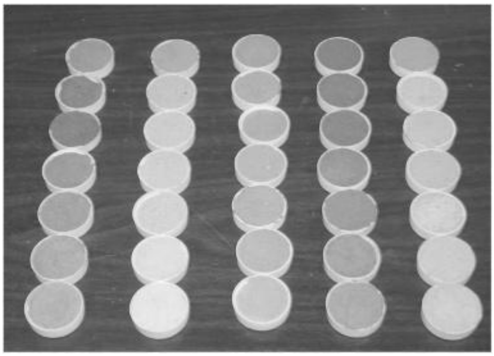


FIG. 8—*Typical natural cement mortar and stucco colors; yellow, red, brown, and black mortar colors are achieved by addition of moderate quantities of iron oxide pigments. Buff to off-white colors are unpigmented mortars made from mixtures of natural cement with lime, as per Fig. 7. (See color insert for color version of this figure).*

natural cement that are still in service today. Some, like the remaining original 1840 brick walls at Fortress Alcatraz in San Francisco Bay, remain in nearly pristine condition after more than 160 years of service. Others are at a point, after 100 or more years of service, where they are ready for their first substantial repointing. Still others have already undergone interventions using materials other than historically accurate replications of their original natural cement mortars.

The option has been restored to perform compatible, durable, sustainable, historically correct repairs in-kind using natural cement. Our most revered historic buildings and structures will in all probability long survive beyond our times, and natural cement is now becoming an important tool in the diverse 21st century restoration/preservation toolbox.

It is staggering to think just how close we came to losing this integral component of our engineering and architectural history.

Conclusions

Objective performance standards for natural cement have been successfully re-established. The newly revised and reinstated ASTM C 10 incorporates essential elements of its previous revisions, while addressing the needs and concerns of contemporary architects, engineers, and conservators.

Successful steps have also been taken toward integrating modern set and flow modifying admixtures into traditional natural cement formulations that will meet the needs, objectives, and expectations of 21st century restoration projects.

Practices associated with color matching today's natural cement mortars, concretes, and stuccos to original, historic materials have also been explored.

Acknowledgments

The work of chemical engineer Nicole Smith, Edison Coatings, Inc., in evaluating effects on compressive strength of varying water-cement ratios and the effects on time of setting of sodium citrate addition is gratefully acknowledged.

The work of David Norris, Riverside Cement Co., in researching and compiling the various historic revisions of ASTM C 10, was invaluable to gaining an accurate perspective on the 20th century history of natural cement standards.

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Linda Willett[1] *and Frederick O'Connor*[1]

Masonry Repairs at Cheshire Mill No. 1, Harrisville, New Hampshire

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ABSTRACT: The first modern-day application of Rosendale natural cement mortars in a significant historic restoration is described. The background of Cheshire Mill No. 1 in Historic Harrisville, New Hampshire, the analyses of its original mortar composition, and the successful use of natural cement for in-kind repointing are detailed.

KEYWORDS: historic restoration, natural cement, historic mortar, repointing, Rosendale cement

Introduction

Masonry repair at Cheshire Mill No. 1 was a relatively small project in Harrisville, a small, out of the way place in southwestern New Hampshire. Harrisville (Fig. 1), is a unique mill village that preserves the scale and setting of the numerous mill villages built on waterpower sites throughout New England prior to the Civil War. It was designated a National Historic Landmark District in 1977 and is said to be the best preserved mid-19th century mill village in the country.

In 1970, the bankruptcy of the Cheshire Mills threatened the future of the town. In response, townspeople and preservationists formed Historic Harrisville to protect the architectural and functional character of the historic village by repairing the mill buildings and leasing them to provide jobs for the town. Historic Harrisville follows the same model today, repairing the town's historic buildings and leasing them to businesses that provide jobs.

Six major mill buildings were purchased in 1970 and another six thereafter. The Cheshire Mills complex, the largest and most significant structure in the NHL, was purchased in 1999. The Cheshire Mills Complex Historic Structures Report completed in 2001, identified timber frame and roof failures at Mill No. 1 that required immediate attention. Masonry, sash, and carpentry needs were also identified and documented.

FIG. 1—*Aerial view of Historic Harrisville.*

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[1] Executive Director and Project Manager, respectively, Historic Harrisville, Inc.

FIG. 2—*Cheshire Mill No. 1, east elevation.*

Repairs Required at Cheshire Mill No. 1

Mill No. 1, built in 1846, stands at the core of the Cheshire Mills and is the complex's most significant structure historically, architecturally, and aesthetically (Figs. 2–4). The continuous use of the building for woolen manufacturing protected it from major alterations and preserved a unique architectural record as well as an archaeological record of manufacturing practices.

In 2002, with funding in hand from the Save America's Treasures Initiative, the New Hampshire Land and Community Heritage Investment Program, the 1772 Foundation, and private donors, extensive repairs

FIG. 3—*Cheshire Mill No. 1, south elevation.*

FIG. 4—*Cheshire Mill No. 1, west elevation.*

FIG. 5—*Close-up view of original natural cement pointing mortar at Cheshire Mill No. 1, west elevation, showing ruled and penciled detailing.*

were undertaken to the roof trusses and roof, internal timber frame, and the rubble walls beneath the mill which enclose the spillway and the turbine pit. The work also included selective repointing of the single wythe block granite walls. The objective of this rehabilitation, first and foremost, was to maintain historic integrity. This was addressed by preserving all sound original materials and by performing any necessary repairs and replacements using in-kind materials. Hence this masonry project is not a complete repointing, but rather a careful undertaking of selective repairs and stabilization.

Historic Mortar Replication

Samples of original mortar from the core of the walls and the pointing mortar were sent to the Scottish Lime Center for analysis in 2000. The core mortar was deemed to be composed of a moderately hydraulic lime binder and a moderately fine-grained aggregate. Replication of this core mortar would be straightforward since lime putty, hot-mixed mortar, and NHL are routinely kept on hand.

The pointing mortar (Fig. 5) presented a greater challenge since it was found to consist of a "probably cementitious binder" and a very fine-grained aggregate. The Scottish Lime Center petrographer was unable to confirm whether the cementitious binder was portland cement. The report went on to recommend that in order to replicate this mortar as closely as possible, a 1+2 portland cement—sand mortar, with the recommended matching aggregate, might be appropriate. Or, if a lime-based mortar was preferred, then a mix consisting of 1 part eminently hydraulic lime, 2.5 parts aggregate was suggested. Having had a fair idea of what the cement mix would look like and experience with Natural Hydraulic Lime, it was clear to us that neither of these two possibilities would provide an appropriate match for the existing mortar, which is tan in color and very clay-like in appearance.

Ken Uracius, a mason and consultant with Stone & Lime Imports, had taken an interest in our earlier work with quicklime and NHL. He suggested the possibility of using Rosendale natural cement and solved the pointing mortar question. Mortar samples were sent to John Walsh, a petrographer and geologist with Testwell Laboratories, and he confirmed that the binder in the mill's existing mortar was Rosendale cement. Working with Uracius and the Rosendale cement, Historic Harrisville Project Manager Fred O'Connor was able to create test panels that provided an acceptable match in strength and appearance.

Repointing on the West Elevation

The west elevation of the 1846 mill is shown in Fig. 4. Figure 6 shows a granite culvert where the building spans the river and water passes beneath it in an arched stone spillway. This structure not only has been able to endure for 160 years with little maintenance, but is also being subjected to constant water exposure.

The masonry walls are single wythe stone, approximately 22–24-in. thick at the base of the structure, narrowing to 11–12 in. in the top-most stones. The masonry has undergone numerous spot repointing

FIG. 6—*Granite culvert spanning the river at Cheshire Mill No. 1, west elevation.*

campaigns over the years, utilizing portland cement-based materials. Fortunately this work was not widespread and most of the original material remained intact.

The most significant losses of original material involved the lime bedding mortars. In many areas complete loss of all original lime mortar was evident, and in some all of the lime binder had been washed out of the joints, leaving just the sand. The natural cement pointing mortar had also suffered some losses and had allowed water to infiltrate, probably facilitating some of the lime mortar losses. More noticeably, the natural cement had weathered and many joints had lost adhesion and the ability to resist water infiltration.

All areas repointed with portland type cements were removed. Any joints with original natural cement that was failing were also cut out. Areas of loss were cleaned and each area was photographed before and after to properly document the work and to ensure that finished restoration work matched the original appearance. Joints were raked out as needed and the loose sand and lime mortar were flushed out with a hose. No bedding material was removed if it was stable. Figure 7 shows a section of wall after preparation for repointing.

Figure 8 shows a prepared joint including one of the original pin stones retained from the initial setting of the stone. Pin stones were used for placement and leveling as well as to provide sufficient space between adjacent stones to allow filling with the lime bedding mortar. At least four pin stones were found to have been used for setting each stone, with greater numbers used for setting larger stones.

FIG. 7—*Removal of incompatible portland cement repointing materials and unsound original mortars was performed prior to repointing with natural cement mortar.*

FIG. 8—*Close-up view of prepared joint showing retention of original pin stones used in the stone-setting process.*

In some places, as shown in Fig. 9, the lime bedding mortar extended to almost the surface of the joint. In many others cement joint were found at least 8 or 9 in. in depth, with no lime bedding mortar present.

Most of the repairs were of vertical joints similar to the one shown in Fig. 10. They tended to be wider than the horizontal joints, perhaps providing water inside the masonry wall with an easier path for egress.

Lime mortar losses were replaced as necessary. Traditional quicklime was slaked on site and a 3 to 1 lime-sand mixture was used. These widely accepted, traditionally-used proportions were employed for all replacement bedding mortar. The sand was added during the slaking process. The blended materials were allowed to age for two to five years to allow natural hydration and full maturity of the slaked lime.

In all, if not most of the joints, galletts of stone and slate were used with the lime mortar to fill the joint to its entirety. The lime and sand were pushed into the joint first, and then galletts were hammered into the joint to ensure a tight and complete fill. This also ensured that there would be no areas with large volumes of lime that could tend not to carbonate entirely, potentially causing a weakened joint. The lime mortar was recessed from the surface to allow for the subsequent pointing cement application. A period of several weeks was allowed from bedding mortar application to the application of the cement pointing mortar, allowing time for the lime to carbonate and provide a stable substrate for the pointing material.

FIG. 9—*Close-up view of prepared joint showing the extension of the lime bedding mortar nearly all the way to the surface of the joint.*

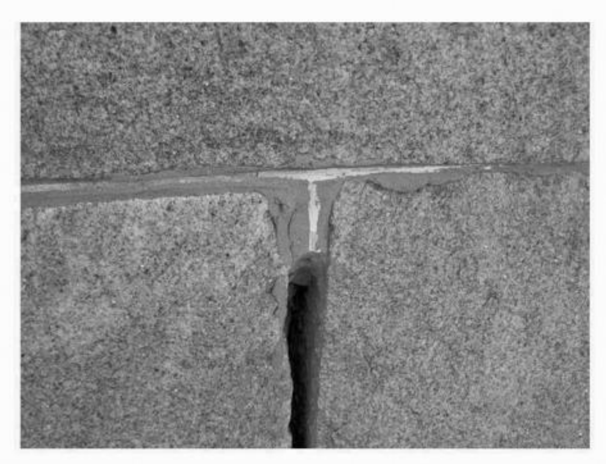

FIG. 10—*Typical vertical joint prepared for repointing.*

The Rosendale cement mortar was then applied to the joint (Fig. 11). Special care was taken to assure that application in each area matched the original pointing mortar in width and depth.

Joint Detailing

The joints of the granite mill, the only stone building in Harrisville, were ruled and penciled (Fig. 5). This detailing is believed to have been part of the original construction and is very noticeable in the pointing cement. The joints were ruled out simply by lining up a straight edge and using a pointing tool to achieve the result. Three different widths of tooling were found, corresponding with the different pointing tools used by the original masons. This suggests that at least three different crews, using different tools, were at work at one time during the original construction. Varying tools of the correct corresponding size were therefore used in performing the repairs, allowing each repair area to match the original tooling dimensions.

FIG. 11—*Joint filled with Rosendale cement pointing mortar prior to detailing.*

FIG. 12—*Frost Free Library, Marlborough, New Hampshire.*

The lines in the original mortar are off-white and appeared to be paint. It is most likely that the paint consisted of oil and lead, as this was commonly used in the 19th century. The currently visible off-white coating does not appear to be the first coating applied, however. A very faint layer of lime wash was observed under some, if not all, of the painted lines examined. This was probably a modified lime wash, in which oil was slaked with the quicklime to produce a more durable material. Over-painting may have been performed later using paint materials typical to the period. Without the addition of oil to the lime wash, any such over-painting would have been likely to fail in adhesion. Widespread paint failure has not been observed.

In an effort to corroborate mortar detailing as historically appropriate, we visited the neighboring town of Marlborough, the location of the quarry that provided the stone for the mill. The half dozen stone buildings examined were all pointed with what appeared to be Rosendale cement and they too were ruled out and penciled (see Figs. 12–15).

Figure 16 shows a wet joint, pointed and ruled. Note that the ruled out dimensions match the width of the tooling in the adjacent, original material. The joint was further worked to soften its appearance and to better blend with original material by dry brushing edges and surfaces after the cement had partially set.

Figure 17 shows a wall section shortly after it was completed. Within a few weeks, the colors and appearances of the new material had blended to more closely resemble the original material. The joint surfaces (Fig. 16) were ruled out but not lined. It was decided that lining would call attention to repairs in a distracting manner, creating an undesirable visual impact on the overall appearance of the masonry.

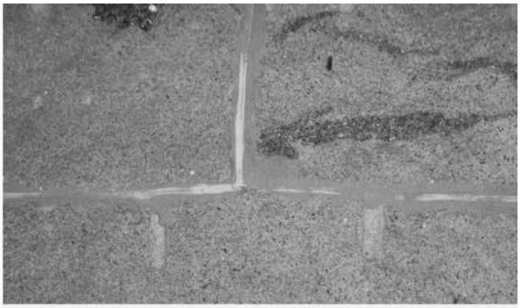

FIG. 13—*Close-up view of ruled and penciled pointing details at Frost Free Library—Marlborough, New Hampshire.*

FIG. 14—*Marlborough Store—Marlborough, New Hampshire.*

FIG. 15—*Close-up view of joint detailing at Marlborough Store—Marlborough, New Hampshire.*

FIG. 16—*Natural cement repointing mortar, after ruling.*

FIG. 17—*Completed section of repointing.*

Interior Plaster Repairs

In the interior space of the mill, the first and second floors have plastered walls. This plaster was also found to be composed of natural cement, rather than the lime that might traditionally be more expected from the time period.

The area shown in Figs. 18 and 19 has had a window frame removed for sash restoration. The cement plaster was originally applied directly to granite interior wall surfaces. At some point the particular window frame started to fall into the interior space. Over the course of many years the adjacent plaster deformed to accommodate the displacement of the window. Given the extreme deformation of the natural cement plaster without loss of integrity, this constitutes a very fine example of just how flexible natural cement can be.

The window frame and sash have been repaired and reinstalled to the original locations. All masonry material was repaired as necessary around the window frame. Eminently hydraulic lime was used as a

FIG. 18—*Failing section of interior wall plaster.*

surface material on the granite stones where the frame and sill of the window sits. This material was chosen because the area collects water due to condensation during summer and frost during winter. Feebly hydraulic lime was used originally, but was not replaced in-kind because it did not perform well in these areas over time. Water was being allowed to enter the wall structure, and eminently hydraulic lime was thought to offer a more durable and water resistant alternative. This was the only exception to the rule of keeping all masonry materials as original as possible.

Figure 20 shows the same plaster area at the window sill height area. This has lost its adhesion to the granite surfaces but not its cohesiveness. Some areas missing plaster exhibit residual coatings of lime wash applied directly to the granite stone walls. This may suggest the plaster was applied at a later time than the initial build. The plaster conforms to the contours of the existing stone walls, and in some areas, depressions in the stone surfaces were filled with cement to achieve a flat finished wall. As a further sign that the plaster was applied later than the original build, the plaster is only present above the finished floor level. There is a subfloor beneath the finished floor, and traditionally, the plaster coatings would have been applied before the finished floor was installed.

Figure 21 is a close-up view of the same window on the right side. There are at least six distinct plaster layers present. These plaster layers appear to have been applied readily on top of one another and probably in a very short time period. No coatings such as paint or lime washes were found to have been applied in between layers. The topmost layers have been painted, as have the edges, and while in color they resemble a lime-based plaster, they are, in fact, natural cement.

As indicated earlier, Cheshire Mill No. 1 sits adjacent to a pond and has a dam and spillway at its side with water passing beneath the structure. The surfaces, particularly on the west side, remain wet most of the time. Water is the most frequent cause of problems in masonry preservation and 160 years of almost constant water exposure has, in fact, taken a noticeable toll on this building.

When we also see what winter brings, the ice pictured in Fig. 22 along with subzero temperatures that you can almost feel, it is clear that this building has indeed been asked to endure harsh conditions. This building stands as a grand example to its builders and the choice of materials that they made. It is our hope that we have made choices that will ensure its ability to withstand the elements for another 160 years.

FIG. 19—*Despite extreme displacement caused by a failing window, natural cement plaster remained intact, illustrating its flexibility.*

FIG. 20—*Cement plaster at window sill level exhibits loss of adhesion, but not a loss of cohesive integrity.*

FIG. 21—*Close-up view of cement plaster at the right side of the window, showing six distinct layers of cement plaster.*

Conclusion

In the case of Mill No. 1, the appropriate restoration solution, successfully utilizing natural cement, presented itself at just the right time. As with other materials and methods, we look forward to the establishment of best practices in the use of natural cements and training that reaches small places and projects like Mill No. 1.

The essential roles that experienced tradesmen play in the success of a project cannot be overstated. Their practical knowledge and interest in materials and methods have an enormous impact and are critical to having historic buildings survive in a meaningful way.

FIG. 22—*Winter view of west elevation.*

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J. Weber,[1] *N. Gadermayr,*[1] *K. Bayer,*[2] *D. Hughes,*[3] *R. Kozlowski,*[4] *M. Stillhammerova,*[5] *D. Ullrich,*[6] *and R. Vyskocilova*[2]

Roman Cement Mortars in Europe's Architectural Heritage of the 19th Century

ABSTRACT: Natural cements calcined at low temperatures, so-called Roman cements, formed an important binder material in 19th century construction and facade decoration of many European cities and towns. As a rule, Roman cement mortars appear well preserved. In order to understand their range of composition and properties, a number of samples from historic buildings were collected and analyzed. Microscopic techniques including scanning electron microscopy were employed along with the assessment of physico-mechanical properties. The study shows that the most significant feature of Roman cement mortars is a wide range of differently calcined clinker relicts within each mortar. These unreactive particles, classified as being either overfired or underfired, obviously play an important role for the mortar properties. The binder relicts are composed of a number of phases in the system Ca-Si-Al-Fe. C_2S and C_2AS (gehlenite) are among the most frequent compounds, their grain size and microstructure depending on calcination temperatures. In particular, the clinkers produced at lower temperatures show nonequilibrium features such as solid solution systems and zoning by partial diffusion. The aggregates found in the mortars cover a wide range of mineralogical compositions reflecting local geological conditions. Cast and *in situ* applied mortars differ in the amount of aggregate, which is generally lower for cast elements. There is no correlation between the amount of inert material and the state of preservation indicated, e.g., by the occurrence of shrinkage cracks. Historic cast mortars show high compressive strengths at comparably low moduli of elasticity. The total porosity is frequently high. This contribution presents the above-mentioned properties and discusses them in terms of the excellent aging performance of the historic Roman cement mortars.

Introduction

This paper is devoted to the use of Roman cements in the 19th and early 20th centuries in Europe and to the composition of historic mortars. Contemporary sources defined Roman cements as being binders produced from argillaceous marlstones by calcining below the sintering temperature and which had to be finely ground since they did not slake with water. The paper is intended to form an introduction to two more in-depth contributions out of a joint research sponsored by the Commission of the European Union, which deal with mechanisms of calcination [1] and of hydration [2].

Roman Cements in Europe

The Roman cement patented 1796 by James Parker in England [3] and later produced there under a number of brand names, took nearly half a century to efficiently spread to the European continent. France, quickly followed by the USA, was among the first nations to start with the production of Roman cements or similar binders in the first decades of the 19th century. Other countries such as the German and the Austro-Hungarian empires originally imported small amounts from England, before they started their own manufacture of Roman cements around 1850, based on local raw materials.

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[1] Institute of Art and Technology/Conservation Sciences, University of Applied Arts Vienna, Salzgries 14/1, A-1013, Vienna, Austria.

[2] Faculty of Restoration, University of Pardubice, Jiráskova 3, CZ-570 01 Litomyšl, The Czech Republic.

[3] School of Engineering, Design and Technology, University of Bradford, Richmond Road, BD7 1DP Bradford, United Kingdom.

[4] Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences ul. Niezapominajek 8, PL-30-239 Cracow, Poland.

[5] Institute of Monuments, Cesta na Cerveny Most 6, SK-814 06 Bratislava, Slovakia.

[6] GWD mbH Berlin, Volmerstrasse 7b, D-12489 Berlin, Germany.

Suitable marlstones could be found in different geologic formations: the best known English Roman cements were made by calcining Septaria nodules in the Eocene London clays or from the Jurassic and Cretaceous formations along the coastlines. In continental Europe, deposits of stratified marls were mined in France, especially in the Jurassic areas of Burgundy and the Cretaceous region near Grenoble. The marls quarried in the Eastern Alps of Austria, Italy, and Germany were of Jurassic, Cretaceous, or Eocene age, respectively. Other important sites of production were situated mainly in the Swiss Pre-alps, in Bohemia and Galicia, today's Southern Poland, and in Western Hungary.

Contemporary handbooks give a number of chemical compositions for 19th century raw materials and Roman cements. Hauenschild [4], e.g., lists the composition of some of the most important brands of Roman and portland cement from continental Europe and England at their time. It can be seen that Roman cements tend to much higher ranges of composition, with a significantly lower amount of CaO as compared to portland cements. Calculating the cementation index [5] according to

$$CI = (2.8\,SiO_2 + 1.1\,Al_2O_3 + 0.7\,Fe_2O_3)/(CaO + 1.4\,MgO), \tag{1}$$

the 11 brands of Roman cement cited by Hauenschild average at $CI = 1.65 \pm 0.46$, while $CI = 1.14 \pm 0.08$ for the 15 brands of portland cement listed in the same source. However, it was recognized by this author that the most relevant parameters for a good Roman cement were the petrographic properties of the marlstone, i.e., its fine and homogenous distribution of grains, sufficiently high amounts of clay and not too much quartz.

The marlstone was crushed to fist-sized pieces and usually fired in continuously operated shaft kilns with alternate layers of coal or coke. Hoffmann kilns are also reported to have been in use. Time and temperature of calcination was controlled empirically, and it was known that some marls, especially those containing elevated amounts of fluxing agents such as feldspars or iron oxides, needed shorter times and lower temperatures [4]. The calcination temperatures had to be high enough to largely enable the decomposition of calcite, but on the other hand sufficiently low to prevent sintering. Batches that were too strongly sintered were considered of no use, while material that was too underburned was frequently admixed to regularly burned stones before grinding, in order to adjust the setting time of the cement.

The calcined material, the Roman cement "clinker," had to be ground to a fine powder. Usually, this was done in pan grinders, passing to different types of cement mills in a later stage. The cement was then packed usually into 250-kg barrels or 60-kg sacks. A short time of storage prior to packing was sometimes recommended to achieve slight retardation of the cement without any loss of quality.

Roman cements were known to set rapidly by the action of water, which made them a binder of choice for a number of applications in building construction.

In the second half of the 19th century Roman cements quickly became an essential building material in most of the Central European as well as in some Northern European countries. In that time of rapid urban growth and improvement of the infrastructure, they played a key role both in construction engineering and facade decoration. The rapidly setting Roman cements came on the market just in time for a mass production of the countless cast elements making up the fronts of buildings, of molded ashlar stones, but also of *in situ* applied renders and outdoor stuccowork. Needless to say, this cement was also frequently employed in technical buildings such as bridges, sewer systems, and reservoirs.

Regarding its use on building facades, there was no general rule as to the question of whether to cover Roman cement mortars with paints or rather leave them visible in order to imitate stone. For England [6] it is known that a too dark color exhibited by some of the early brands was regarded as a negative aspect to be covered by a light coat of limewash or oil paint. Figure 1 shows such an example in which the paint has been largely weathered away. In most buildings of the alpine areas of France [7], the local Roman cement mortars were intended to resemble stone; even load-bearing ashlars were cast from Roman cements. The imitation of terracotta or natural stone was a frequent intention when Roman cements were used in many of the Gruenderzeit facades in Central European cities and towns, where eventually uncoated cast elements were surrounded by painted renders. Towards the decline of this architectural style in the eve of World War I, even those elements seem to have been painted more frequently.

Figures 2 and 3 show two examples of the use of Roman cements in the architecture of continental Europe.

The quick decline of Roman cements in favor of portland cement from the beginning of the 20th century had a number of causes, the most prominent being probably the changing style in architecture

FIG. 1—*Facade dating from the middle of the 19th century with stucco of dark-brown Harwich Roman cement; Harwich, England.*

towards a modern functionalism, with the absence of ornaments. The decline is shown in Fig. 4 for consumption within the Austro-Hungarian empire, one of the most important producers.

Contemporary Technical Regulations

Reflecting its importance in contemporary building construction, Roman cement is the subject of a number of scientific and technical books of the 19th and early 20th centuries. They define them as natural highly hydraulic binders, produced by firing marls—limestones containing clay—below their sintering temperature and grinding the burnt stones to the required fineness. In this context it has to be noted that the term "natural" was applicable also to a number of portland cements similarly produced from marls; their properties would also have been dependent on the raw materials available.

FIG. 2—*Facade dating 1878 with light-brown Roman cement stuccoes covering the ground floor; Vienna, Austria. This is one of a few examples of a surface that was never painted.*

FIG. 3—*Doorway lintel on a building dating from 1904–1906, Roman cement cast, showing the excellent state of preservation characteristic of this material; Cracow, Poland. The building has meanwhile been restored with the use of modern Roman cements.*

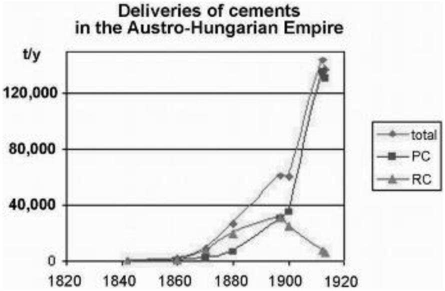

FIG. 4—*Rise and decline of Roman cements in continental Europe by the example of amounts of cement delivered in the Austro-Hungarian Empire from the start of cement production until the end of World War I. RC=Roman cement, PC=Portland cement. Figures compiled from [24].*

Most authors draw distinctions among rapid, medium, and slow Roman cements, depending on setting times of less than 7 min, 7 to 15 min, and over 15 min, respectively. An invaluable source of technical information on historic Roman cements is the Austrian standard from 1880, modified in 1890 [8,9]. The features specified by the norm are: volume consistency under water and in air, fineness of grinding, and tensile and compressive strength. The latter values are given in Table 1, which also includes portland cements in the sense of the 19th century technology. Fineness of grinding of Roman cements required the following parameters: at least 64 % to pass the 2500 mesh sieve, and at least 82 % to pass the 900 mesh sieve.

Information on the composition and use of Roman cement mortars can be gathered from the historic handbooks as well as by observations on site and by laboratory analyses of historic mortar samples. Various guidance on the preparation of mortars can be found in the literature, especially regarding the aggregate to cement ratio. Table 2 gives some formulations with the lowest amounts of aggregate being advised for casts. Even if the proposed proportions have been obviously varied widely, they are in general in line with the results of analysis performed on historic mortars. Such casts produced with sometimes very little aggregate reveal the highest strength among all types of Roman cement mortars investigated.

TABLE 1—*Strength specifications for Roman and Portland cement mortars as given by the Austrian norm of 1880 ([8] and of 1890 [9]); d = days.*

Age	Tensile strength			Compressive strength		
	Roman cement			Roman cement		
	Quick $\leq$15 min	Slow $>$15 min	Portland cement	Quick $\leq$15 min	Slow $>$15 min	Portland cement
7 d	$\geq$0.4 N/mm^2	$\geq$0.5 N/mm^2	$\geq$1 N/mm^2		Not specified	
28 d	$\geq$0.8 N/mm^2	$\geq$1 N/mm^2	$\geq$1.5 N/mm^2	$\geq$6 N/mm^2	$\geq$8 N/mm^2	$\geq$15 N/mm^2

TABLE 2—*Compilation of some formulations of Roman cement mortars given by 19th century textbooks as, e.g., [10–12], collected by Deskoski [13]. Although not defined, it can be assumed that the ratios refer to units of volume rather than weight.*

	Roman cement	Sand	Gravel
Compressed concrete	1	2	4
Masonry mortar	1	7	-
Render	1	3–5	-
Run stucco	1	2–3	-
Casts	1	1–2	-

FIG. 5—*Detail of a cast Roman cement element after uncovering from a layer of cement spray mortar; such work is time consuming if carefully executed and would therefore be performed only exceptionally.*

Current State of Preservation

The number of still existing buildings encompassing Roman cement mortars is sufficiently large to raise the interest of a group of experts in restoration and maintenance. Although the facades have suffered from air pollution in a usually urban environment, have witnessed two wars, and in most cases have undergone a number of alterations and refurbishments, there are many examples of excellent states of preservation of the originals. Several later paints cover most of the elements and renders, and in some cases these can be considered protective. However, even where technically unnecessary, there is nowadays a tendency to remove those layers before applying fresh paints in the course of restoration. This causes again risks, since uncovering of large areas of render is a costly task and inappropriate techniques are likely to be used. Figure 5 reveals a frequent case encountered in today's restoration, where removal of later layers from a perfectly preserved cast ornament is an aesthetic rather than a technical question. In this respect, careful stratigraphic studies on cross sections (Fig. 6) form an important step in the process of decision making; in the present study they have been performed for a number of buildings but will not be referred to in this paper.

Micro-cracks, forming an irregular network at the surface of Roman cement renders and casts, are a frequently observed phenomenon. They are probably due to early-stage drying shrinkage und usually do not produce any damage.

When severe decay of Roman cement mortars is observed on exteriors of buildings, this is normally due to the action of frost or soluble salts caused by an excess of moisture as a consequence of failures; for example, of the gutter system of the building. Another source of failure can be found in improper craftsmanship; e.g., when Roman cement mortars have been applied as a second coat on softer and more porous lime-based renders.

In spite of its generally good state of preservation, the conservation, repair, and reconstruction of Roman cement facades forms an important part of today's architectural conservation activities in Europe. This is why the insufficient understanding of the historic material and the lack of appropriate binders lead to the current research focus on Roman cements.

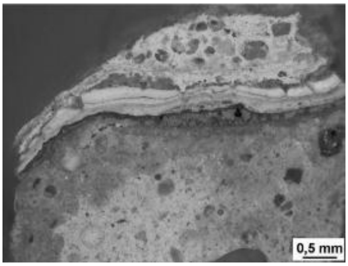

FIG. 6—*Microscopic cross section of a Roman cement render sample carrying a number of later paints with a final cement coat. Careful removal of such layers is a key task in many restoration works.*

Where no specific risk factors can be stated and no excess of water due to failures has entered the structure, most Roman cement casts and renders are well preserved and have retained even the finest details of their surface. Due to improper craftwork, however, there may have existed several cases of less durable renders, especially where a compact Roman cement set coat had been applied on a soft first coat, e.g., of lime mortar. Such surfaces may show extensive flaking and loss of material, and as a rule, no attempt to keep the render is undertaken in such a case.

Analysis of Historic Roman Cement Mortars

In order to more fully understand historic Roman cement, mortar analyses were undertaken to analyze various aspects of the material. The mortar analyses were performed on a number of samples collected from buildings in the UK, Germany, Austria, Poland, the Czech Republic, and Slovakia. They focused on obviously sound and unweathered Roman cement mortars. The aim was to develop insight into the composition of binders in order to understand the historic processes of cement production, and to study the range of composition of the mortars in terms of the composition of the aggregate, aggregate:cement ratio, porosity, and mechanical properties.

Methods of Analysis

The analytical approach followed two routes. The first was a microscopic study including the use of scanning electron microscopy. By such means, the aggregates were analyzed for their size, shape and mineral composition, and the binder was assessed for its microstructure, chemical composition, and the mineral composition of relict clinker phases. The second approach was based on the separation of the aggregate from the binder followed by chemical and mineral analysis of the binder and sieve fractioning of the aggregate.

Microscopy sections were prepared from the mortar samples both as petrographic thin sections and as polished sections perpendicular to the surface of the sampled element. They were studied under the polarizing microscope at transmitted or incident light, respectively. Digital micrographs of thin-section images taken at low magnifications were then edited and processed by means of a DIPS 4.0 software program to calculate class percentages of grain size for each petrographic species of aggregate. In the same way but using polished sections, phenograins of cement were assessed. These sections were also studied for the stratigraphy of their surface layers. The polished sections were then coated with carbon and investigated by means of a scanning electron microscope (SEM) fitted with an energy-dispersive X-ray analytical system (EDX). Quantitative analyses of spots down to 5 μm in diameter were produced on a standard-free base.

Separation of the aggregate from the binder was performed on mechanically separated layers of a sample, using a combination of manual and chemical procedures. Diluted hydrochloric acid was used and its concentration was varied according to the presence or absence of carbonate aggregate. The binder underwent a classical chemical analysis comprising determination of CaO, MgO, SiO_2, Al_2O_3, Fe_2O_3, part insoluble in HCl and Na_2CO_3, as well as of loss of ignition at 1000°C. The analyses were performed according to [14]. The cementation index (CI) was calculated according to formula (1).

X-ray diffraction patterns were recorded for the binder portions and analyzed using the quantitative Rietveld refinement. In this method, contents of crystal phases and amorphous component are obtained, by fitting the experimental data with X-ray diffraction patterns calculated for selected phases from the crystallographic data.

Size fractions of aggregates after separation were obtained by means of a set of analytical sieves according to [15].

The samples for the measurements of physical-mechanical parameters represented different types of Roman cement mortars, such as casts, renders with high and low ratios of cement:aggregate, and finally a blend of Roman cement with lime. The latter, a rather common procedure to produce soft renders at their times, can be easily identified with the naked eye by its white lumps of badly dispersed lime and was confirmed through microscopic investigations.

Care was taken to choose single-layer mortars of characteristic appearance and with no sign of weathering or alteration. According to the minimum dimension of the elements available, a specimen

FIG. 7—*Cross section of a typical Roman cement cast mortar with a very low amount of aggregate and some large gravels; the rim has residues of glue or oil steaming from the mold or the release agent, respectively. The long side of the element is about 30 cm (photo: Chr. Gurtner).*

thickness of 2 cm was chosen for most tests. The exact size was obtained by cutting with a diamond saw, thus removing surface layers that would influence the values related to water transport. As a rule, a minimum of three specimens of each sample were measured for each test, and the arithmetic mean value was calculated from the readings.

All physical tests followed the procedures established by the European Standards [16–19], with only minor amendments to the prescribed approach. In particular, this refers to the size and shape of samples measured for their water vapor diffusion, which were square with a surface area of 20 cm^2 instead of spherical with 200 cm^2 as required by the Standard.

The mechanical strength parameters, on the other hand, were tested following the norm wherever possible [20]. However, the variation in sample size from that specified by the Standard was a result of the thickness of the original renders being less than 4 cm. Thus, the compressive strength of the mortars was assessed using carefully paralleled prisms of $4 \times 4 \times 2$ cm. According to a series of comparative tests performed by the authors, the readings obtained in this way should be multiplied by a factor of 1.4 to match the regular cubic sample test values. The flexural strength was measured with samples of the dimension $2 \times 2 \times 16$ cm. Although care was taken in sample preparation (by sawing from retrieved material) the parallelism of the sample sides was not that which would be achieved from a molded modern sample. This may lead to a small underestimate of the true flexural strength. The dynamic elasticity modulus was measured with mortar samples of the size $2 \times 4 \times 16$ cm, following the prescriptions given by Knoefel and Schubert [21], based on the ultrasound-impulse-velocity method. The modulus was calculated according to

$$\text{dyn}\, E_s = \rho R v^2 \times 10^{-6}\ [\text{N/mm}^2]$$
$$\text{where } \rho R = \text{bulk density};\ v = \text{velocity in m/s.} \qquad (2)$$

Knoefel and Schubert [20] state that the dynamic elasticity modulus is about 30 % higher than if measured statically.

Results

Mortars and Aggregates

A striking observation made by microscopical techniques as well as by sieve fractioning was a wide range of ratios of aggregate to cement: for cast and hand-run mortars, the aggregate contents are low: typically 20–25 %. For renders and especially pointing mortars, the amount of aggregate is usually higher: about 40–50 %. Regarding the size of the aggregates, the results showed for the majority of Roman cement mortars very fine sand with a unimodal grain-size distribution. Distinctly bimodal curves were, however, found in samples taken from large cast elements with an example being shown in Fig. 7: a clear tendency of higher amounts of coarse aggregate was evidenced for such mortars as opposed to renders and *in situ* run elements. In spite of this, for more than 90 % of analyzed samples the mean values plotted below 1 mm, which points to the use of much finer aggregates than recommended in modern standards for

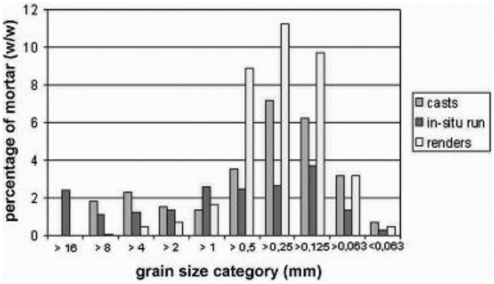

FIG. 8—*Grain size distribution of aggregates found in historic Roman cement mortars from casts, in situ run elements and renders; mean values of a total of 39 samples measured by sieve-fractioning. (See color insert for color version of this figure).*

mortars and renders. Figure 8 gives the grain size distributions for the three groups of Roman cement mortars, calculated statistically from a number of analyses.

The shape of aggregate grains varied from round to very angular and from low to highly spherical. Only the coarse fraction found in cast mortars was always of a well-rounded gravel type.

Microscopic techniques revealed that a wide range of different mineral materials were used as aggregate, which reflected local geological conditions (Fig. 9). Thus, the analyzed mortars from continental Europe contain natural mixtures of various types of carbonate and siliceous aggregates in differing ratios, while in the English mortars limestone aggregates prevail. It must be kept in mind, however, that due to the limited amount of samples and to the high degree of variation in the nature of the aggregate, no claim can be made that this sample of aggregates (Fig. 9) is proportionally representative of the range used in the 19th and early 20th centuries.

Binders

Chemical analyses of separated binders establish the historic Roman cements at an average cementation index according to Eckel [5] of 1.5 within a range of 1.4 to 1.7. This index, the formula of which is given

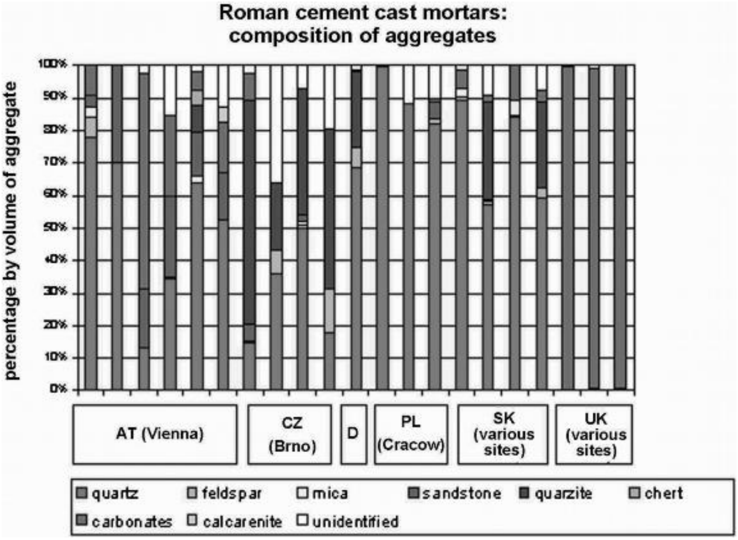

FIG. 9—*Mineral composition of aggregates in Roman cement cast mortars, showing regionally different types; similar holds for in situ run mortars and renders. (See color insert for color version of this figure).*

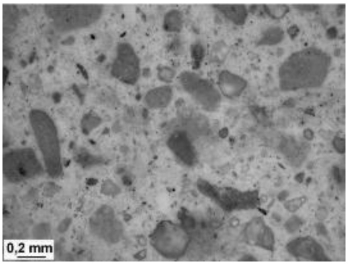

FIG. 10—*Typical binder appearance of a Roman cement mortar; all components in the image are cement relicts rather than sand grains. Polished section, incident light.*

earlier in this paper, was established to allow comparison of cements of different oxide composition based upon assumed reactions. Though several objections can be raised against the usefulness of the cementation index to describe reactions in low temperature cements, it is nevertheless a suitable parameter to compare the chemical compositions of natural cement stones.

The phases identified in the mortar binders were crystalline unhydrated components of primary Roman cements such as larnite, wollastonite, and gehlenite, further calcite as a mineral of relict or rather secondary origin, occasionally gypsum and ettringite, and an amorphous component in the average range of 33 % which appears to be poor in calcium—on an average the ratio of CaO/SiO_2 equals 0.5 according to theoretical calculations. This is probably due to a process of carbonation.

By use of microscopic techniques it was found that a most characteristic feature of the Roman cements is the inhomogeneous structure of their binders: up to 27 % of a mortar was found to consist of distinct lumps embedded in the groundmass (Fig. 10), "phenograins" according to the nomenclature by Diamond and Bonen [22]; in some cast mortars their amount can even outmatch the inert aggregate. What is observed under the microscope as phenograins of different color shades was revealed to be a variety of cement compounds (Fig. 11) which, for quite different reasons, were either not or just partly prone to hydration. Embedded in the hydrated matrix, they usually show excellent adherence to adjacent material and act as fillers such that they are likely to absorb shrinkage strains. A thorough investigation by means of SEM/EDX permitted the classification of the lumps into three major groups, i.e., overfired, well fired, and underfired (Fig. 11). Their grain size distribution in historic mortars is depicted in Fig. 12.

The first group of phenograins (overfired) comprises relatively coarse crystals of belite (C_2S), wollastonite (CS), gehlenite (C_2AS), and several minor compounds such as rankinite (C_3S_2), brownmillerite (C_4AF), leucite, and anorthite. Local melting can be stated for many of these lumps, and it is thus obvious that they were formed at elevated temperatures or in the presence of a fluxing agent such as alkalies.

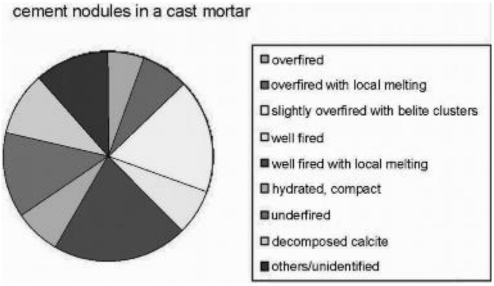

FIG. 11—*Relative amount of the various types of cement relicts in the binder of a single sample from a typical historic Roman cement cast mortar, analyzed by thin-section microscopy combined with SEM/EDX; total amount of phenograins: 69. All types of phenograins are represented in the mortar at nearly equal proportions. (See color insert for color version of this figure).*

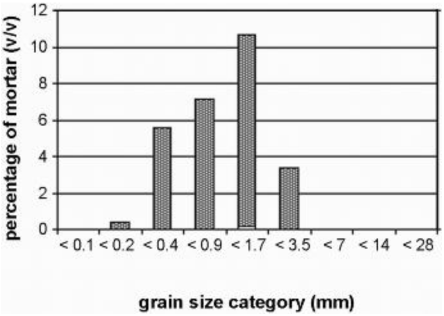

FIG. 12—*Range of grain sizes of binder phenograins in cast Roman cement mortars, obtained from microscopic images. Sizes refer just to the remnant portion of the cement, while the hydrated portion was probably finer; thus, the graph gives only an idea about the historic fineness of cement grinding in the coarse range.*

Obviously, most of the compounds are of the nonreactive type, and belites are too coarse to hydrate (Fig. 13). Marginally, however, these phenograins can be surrounded by a rim of hydration product of a compact appearance [Figs. 14(*a*) and 14(*b*)].

In some mortars, elevated amounts of vitreous matter indicate even more efficient melting. This feature was found particularly in some early 19th century mortar samples from England. It can be hypothesized that their use of mineral coal or coke as opposed to wood or lignite in most of the continental kilns may have produced Roman cements at higher temperature.

In the "well fired" group of lumps, two types can be distinguished: a nonreactive and a reactive one. The first type (Fig. 15) is characterized by grains of silica with strong zoning from their core to the rim, caused by inward diffusion of Ca and K ions into quartz grains originating from the marl. Occasionally, such silica grains have empty cores that are interpreted as being caused by a minute amount of melt formed in the places with highest concentrations of potassium, i.e., the place where the melting point is lowest. Such compounds are regarded "well burnt" because at their margins the compositions come close to belite (C_2S), and their immediate surroundings appear to be fully hydrated.

The second type of "well-fired" phenograins has no unhydrated compounds, consists of fibrous calcium-silicate-hydrate (CSH), but is more compact and brittle than the bulk cement matrix (Fig. 16). Such pseudomorphs of cement grains frequently show cracks that are believed to have formed by the action of chemical shrinkage. The cracks do not propagate into their surrounding, which is more porous and elastic.

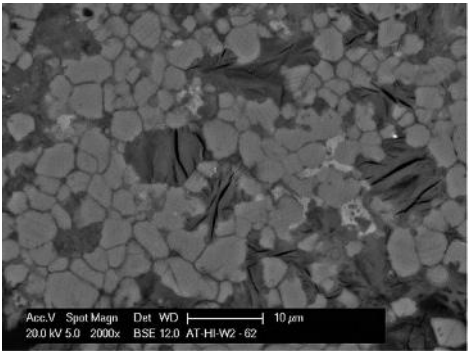

FIG. 13—*Belite crystals in a phenograin, SEM.*

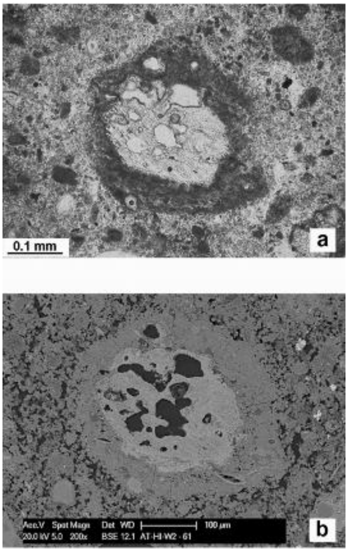

FIG. 14—*Cement phenograin classified as "overfired with partial melting" with extremely dense hydrated rim; thin-section microscopy (a) and SEM (b).*

The third group of phenograins—underfired—has internally kept the fabric of the raw material, with a parallel orientation inherited from the marl, quartz largely unaffected by diffusion processes, and occasional fossil structures which sometimes are of a calcitic nature.

A typical 19th century Roman cement would contain phenograins from all of the above described groups side by side in similar amounts (Fig. 11). Just in a few samples was there a clear dominance of overburned relict phenograins, as for some English Roman cements (see above) and for thin set coats of some continental renders. As a rule, such mortars are poor in aggregate and appear very hard and compact. Even if no model of explanation can be given so far, it is clear that the nature of the phenograins is of importance for the properties of the mortar since they assume the role of aggregates in shrinkage control, being at the same time very well bound to the hydrated binder matrix.

More precise ideas about the nature of the phenograins in Roman cements and the role they play for the mortar properties require further studies.

Physico-mechanical Properties of the Mortars

A number of historic Roman cement mortars were studied for their mechanical properties and their parameters related to the porosity. As stated earlier in this paper, the samples were selected according to the groups: Roman cement casts with their typically low amount of aggregate, Roman cement renders both with low and high amounts of aggregate, and renders prepared with a blend of Roman cement and lime. The results are given in Table 3. For a number of reasons, however, the values are only indicative and of a preliminary nature: first, because they were obtained from a very limited number of historic mortars—it is rarely possible to collect the required amount of material from historic structures; secondly, because the sample size deviates from the prescriptions of the norm, at least as far as mechanical tests are concerned. Nevertheless we believe that the values given are representative of key properties of historic Roman cement mortars, and the findings can be discussed as follows:

- In general, Roman cement mortars are relatively strong and brittle, but at the same time they possess a considerably high porosity accessible to water.
- The amount of aggregate seems to have surprising and contradictory effects on the mechanical properties; in fact, the obtained data cannot be interpreted just in terms of the cement:aggregate ratios, but would require more information on the specific conditions of processing and curing of

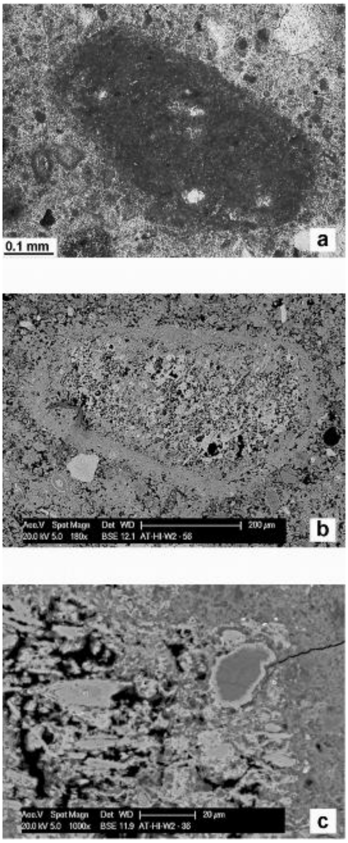

FIG. 15—*Cement phenograin classified as "well fired" with zoned silica with a dense hydrated rim; thin-section microscopy (a) and SEM (b and c); such phenograins have formed in quartz-rich regions of a marl.*

such cast and *in situ* applied mortars respectively. It can be stated, however, that the measured values confirm the observation that especially cast mortars, being poor in aggregate, are usually very strong but tend to have fine cracks as a result of internal stresses developed in the course of shrinkage processes. Tensile stresses on such mortars can cause failures at relatively early stages.

- With respect to the mortar porosity and related properties, low amounts of aggregate result in significantly increased values, while the admixture of lime to the cement increases the porosity further.

Summary of Results and Conclusions

Roman cements played an important role in architectural construction of the 19th and 20th centuries. They were produced out of crushed stones in kilns of different types and sizes, using various fuels at relatively low temperatures. A uniform quality was unlikely to occur for these reasons. Nevertheless, the analyses of historic mortars from all over Europe have shown a number of significant similarities in respect to the binders. All studied Roman cements are characterized by a high amount of phenograins in their matrix, which have been recognized to represent not ideally calcined reaction products from the process of firing. They have been classified as overfired, well fired, and underfired, and they can be found together in one and the same batch. This is a consequence of various factors: (1) the temperature gradients in a traditional

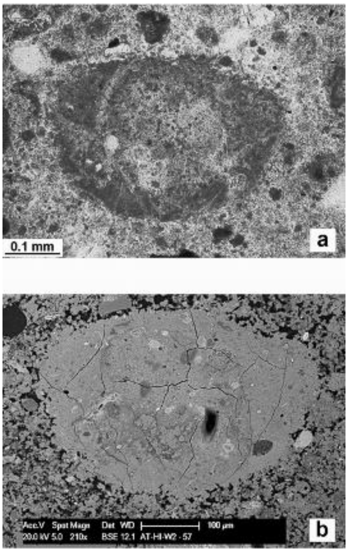

FIG. 16—*Cement phenograin classified as "well fired," fully hydrated, with extraordinary compact structure; thin-section microscopy (a) and SEM (b).*

shaft kiln, (2) the inhomogeneous temperature distribution within each single chip of cement stone, (3) the natural inhomogeneity in the chemical and mineral composition and the fabric of any natural stone, (4) the intentional blending of differently fired materials to control setting properties.

The cement phenograins are believed to be of importance for the performance of a Roman cement mortar, since they act as aggregates and should be accounted for in the design of optimum mortars within the analyzed large range of aggregate:cement ratios. Their occurrence is inherent to a Roman cement even if produced by modern means. This is because the low temperatures of calcination and short residence times would always favor unevenly distributed conditions of reaction. The calcinations performed on basis

TABLE 3—*Properties of some historic Roman cement mortars: mean values of 3–5 readings and deviation in case of cast mortars, where samples from two different casts had been measured. Values are not corrected for deviations of sample size (note the comments in the methods section).*

Property	Unit	Cast	Render 1 (rich in aggregate)	Render 2 (poor in aggregate)	Render 3 (Roman cement-lime blend)
Binder:aggregate ratio	w/w	1:0.5±0.2	1:1.5	1:0.1	1:0.5
Compressive strength	N/mm^2	47.9±2.5	18.4	56.8	10.7
Flexural strength	N/mm^2	3.0±0.7	2.4	0.8 (?)	0.6
Elasticity modulus	kN/mm^2	18.2±1.7	31.3	11.4	5.4
Bulk density	g/cm^3	1.62	1.85	1.47	1.4
Water-accessible porosity	% v/v	30.7±2.1	19.5	37.1	39.3
Total water absorption by immersion (24 h)	% w/w	18.6±1.7	10.4	25.0	27.5
Water absorption coefficient	$kg/m^2\sqrt{h}$	7.0±0.7	4.42	12.75	22.67
Watervapor diffusion coefficient μ		23.5±0.5	28	20	18

of the results from the optimization program [1] have in fact produced excellent Roman cements, regardless of the kiln type employed; i.e., electric kilns and a rotary kiln.

The microscopic studies also enabled the evaluation of the fineness of cement grinding in the historic process. A maximum of sizes of phenograins occurs in the range of 1 mm, a clear indication that the "maximum fineness" required by contemporary technical prescriptions was in fact not achieved. In light of the conclusions stated above, Roman cements ground too finely would lose the benefits derived from the cement phenograins.

Historic Roman cement mortars show a large variety of cement:aggregate ratios though mortars rich in cement prevail; in particular, cast mortars have extremely low amounts of inert material. No specific petrographic nature and shape of aggregate was detected, despite the coarse portion of continental cast mortars that is typically composed of well-rounded gravel. Microscopic studies suggest that the phenograins contained in all Roman cement binders to a significant amount play an important role in the mortar performance. Further studies are needed, however, to establish more exact relationships among the ratios of hydrated binder portion, phenograins, and inert filler. A similar effect is generally stated for lime mortars based on lime putty produced by slaking quicklime in the traditional "dry" way, i.e., without an excess of water and just for short time spans; such putties contain numerous lumps of undispersed lime, and they need much less filler to form good mortars. They are at present facing a comeback in the field of restoration.

The measurement results of physico-mechanical properties achieved for Roman cement mortars which were exposed over a period of roughly 100 y assign them a very high mechanical strength and a high modulus of elasticity. Cast mortars that have the least amount of aggregate show the highest compressive strength, a clear indication of the strong nature of the Roman cement binder. Their total open porosity is, however, surprisingly high, which makes these materials an interesting alternative to modern portland cement products. Addition of lime to the cement results in significantly lower strength at higher elasticity and porosity.

It should be recalled that the study presented in this paper is in fact just part of a larger research on Roman cements in Europe, which is clearly directed towards issues of conservation and restoration of architectural heritage. The research on a European level was initiated because a gap in the knowledge of Roman cement mortars was clearly identified. Little was known of their material parameters, and hence a number of untrue assumptions has been leading to improper measures of restoration. In addition, no appropriate binders were available to the restoration market, and therefore another important task of the project was to create a base for the future production of Roman cements. One of the most important consequences in the context of practical questions was to scientifically prove that the state of preservation of architectural elements made of Roman cement is generally excellent. Another result of interest was the high tolerance of the mortars in respect to mixture recipes. Nevertheless, typical cement:aggregate ratios have been identified which, together with a test series based on reproduced Roman cements, provided guidance for the development of the recently published advice to the restoration community in Europe [23]. In this way, two crucial aspects of restoration have been addressed: an improved knowledge of material properties and hence of decay processes of Roman cement mortars, and the key to produce Roman cements and to prepare good mortars with them. Scientific studies will, however, continue in order to yield further insight into the mode of action of this outstanding binder.

The coming period will see a number of scientific publications not only in journals of material science but also in periodicals of architectural conservation.

Acknowledgments

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D. C. Hughes,[1] D. Jaglin,[1] R. Kozlowski,[2] N. Mayr,[3] D. Mucha,[2] and J. Weber[3]

Calcination of Marls to Produce Roman Cement

ABSTRACT: Marls were identified from a range of European sources and assessed for their Cementation Index, as proposed by Eckel. Two were selected for calcination in a laboratory kiln; one from Folwark in Poland (CI 1.75) and one from Lillienfeld in Austria (CI 2.03). Analysis of historical documents, while not revealing precise kiln conditions, does suggest that they were such as not to yield complete decarbonation of the calcite. Consequently, a series of calcinations was undertaken in which the peak temperature control of the kiln was set in the range 730°C to 1100°C, with residence times in the range 150 to 1250 min. The airflow through the kiln was sufficient to maintain a minimum oxygen content of at least 12 %. The resulting clinker was ground to comply with the 19th century Austrian Norme. Pastes were produced at $w/c = 0.65$ and assessed for setting time and strength development (6 h to 1 year). Both parameters were highly dependent upon calcination conditions with both "low" and "high" calcinations producing slower setting and slower strength development than intermediate conditions. Two strength development profiles were identified; one being the expected continuous increase of strength, albeit with a declining rate of increase with time, while the other showed a three-step sequence of high initial strength, a dormant period which could last for many weeks and a final increase in strength to an age of one year. The cements were compared using X-ray diffraction (XRD). Considerable variation in the composition was noted and related to the calcination conditions. Of particular interest is the formation of both α'-belite and β-belite under differing calcination conditions. Clinker particles were also compared using the SEM in back-scattered electron imaging mode and the development of morphology observed.

KEYWORDS: Roman cement, calcination conditions, clay type, setting, strength development, mineralogy

Introduction

The research described in this paper forms one of three presentations to the 2nd American Conference on Natural Cements held in Washington, DC, 30–31 March 2006 based upon work performed in the EU funded ROCEM Project. A description of the use of Roman cement within a European context is given by Weber et al. [1] and forms a valuable introduction to the topic. This paper focuses on the calcination of marls to produce satisfactory Roman cements.

The historical cements were produced from a wide range of geological sources. Hence, it should be acknowledged from the outset that the term "Roman cement" is only applicable as a generic classification of such natural cements—each source yielded its own properties yet was characterized by rapidly setting cements of a varying brown color. The technology to produce Roman cement was first developed in the UK, spread to continental Europe and then across the world, with the U.S. being a major producer. During this period the world underwent major changes as technology developed throughout the Industrial Revolution; therefore, it is not surprising that descriptions of production techniques are not only vague by modern standards but also develop throughout the period.

Roman cement was patented in 1796 although there is circumstantial evidence to suggest that the actual discovery by Parker was several years earlier [2]. The cement stones, or septaria, were initially collected from the foreshore of the Isle of Sheppey in the Thames Estuary to the east of London, UK. The need to reduce the size of the stones to a uniform size to ensure consistent calcination was recognized early in the 19th century [3]. In the UK, this task was often left to young boys to undertake using hammers. Parker's patent states that the cement stones should be burned "with a heat stronger than that used for burning lime" "nearly sufficient to vitrify them" [4]. The calcination time has been variously reported as

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[1] School of Engineering, Design and Technology, University of Bradford, UK.

[2] Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences, Cracow, Poland.

[3] Institute of Conservation Sciences and Restoration Technology, University of Applied Arts, Vienna, Austria.

TABLE 1—*Calcination parameters (residence time is defined as the time at which the kiln was set to maintain the maximum temperature).*

Marl	Residence Time (min)	Maximum Temperature (°C)
AT-L1	100–600	870–1100
PL-F104	150–1250	750–1050

being between 30–72 h [3–5]; such times would include the heating, residence, and cooling cycles. Pasley [6] specifies gradual heating, to prevent bursting, to a full red heat for 2–3 h and that correct calcination has occurred when there is no effervescence upon a calcined stone being immersed in dilute muriatic (hydrochloric) acid and the correct color being observed. The latter condition was applied to prevent the misclassification of over-burned material. Mitchell [7] reports that if the heat was high enough to completely decarbonate the stone then an inferior cement was produced.

Writing early in the 20th century, Eckel [8] surveyed the manufacture of Roman and natural cements, largely from an American perspective. In different parts of the book he makes two contrasting statements—(1) that "burning takes place at a temperature that is usually little, if any, above that of an ordinary lime-kiln" (elsewhere stated to be 900°C) during which "the carbon dioxide of the limestone is almost entirely driven off," and (2) "in most cases, the temperature is carried to 1100°C–1300°C." He also recognized that over-burning yielded inferior cements. Notwithstanding the conflicting guidance of Eckel, there might appear to be a conflict between the general advice of Eckel and Mitchell, which is not surprising given the state of technology in the 19th century. However, the calcination conditions are specific to the actual kiln and its management, the available fuel type, and the source of stone or marl. Eckel acknowledges this latter variability and states that cements with a higher Cementation Index (CI) (Eq 1) should be calcined at a lower temperature; a temperature of 900°C or a little higher being sufficient for a CI of 2.0. The index was an attempt to permit comparison of cements of different oxide composition based upon assumed reactions. While they would be challenged these days it does provide a contemporary basis for judging marls.

$$CI = (2.8 * SiO_2 + 1.1 * Al_2O_3 + 0.7 * Fe_2O_3)/(CaO + 1.4 * MgO) \tag{1}$$

This paper describes the calcination of two marls together with the mineralogy and mechanical properties of their cements. The temperature range over which calcination was undertaken was informed by a pilot study using septaria collected from Whitby [9], which were used to produce Atkinson's or Mulgrave cement in the 19th century. The hydration of cements produced in the ROCEM project is described in the paper by Vyskocilova et al. [10] presented at this conference.

Experimental Details

Two marls have been used; one was sourced from a quarry which had supplied material for the historic production of Lilienfeld cement in Austria (AT-L1) while the other was selected from an active quarry in Folwark, Poland (PL-F104) where access is readily available to a suitable bed of stone.

The identification of the clay minerals in the marls was carried out according to Brindley and Brown [11] and Moore and Reynolds [12]. The mineral content was evaluated semi-quantitatively according to Schultz [13]. Total porosity of each marl was analyzed by mercury intrusion porosimetry in the range 440–0.0035 μm. The BET surface area was measured by nitrogen adsorption at 77.5°K.

For calcination each marl was reduced to fragments of approximately 7–10 mm thickness. An electric kiln (Carbolite GPC12/36) was used and an airflow was maintained through the kiln to ensure that a minimum oxygen content of 12 % was maintained during the decarbonation phase of calcination. The calcination parameters of the marls are summarized in Table 1. During the calcination of AT-L1 a large temperature gradient was observed throughout the charge of marl fragments. Thus, for the calcination of PL-F104 the batch size was reduced from 10 to 5 kg and a baffle system introduced to minimize the impact of the injected and unheated air on the heat cycle of marl fragments in proximity to the inlet port. While this reduced the temperature gradients within the kiln it did not eliminate them. The average maximum temperature of the AT-L1 calcinations which occurred within the bulk of the fragments is likely to be approximately 100°C lower than the kiln set temperatures while that for the smaller charge of

TABLE 2—*Particle size distribution of all cements.*

Sieve Size (μm)	Proportion Passing (%)
212–425	16.6
106–212	16.6
<106	66.7

PL-F104 is some 50°C lower. Since it is not the intention of this work to yield absolute comparisons between the temperatures for each marl the temperatures cited herein are those set on the kiln controls.

Samples of each cement were analyzed by traditional wet chemical techniques to determine their oxide composition and X-ray diffraction to determine their mineralogy. XRD patterns were collected using a Siemens D5005 diffractometer (CuK$_\alpha$ radiation, 40 kV, 40 mA) equipped with a diffracted-beam graphite monochromator. Silicon powder, 325 mesh from Aldrich, was added as an internal standard to quantify the amorphous phase content. The measurements were performed between 2 and 70° of 2θ with step size 0.04°, 4 s/step. Contents of phases were calculated by the Rietveld method using the TOPAS software [14]. During refinement the fundamental parameter approach was applied [15] and the following parameters were refined: zero, displacement, background, overall temperature factor, and for each phase scale, crystal size, and cell parameters with changes restrained to 1 %. Polished surfaces were analyzed in a Philips Environmental Scanning Electron Microscope (ESEM) to study the morphology of calcined products. Sample preparation included vacuum-embedding the fragments in epoxy resin, dry grinding and polishing, and coating with carbon to achieve electrical conductivity. The sections were studied under high vacuum at an acceleration voltage of 20 kV using a back-scattered electron detector (BSE).

The calcined marl fragments were ground using a Retsch BB200 MANGAN crusher. Each cement was sieved (Table 2) to meet the specification of the 19th century Austrian Norme given in Ref. [16].

Pastes were produced for each cement at a water to cement ratio of 0.65. These were subject to the determination of the final setting time (pastes were placed in 35-mm film canisters in order to minimize the usage of materials). Setting of the pastes was measured using the standard Vicat needle for establishing "final set" (BS EN 196-3:2005). The standard procedure of producing pastes at a specified consistency was not possible given the extreme rapidity of set. Hence, a modified procedure based on pastes of $w/c = 0.65$ was adopted; this value was itself pragmatically chosen as yielding the necessary fluidity to cast paste samples of the most rapidly setting cements. Pastes were also molded into 120-mm by 22-mm diameter cylinders. These were subsequently sawn into 22-mm by 22-mm diameter cylinders for compressive strength testing at ages of 6 h to 1 year following water curing at 20°C (four samples were tested at each age). An Instron 4206 was used at a crosshead speed of 0.5 mm/min together with a ball-seating arrangement to ensure uniform application of stress.

Composition of Marls and Cements

Marls

Tables 3 and 4 show the chemical and mineralogical composition of the two marls. They are of similar chemical composition although the Cementation Indices (CI) are slightly different. However, significant differences are revealed by the mineralogical composition. AT-L1 contains more silica present as quartz than does PL-F104. Significant differences are also found in the clay mineralogy, with swelling smectite occurring in PL-F104 while AT-L1 is dominated by illite together with chlorite. The clay type may account for the more porous fabric of PL-F104 as evidenced by the higher porosity and surface area as a result of a lower degree of cementation by calcium carbonate associated with having undergone a weaker diagenesis. Further details may be found in Weber et al. [17].

TABLE 3—*Mean chemical compositions of marls.*

	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	CaO	MgO	SO_3	Na_2O	K_2O	CI
PL-F104	21.35	1.79	5.30	0.41	36.62	1.08	0.49	0.16	1.07	1.75
AT-L1	22.55	2.88	7.08	0.44	34.06	1.35	0.05	0.47	1.47	2.03

TABLE 4—*Mineral compositions and porosity characterization of marls.*

	XRD						
	Quartz	Feldspar	Calcite	Dolomite	Clay Minerals	Mercury intrusion (MIP) Total Porosity (v/v)	BET Specific Surface Area (m^2/g)
PL-F104	4	0	71	1	24 (Smectite)	23.5	33.0
AT-L1	9	2	63	3	23 (16 % illite +7 % chlorite)	7.3	6.8

Cements

Figures 1 and 2 show the mineralogical composition of cements as a function of their calcination. Although precautions were taken to minimize the variation of temperature both within the charge of marl fragments and each fragment itself, a variation does exist. Hence, any given cement will contain characteristics reflecting a small range of temperatures. However, these are likely to be much less than those observed by Weber et al. [1] in historic Roman cement mortars.

An increase in calcination conditions is accompanied by a decrease in both calcite (Fig. 1(*a*)) and quartz (Fig. 1(*b*)), both being unreacted marl components; calcite is completely reacted following the most intense calcination conditions studied. In contrast, the free lime content shows a maximum at intermediate conditions; two reactions are involved, namely the release of lime from the decarbonation of the calcite and its subsequent combination into compounds such as belite and gehlenite. Hence, at intermediate conditions considerably more lime is being liberated than consumed, with PL-F104 yielding substantially higher free lime contents than AT-L1. This feature is possibly a reflection of the presence of coarse quartz crystals which require high temperatures to fully combine with liberated lime, calcite being present in "coarse" fossils, and local inhomogeneity [17].

The relatively low calcination temperatures produce very reactive free lime which has been observed to convert rapidly to calcium hydroxide during laboratory processing and storage of the cements. Indeed, a comparison of lime found in calcium hydroxide (by XRD) and free lime (by chemical analysis) suggests that the maximum free CaO may be around 4 % rather than the 12 % shown. Even 4 % is considered a high value when considering portland cements but samples did not show signs of distress upon water immersion unlike others produced in this laboratory.

As expected, the amount of crystalline material increases and the amorphous material decreases (Fig. 2(*a*)) with the intensification of the calcination conditions. PL-F104 yields less content of the amorphous and more crystalline phases than AT-L1 and is a function of the greater reactivity of the smectite minerals [17]. The amorphous phase comprises predominantly poorly- or micro-crystalline calcium aluminate and silicate products of the reaction between dehydroxylated clay and lime, which are undetectable by XRD; these would be expected to be hydraulic in nature. It may also contain unrecombined dehydroxylated clays which provides the possibility of pozzolanic activity within the cement. The increase in crystalline phases is accounted for by increases in both gehlenite (Fig. 2(*b*)) and total belite (Fig. 2(*c*)). While the increase in both minerals is found at similar calcinations of PL-F104, AT-L1 displays a different relationship with the peak belite being first achieved at lower calcinations than those required to yield the maximum gehlenite content. The source of silica for the increase in total belite content may be found both in the amorphous phase and the quartz. The reaction of the latter is shown in Fig. 3. At the lowest temperatures the quartz grains are completely unreacted. With increased calcination both potassium and calcium diffuse into the quartz grains and belite is found in the reaction rims while at the highest temperatures the degree of reaction is higher and the rims show well-defined crystals of mono-calcium silicate and belite. There is a difference in morphology between the two marls at the highest temperatures. Whereas the modifications in PL-F104 result from solid-state reactions there is evidence of some melting in AT-L1 evidenced by hollow cores to some grains. The higher potassium content of the marls would account for this.

Unlike many commercial hydraulic limes available in the UK, belite is found in two polymorphs. The α'-belite polymorph (Fig. 4(*a*)) is the first to form at low temperatures [18] and is transformed to β-belite as the conditions are increased (Fig. 4(*b*)). In the case of PL-F104 the transformation is complete for the calcination temperatures of 1000°C and greater. In order to strengthen the analysis of mineralogy by XRD

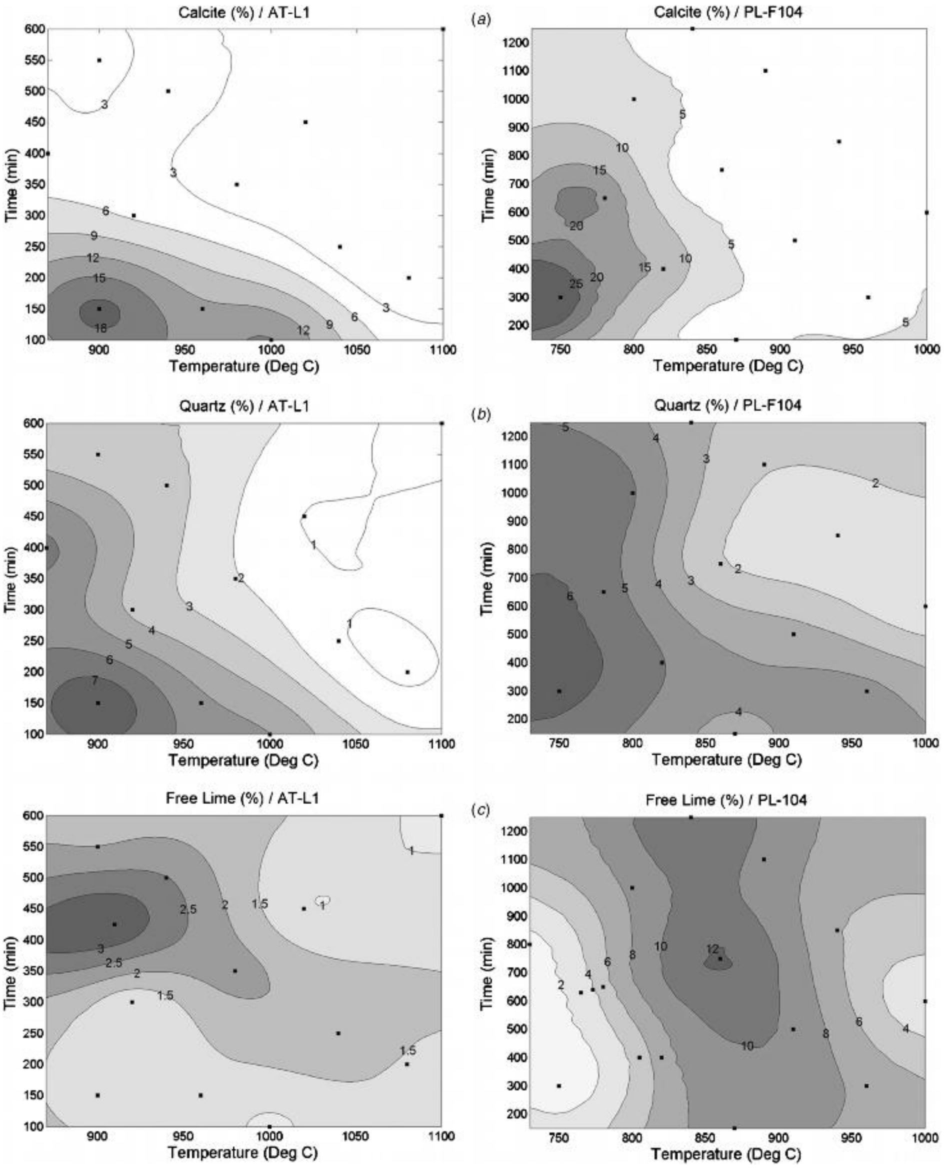

FIG. 1—*Cement composition as a function of calcination conditions; (a) calcite, (b) quartz, and (c) free lime.*

analysis, the crystal size is constrained. However, if left as a variable then the size of belite is seen to increase with calcination conditions and the critical crystal size of α′-belite may be in the region of 35 nm.

It is worth noting that none of the other Bogue compounds found in portland cement (C_3A, C_4AF, or C_3S) were identified.

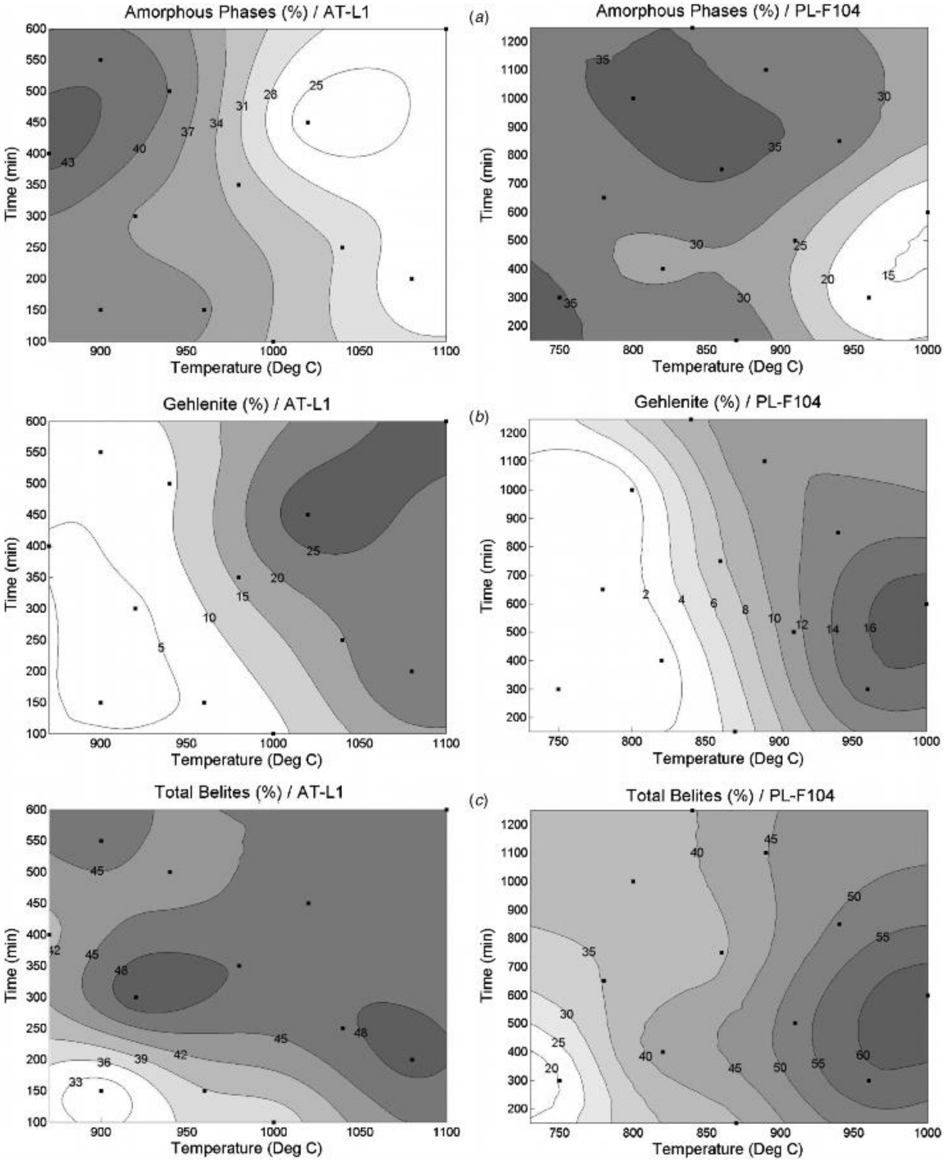

FIG. 2—*Alumino-silicate composition as a function of calcination conditions; (a) amorphous phases, (b) gehlenite* (C_2AS), *and (c) total belite* (C_2S).

Properties of Cement Pastes

Setting

The final setting times of the cements are shown in Fig. 5. It is apparent that the criterion of a rapidly setting cement has been achieved with the fastest setting times of approximately 1.5 min being achieved for both AT-L1 and PL-F104 which are in line with the classification of Ciment Prompt devised by Gobin

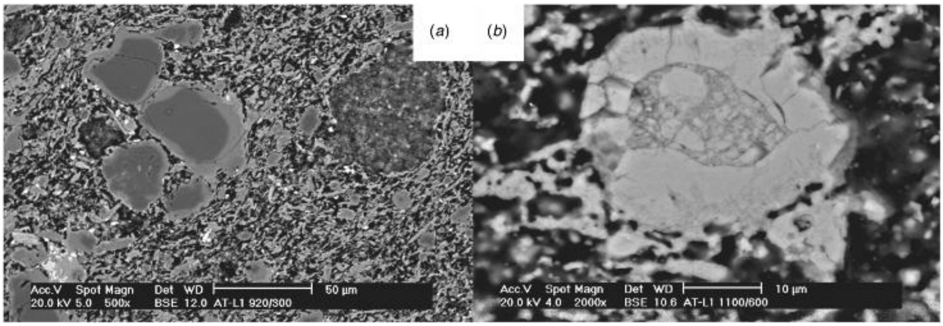

FIG. 3—*Showing reaction rims developing around unreacted quartz grains in cements from AT-L1; (a) 920/300 and (b) 1100/600.*

[19]. Clearly, there will be a need for the use of retarders and this will be the subject of a future publication. It is apparent that PL-F104 yields rapid setting over a wider range of calcination conditions than does AT-L1. If the performance of the two marls is combined, it is apparent that the longer setting times are recognized at both of the “extremes” of calcination parameters studied. Such behavior was also observed in a single marl during the pilot study for the ROCEM project [9]. Given the lack of identifiable crystalline calcium aluminates the source of the rapid setting is to be found within the amorphous phases [10].

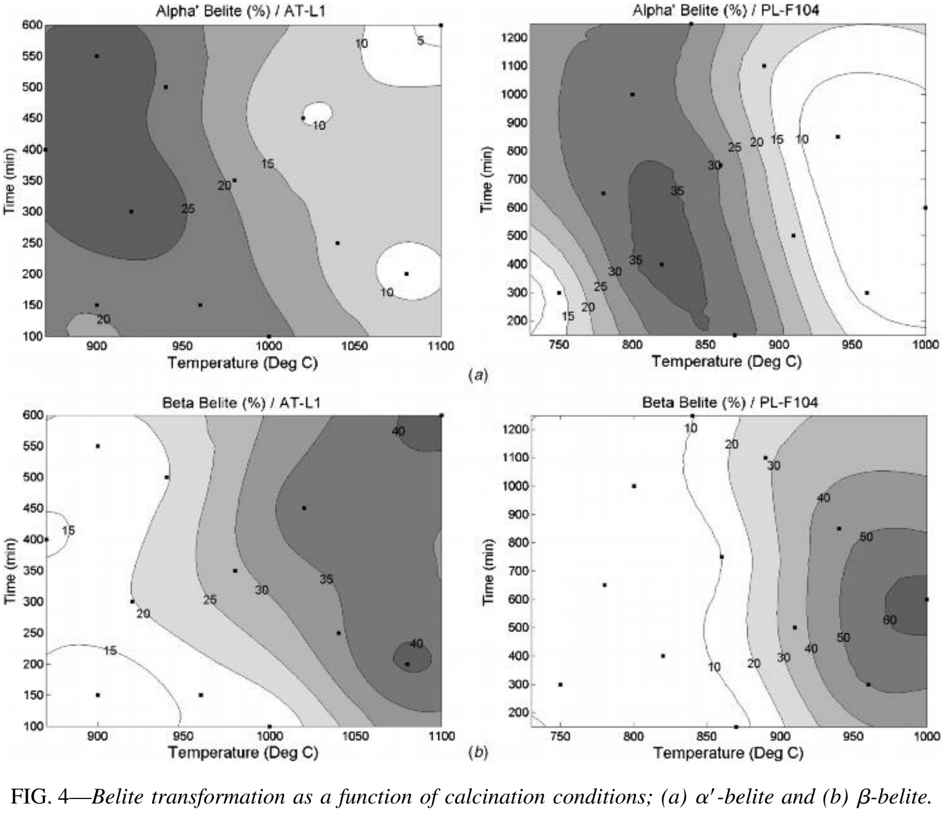

FIG. 4—*Belite transformation as a function of calcination conditions; (a) α'-belite and (b) β-belite.*

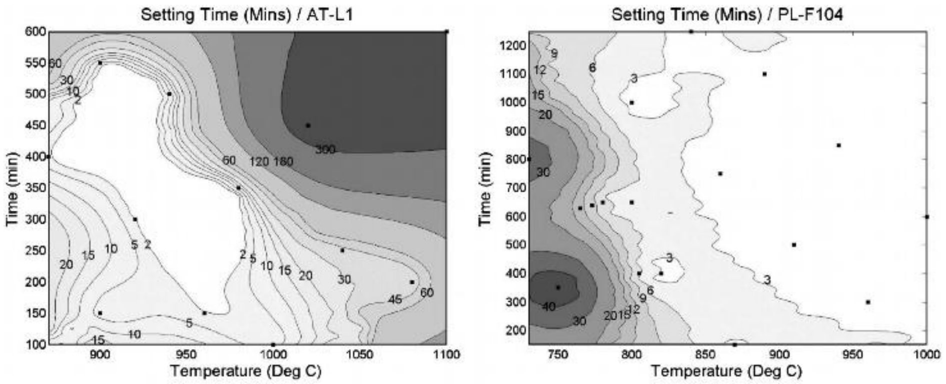

FIG. 5—*Final setting time of pastes at w/c = 0.65-(a) AT-L1, (b) PL-F104.*

Strength Development

The strength data for both cements are shown in Tables 5 and 6 with strength development profiles for selected cements in Figs. 6 and 7.

It is apparent that the strength development profiles (Figs. 6 and 7) are not those which would be expected for portland cements and differ broadly between the two cements. Those for AT-L1 are generally characterized by the attainment of an early strength followed by a dormant period of variable length, which may last for up to eight weeks. This is followed by a period of accelerated strength gain with a subsequent decrease being observed in some cements. In contrast, PL-F104 shows only a few examples of a dormant period and those occurred in cements calcined at more intense conditions. For both marls, the cements produced at the highest intensities of calcination yielded the most inferior strengths. These conditions also

TABLE 5—*Strength (MPa) data for AT-L1.*

Age (weeks)	870/ 400	900/ 150	900/ 550	920/ 300	940/ 500	960/ 150	980/ 350	1000/ 100	1020/ 450	1040/ 250	1080/ 200
0.035	2.03	0.82	3.35	3.62	1.49	1.19	0.44	0.5	0.07	0.17	0.12
0.14	2.56	0.94	3.69	3.81	1.73	1.26	0.51	0.53	0.06	0.14	0.11
1	2.44	0.9	3.8	4.41	1.73	1.52	0.44	0.55	0.09	0.21	0.11
2	4.31	1.05	3.85	4.26	1.72	1.65	0.64	0.61	0.09	0.24	0.12
4	15.71	1.17	3.8	4.29	2.25	1.81	2.78	0.54	0.14	0.56	0.27
8	17.64	1.62	10.05	6.87	11.11	2.69	10.63	0.8	0.32	4.51	1.86
16	19.07	9.23	17.92	18.69	16.42	12.44	14.11	9.74	3.01	13.05	7.79
26	20.38	13.32	18.79	19.31	17.95	15.43	15.21	14.72	4.7	13.56	10.03
39	19.01	15.37	19.74	18.45	20.02	15.67	14.93	14.18	5.86	15.84	9.99
52	23.06	15.26	20.73	18.47	20.86	16.89	15.91	18.99	6.63	16.46	11.29

TABLE 6—*Strength (MPa) data for PL-F104.*

Age (weeks)	730/ 800	750/ 350	765/ 630[a]	773/ 640[a]	780/ 650[a]	800/ 650[a]	800/ 1000	805/ 400[a]	820/ 400[a]	840/ 1250	860/ 750	860/ 750	870/ 150	890/ 1100	910/ 500	940/ 850	960/ 300	1000/ 600	1050/ 600
0.035	0.23	0.24	0.19	0.17	0.26	0.33	0.73	0.34	0.68	0.29	0.23	0.23	0.41	0.35	0.48	0.47	0.23	0.65	0
0.14	0.32	0.37	0.3	0.22	0.37	0.41	0.76	0.38	1	0.32	0.31	0.31	1.13	0.37	0.53	0.51	0.26	0.57	0.18
1	1.46	1.21	1.66	2.59	4.18	2.24	2.81	1.85	6.89	0.64	0.82	0.82	4.81	0.42	0.54	0.42	0.27	0.39	0.2
2	3.83	3.48	4.83	6.71	11.79	5.17	8.6	4.89	11.1	2.21	1.78	1.78	7.89	0.94	1.09	0.53	0.46	0.5	0.23
4	8.33	7.1	9.56	11.41	14.12	9.07	12.71	11.34	14.35	9.35	7.38	7.38	10.45	5.45	8.47	3.71	1.63	1.4	0.25
8	10.92	8.57	13.61	13.74	16.02	11.4	16.55	15.27	17.04	11.68	12.2	12.2	13.6	12.83	14.91	14.54	9.31	11.86	0.25
16	12.84	11	15.91	17.21	17.89	12	21.1	17.21	21.36	12.05	13.33	13.33	15.82	15.84	16.91	17.77	11.28	14.77	0.23
26	13.47	15.34	19.09	19.77	21.49	14.05	19.45	17.04	20.86	13.39	13.14	13.14	17.32	16	17.57	19.52	13.29	17.07	1.03
39	13.96	14.93	19.34	21.59	21.46	17.22	19.05	20.01	21.34	14.56	15.57	15.57	19.61	16.93	18.35	18.87	13.43	19.9	1.5
52	15.04	16.87	20.17	20.73	20.57	17.12	19.93	19.78	23.19	14.26	15.15	15.15	18.43	18.96	17.72	18.44	13.66	20.81	1.39

[a] The preponderance of calcinations in this region was to refine the performance in the zone of the optimum cements and data are included here for completeness.

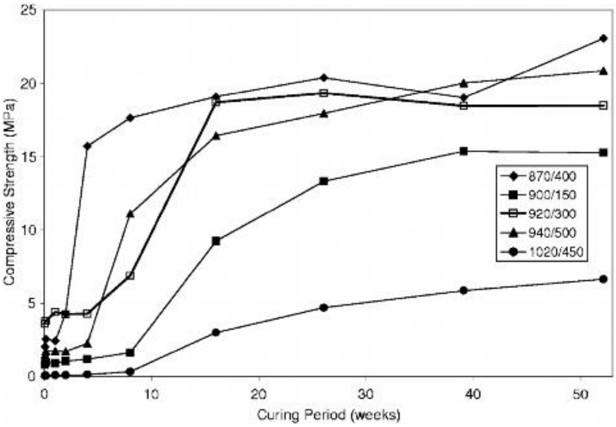

FIG. 6—*Some strength development profiles for AT-L1.*

produced the highest degree of decarbonation (Fig. 1(*a*)) so corroborating the comments of Mitchell in the 19th century that complete decarbonation produces inferior cements. However, 19th century kilns would have needed a higher temperature to ensure complete decarbonation of the total charge as a result of the large temperature profiles within the kiln. Hence, such a cement would have contained a larger proportion of over-burned product than the laboratory kiln used to produce the current cements. The higher initial strengths of AT-L1 may make it the more suitable cement for cast ornaments since it will permit very early removal of the objects from their molds. The issue of the dormant period and its relation to compositional parameters will be addressed in a future publication.

It is apparent that AT-L1 yields the highest strengths at the earliest age of 6 h and that this occurs at relatively low calcination temperatures (Fig. 8). By the age of one year, while the highest strengths remain found in low temperature cements, there is less influence of calcination conditions. The strengths are much less than are found in a modern portland cement although they compare well with strengths published by Skempton [20] for portland cements of 1860; the new cements also meet the requirements of the previously mentioned Austrian Norme (reported by Weber et al. [1]).

The optimization of PL-F104 is assisted by the consistency of its relative behavior at all ages and good quality cements may be located in the region of 780/650 to 820/400. However, AT-L1 is not so consistent and yields a different optimum when considered at an age of 6 h (920/300) rather than at later ages

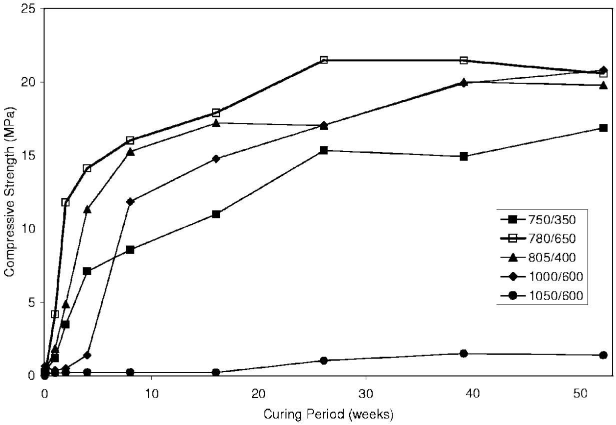

FIG. 7—*Some strength development profiles for PL-F104.*

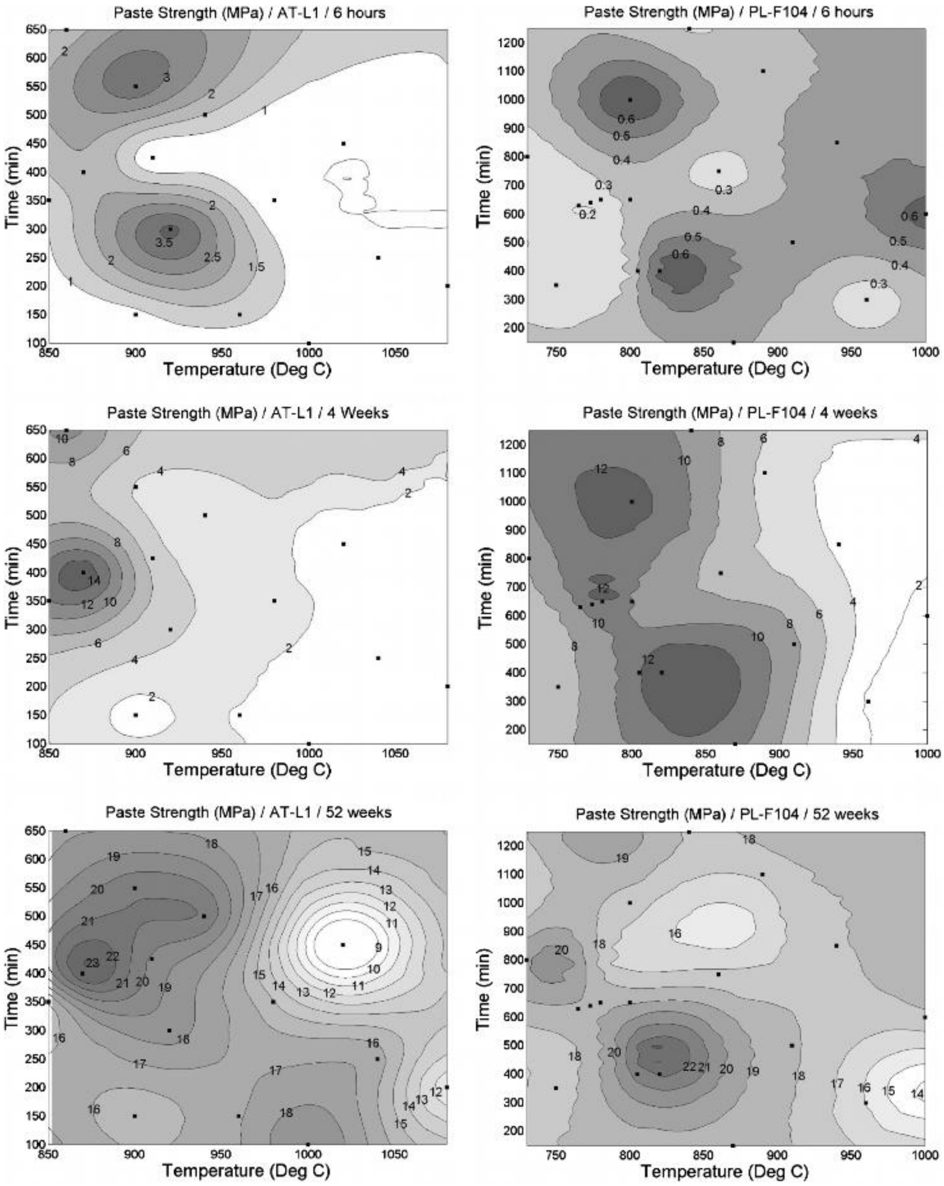

FIG. 8—*Strength data for AT-L1 and PL-F104 at three ages.*

(870/400). In the UK of the mid-19th century cement strength was assessed by building brickwork cantilevers using mortars as the binding agent; the strength being assessed by the number of bricks in the cantilever. Only a short interval was left between the addition of each brick; hence, optimum cements are likely to have been those which gave sufficient strength within a few hours rather than 28 days as used today.

Although the optimum cements (at four weeks) would indicate that AT-L1 (CI=2.03) requires a higher calcination temperature than PL-F104 (CI=1.75) it should be remembered that Eckel stated that the higher temperature for lower CI was needed to "secure perfect combination of the lime and clay." In this case, PL-F104 needs to be burned at a higher temperature to yield the same free lime content (Fig. 1(*c*)).

It was suggested in the Introduction that a conflict might exist between the advice from Eckel and Mitchell. Certainly, a high degree of calcination produces an inferior product and optimum cements have been produced at lower temperatures than the 1100–1300°C suggested by Eckel. However, the contemporary observations that calcination should be no more than necessary to nearly decarbonate the marl do not indicate a need for calcite; it reflects the composition of the belite and amorphous phases. It is apparent that the optimum PL-F014 is found in the region of maximum α'-belite with a calcite content of some 10–15 %; the content of the amorphous phase is also high. The presence, per se, of calcite does not make an actual contribution to cementitious characteristics; rather it is an indicator of a well-calcined cement. Within the prevailing kiln conditions it is likely that as the temperature was raised to achieve higher decarbonation the simultaneous transformation of more-reactive α'-belite to β-belite occurred. In addition, the presence of unreactive gehlenite would have likely increased. Work is continuing on the use of a rotary kiln to yield closer temperature control and refine the understanding of the relationship between strength, α'-belite production and decarbonation. However, the inhomogeneity of the marl source will complicate this interpretation. The optimum AT-L1 is more dependent upon optimization criteria but the previous general observations also apply. The qualitative descriptions of the early 19th century authors on calcination conditions and cement characteristics have been confirmed by this research. The comments made by Eckel should be interpreted within the realization that he does not identify the location in the kiln at which he has determined temperatures and so has not accounted for temperature gradients within the kiln.

Following the laboratory work in the small kiln, work has continued using an electric kiln with very close temperature control *within* the charge of stone fragments and using a batch size of some 260 kg. This has yielded good quality cements and will be reported elsewhere together with an evaluation of production using an oil-fired rotary kiln.

Conclusions

High quality rapid setting Roman cements have been produced in a laboratory kiln which have met with the approval of conservators within the ROCEM project. The optimum cements require low calcination temperatures and are associated with the maximum α'-belite content, a high amorphous phase of uncertain composition together with a residual calcite content indicating incomplete calcination. It has been found that the strength of the cements is more sensitive to changes in the maximum calcination temperature than changes in the residence time.

Two strength development profiles have been identified, one of which is characterized by a dormant period which may last for several weeks. A comprehensive knowledge of clay type in the original marl as well as that of the crystalline and amorphous phases is essential to understand the performance of Roman cements.

Acknowledgments

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R. Vyskocilova,[1] *W. Schwarz,*[2] *D. Mucha,*[3] *D. Hughes,*[4] *R. Kozłowski,*[3] *and J. Weber*[5]

Hydration Processes in Pastes of Roman and American Natural Cements

ABSTRACT: Hydration of five Roman and American natural cements was analyzed using X-ray diffraction, mercury intrusion porosimetry, and scanning electron microscopy of cement pastes. Two cements were prepared in the laboratory by burning marls from geological sources in Poland (Folwark) and Austria (Lilienfeld). The selection of raw materials and burning conditions were optimized so that the hydraulic nature and appearance of the final burnt materials matched as closely as possible historic Roman cements widely used in the 19th and the beginning of the 20th centuries in Europe to decorate buildings. Three other cements are produced commercially: quick setting Prompt cement from Vicat, France, and Rosendale cements from Edison Coatings Inc., USA. The hydration of the cements studied was shown to comprise two distinct stages. The immediate setting and early strength is due to the formation of calcium aluminum oxide carbonate (or sulfate) hydroxide hydrates. The development of long-term strength is brought about by the formation of calcium silicate hydrates. Similarities and differences between the individual cements are discussed.

KEYWORDS: Roman cement, natural cement, Rosendale cement, Prompt cement, hydration of cements, porosity, strength, calcium aluminate hydrates

Introduction

There is a general agreement in the historic literature and standard specifications that natural cements were highly hydraulic binders produced by calcining naturally occurring limestones rich in clay minerals below the sintering point and then grinding the burnt material to a fine powder [1,2]. The natural cements obtained could then differ both in performance requirements and applications. After around 1850, European Roman cements were principally used for the economic and easy manufacture of stuccos for the exterior of buildings. Therefore their important performance requirement, specified in the Austrian Standard of 1878 [1], was short setting time below seven minutes, especially important for casting architectural decorative details. In contrast, the ASTM Standard Specification for Natural Cement (C 10) standard of 1974 [2] specifies 30 minutes as a minimum set time, which points to additional uses of American natural cements in masonry mortars or cast-in-place concrete. Both cement types were used for masonry mortar but the slower setting of the American natural cements would have yielded a more manageable material for use by the bricklayers. The differences in performance between various historic natural cements could result from differences in geological sources exploited, different chemistry of the burnt materials, and different hydration mechanisms and strength development. It is acknowledged that while the European and American cements belong to the same family of low-energy cements, they were the subject of different specifications and nomenclature. Consequently, care must be taken when comparing and discussing the various materials. In particular, we use the term Roman cement to describe cements produced from both calcitic septarian nodules and marls. The majority of UK cements were produced from the former nodules while in continental Europe marl was the usual source. Despite this difference, the term “Roman cement” and its translation into various national languages was widely used to describe natural cements from both sources.

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[1] Faculty of Restoration, University of Pardubice, Litomysl, The Czech Republic.
[2] CAS Composite Anode Systems GmbH, Vienna, Austria.
[3] Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences, Cracow, Poland.
[4] School of Engineering, Design and Technology, University of Bradford, UK.
[5] Institute of Art and Technology, University of Applied Art, Vienna, Austria.

The convention adopted for this paper is that the term “Roman cement” is applied to European rapid-setting natural cements and “American natural cement” is applied to materials meeting the ASTM C 10 standard specification.

The present work looks at the composition and hydration of several Roman and American natural cements. Developing an insight into these differences is the principal aim of the present paper, as better understanding of the chemistry and performance of these materials is a vital condition for their proper application in conservation of historic mortars as well as for the optimization of their production.

This paper is one of three presented to the 2nd American Natural Cement Conference held in Washington DC, 30–31 March 2006. A description of production and use of Roman cements in Europe is given by Weber et al. [3]. It is based on contemporary written sources and a critical examination of the historic Roman cement mortars collected from a wide range of buildings across Europe. The second paper by Hughes et al. [4] describes the calcination of two marls from geological sources in Poland (Folwark) and Austria (Lilienfeld), together with the mineralogy and mechanical properties of the cements obtained. The paper has shown that the hydration of Roman cement pastes proceeds according to a two-step mechanism:

Step 1—Roman cement pastes harden within a few minutes after the initial set. Six-hour strength values of up to 4 MPa are obtained. This high initial strength makes the cements suitable for casting architectural details since it permits very early removal of the objects from their molds.

Step 2—After a varying dormant period, depending on the type of Roman cement, further strength development leads to high final strength values—after one year compressive strengths exceeding 20 MPa were measured. Historic Roman cement mortars, collected within the recent study [3] showed compressive strength values of up to 50 MPa.

In the present work, changes in the phase composition of Roman cements were followed during their hydration. In-situ X-ray Diffraction (XRD) of pastes [5,6] was used to follow growth of the crystalline hydrates and mercury intrusion porosimetry (MIP) to gain insight into growth of amorphous hydration products into the pore space of hardened pastes. XRD of pastes of further natural cements available commercially was performed for comparison. Correlations between changes in the phase contents and porosity structure, and the strength development were sought.

Materials and Methods

Materials

Five cements were studied. Two were Roman cements burnt in the laboratory at the School of Engineering, Design and Technology, University of Bradford, UK, as described in [4]. One cement was burnt from the Lilienfeld marl, Austria, at 920 °C for 300 min and the other from the Folwark marl, Poland, at 820 °C for 400 min. The designation of calcination parameters represents the maximum temperature and the residence time for which it was held. It should be noted that temperature gradients existed within the 5–10 kg charges of marl fragments, such that the maximum temperature within the core of the charge did not attain the “set” temperature on the kiln controls. However, the variation in temperature was an order of magnitude less than that experienced in commercial kilns. More detail may be found elsewhere [4]. The selection of raw materials and burning conditions were optimized so that the hydraulic nature and appearance of the final burnt materials matched as closely as possible features of Roman cements as they are known from archival sources or can be derived from analyses of the preserved historic Roman cement mortars [3]. Their strength development profiles were different though both attained high long-term strength and both cements were positively assessed in workshop and conservation tests.

In addition, one commercially-produced European natural cement was investigated: Prompt, supplied by Vicat, France. The burning temperature for Prompt is up to 1200 °C but covers a wide range. The Prompt cement has been produced for more than 150 years by burning marl deposits at Chartrouse in the Rhône Alps at moderate temperatures [7]. The historic mortars based on the Prompt cement attain a compressive strength of about 20 MPa [8].

Two American natural cements investigated were Rosendale Mix and R116 by Edison Coatings Inc., USA. The burning conditions for the Rosendale cements are not known. They are produced from argillaceous sedimentary rocks but with much higher dolomite contents than the European Roman cements; they are often referred to as “argillaceous dolostones.” When compared to Roman cements, they set more slowly during 20–60 min. [9]; also their strength development is rather slow. The compressive strength of historic mortars attains around 13 MPa [10]. According to the information obtained from the producer, the R116 variety was obtained from a geological layer which yielded faster setting cement and higher in strength than the standard mix cement.

Pastes of Roman cements were produced at the water-cement ratio of 0.65. This is at odds with the convention of producing pastes at a common consistency. However, with cements which set so rapidly it is impossible to achieve a static consistency since stiffening occurs as soon as the pastes have been sensibly mixed. Indeed, this rapid and dynamic characteristic meant that measurement of setting was confined to that of final set only. The value of water-cement ratio was practically determined as being that which yielded a consistency permitting the casting of the most rapidly setting pastes into the compression cylinders before their consolidation was compromised. Hence, the value of 0.65 is arbitrary on scientific grounds but does allow practical comparisons to be made. It has also turned out to be the value commonly used by conservators preparing mortars for the production of cast elements.

Methods

Wet chemical analyses to determine oxide composition of cements studied followed the procedures of the European Standard EN 196-2: 2005. X-ray diffraction was used to determine their mineralogy as described in Ref. [4].

For a qualitative evaluation of crystalline hydration products, pastes immediately after mixing were placed in sample holders and covered with a polyethylene foil to prevent evaporation of water and reaction with carbon dioxide. In-situ X-ray diffraction spectra were recorded between 8–55° 2θ at a step of 0.04° 2θ, 3 s/step for the curing time of 4 h. The method of the in-situ X-ray diffraction of cement pastes is described in detail in Refs. [5,6].

Additionally, porosity structure and strength development were determined for two Roman cements. For porosity structure measurements, prismatic specimens of 20 by 2 by 2 cm were cast in steel molds. The samples were demolded immediately after setting and cured under 100 % RH until tested. After the predetermined curing period, specimens for porosity structure measurements were taken and immediately soaked in acetone for 24 h to stop the hydration of the cementitious materials. They were placed in a rotary vacuum flask at 20°C for 4 h to remove acetone and to be dried. The porosity structure of the paste samples was determined using a Poremaster mercury intrusion porosimeter from Quantachrome, allowing the study of pore sizes in the range 440–0.0035 μm. The measurements of strength are described in Ref. [4].

Fracture surfaces (gold spattered) of the pastes of Roman cements were examined by secondary electron images under high vacuum in a scanning electron microscope (SEM) to study the morphology of hydrated products.

Results and Discussion

Chemistry and Mineralogy of the Cements Studied

The oxide and mineralogical compositions of the cements studied are given in Tables 1 and 2.

The marked difference between the European Roman cements and the Rosendale cements is high magnesium content in the latter case at the expense of calcium due to the dolomitic nature of the argillaceous dolostones.

More significant differences are revealed by the mineralogical composition of cements. It shows for all cements analyzed a considerable progress of the reactions taking place on calcinations of the marls and dolostones: the decomposition of calcite to lime and its reaction with quartz and clay decomposition products to give belite and, at higher temperatures, gehlenite. The Folwark Roman cement has mineralogical composition characteristic of comparatively low temperatures of burning. It contains still a considerable amount of undecomposed calcite and free unreacted lime which has transformed to calcium hydroxide—portlandite—by reaction with moisture contained in air. A characteristic feature is a high proportion of α' belite dominating at low calcinations, little β-belite, and no gehlenite. The Lilienfeld Roman cement and Prompt have undergone more intense calcinations as indicated by the decrease in the

TABLE 1—*Chemical composition of Roman and American natural cements investigated.*

Cements	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	LOI	Cem. Index
Folwark Roman Cement	27.9	6.9	2.5	48.2	1.6	0.6	0.3	1.5	0.4	10.0	1.7
Lilienfeld Roman Cement	29.1	9.2	3.6	46.8	1.5	<0.1	2.1	0.7	0.4	6.5	1.9
Prompt	19.1	7.1	3.3	52.8	3.5	3.7	0.6	1.6	0.4	7.7	1.1
Rosendale Mix	31.3	5.0	2.4	32.3	17.6	0.9	0.5	2.0	0.3	7.8	1.7
Rosendale R116	27.8	4.8	4.0	34.1	20.0	1.1	0.8	2.0	0.3	5.2	1.4

calcite content and increase in both β-belite and gehlenite. Small amount of brownmillerite could be unequivocally identified in Prompt by one of its strong reflections at 12.19° 2θ ($d_{020}=7.25$ nm) which does not overlap with maxima of other phases present. Prompt was found also to contain a small but clearly detectable amount of calcium aluminum sulfate oxide $Ca_4Al_6O_{12}(SO_4)$—ye'elimite, reflecting a relatively high sulfur content in the raw material. Neither crystalline ferrites nor aluminates have been detected in any of Roman cements burnt within the present study, even after a selective dissolution of free lime and silicate phases in a solution of salicylic acid in methanol (SAM) [11]. Their absence is due to low calcination temperatures at which the cements were produced. Due to more intense calcination conditions for Prompt, a particular attention was paid to a possible presence of small amounts of alite or crystalline calcium aluminates but they were below the limit of detection, at least in the sample used in the present study.

The two Rosendale cements cannot be directly compared to Roman cements and Prompt due to their different chemistry resulting from high contents of magnesium oxide—periclase—and quartz. It can be observed that the periclase content of the cements is similar for both oxide and mineralogy (Tables 1 and 2, respectively) suggesting that its recombination into new minerals is minimal at best. No maximum at 12.19° 2θ characteristic of brownmillerite was observed; however, small amounts of the phase cannot be excluded as its strongest reflection overlaps with the maxima of the two modifications of belite.

All cements contain a substantial amount of amorphous or microcrystalline products of dehydroxylation of clays and their reaction with lime.

It is apparent that in all cements a complete reaction of the original components has not occurred. Indeed, if it is assumed that all of the CaO exists only in either C_2S or C_2AS then only Prompt has the potential for combination of all of the silica into these minerals; the other cements would be expected to contain uncombined silica, most likely in the form of quartz. The cements with the least silica binding capability are those from Rosendale and the quartz content shown in Table 2 reflects the inverse of this capability. To achieve a higher degree of combination of silica and decomposition of calcite would require much more intense calcination conditions, but this would lead to the production of inferior cements [4].

TABLE 2—*Mineralogical composition of Roman and American natural cements investigated.*

	Folwark RC 820°C/400 min	Lilienfeld RC 920°C/300 min	Prompt	Rosendale Mix	Rosendale R116
Quartz	5	4	1	14	12
Calcite	16	6	14	10	7
Portlandite	10	0	3	3	2
α′-belite	36	30	13	9	15
β-belite	4	20	20	10	13
Gehlenite	…	4	4	5	5
Periclase (MgO)	…	…	3	19	25
Brownmillerite	…	…	5	…	…
Ye'elimite	…	…	2	…	…
Total Crystalline Phases	71	64	65	70	79
Amorphous Components	29	36	35	30	21

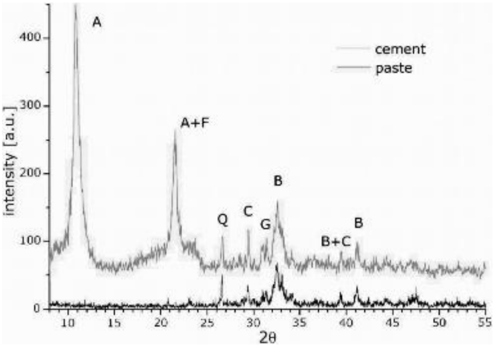

FIG. 1—*X-ray diffraction pattern of Lilienfeld Roman cement and its paste cured for four hours. A= the C-A-H phase, B=belite, BR=brownmillerite, C=calcite, E=ettringite, G=gehlenite, L=lime, P=portlandite, Pe=periclase, Y=ye'elimite. Reflection F comes from a foil covering the hydrating sample.*

Hydration Reactions

Figures 1 and 2 compare X-ray diffraction patterns of the Lilienfeld and Folwark Roman cements, respectively, with those of pastes of the same cements after four hours from the beginning of the hydration reaction. The patterns of pastes contain all reflections of crystalline phases present in the original cements. Additionally, several reflections corresponding to a hydrated AFm phase are observed. AFm phases have the general formula $[Ca_2(Al,Fe)(OH)_6]\cdot X\cdot xH_2O$, where X denotes one formula unit of a single charged anion like OH^- or Cl^-, or half a formula unit of a doubly charged anion like SO_4^{2-} or CO_3^{2-} [12]. The observed maxima matched closely calcium aluminum oxide carbonate hydroxide hydrate $2[Ca_2Al(OH)_6]\cdot 1/2CO_3\cdot OH\cdot 5.5H_2O$ in which OH^- and CO_3^{2-} serve as X anions. The compound is written in cement chemical nomenclature as $C_4A\bar{C}_{0.5}H_{12}$ where C=CaO, A=Al_2O_3, H=H_2O, $\bar{C}=CO_2$, and will be called hereafter the C-A-H phase. The structure of the compound was described by Fischer and Kuzel [13]. As for all AFm phases, the unit cell is based on a hexagonal structure with $a=0.577$ nm; c is 4.92 nm. The strongest reflections are at 10.78° 2θ ($d_{006}=0.82$ nm) and 21.66° 2θ ($d_{0012}=0.41$ nm). The amount of the C-A-H phase formed after four hours hydration differs between the two cements. In the Lilienfeld cement paste, it is formed in large quantities whereas the same reaction is less efficient for the Folwark cement. These types of C-A-H phases are commonly associated with early strength development in rapid hardening cements [5] or with the hydration and hardening of dehydroxylated clay minerals in the presence of hydrated lime [14,15]. The C-A-H phases may only be formed from amorphous or poorly-

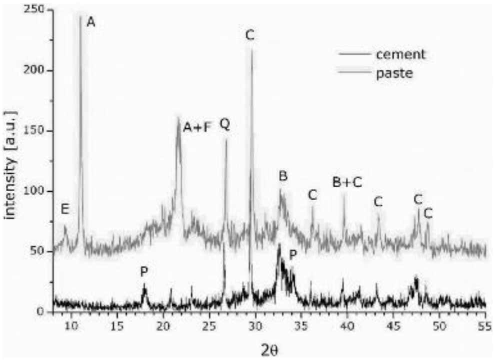

FIG. 2—*X-ray diffraction pattern of Folwark Roman cement and its paste cured for four hours. Description of diffraction maxima as in Fig. 1.*

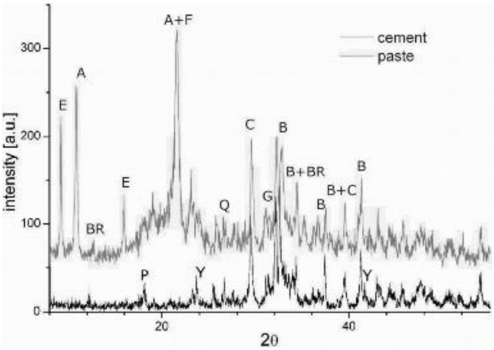

FIG. 3—*X-ray diffraction pattern of cement Prompt and its paste cured for four hours. Description of diffraction maxima as in Fig. 1.*

crystalline components of the cements as no crystalline aluminate phases like C_3A or $C_{12}A_7$ could be detected by X-ray diffraction. The nature of amorphous components and their reactions on contact with water are the subject of further investigations.

The early hydration and hardening of the Prompt cement from Vicat coincides with the formation of C-A-H and ettringite $C_6A\bar{S}_3H_{32}$ (Fig. 3). The latter phase manifests itself by its most prominent maxima at 9.1° 2θ (d_{100}=1.08 nm), 15.8° 2θ (d_{110}=0.62 nm) and 22.9° 2Θ (d_{-1-14}=0.43 nm) [16] and is due to the high SO_3 content in the Prompt cement. The presence of the C-A-H phase is somewhat unexpected; high SO_3 should rather lead to the formation of Afm-monosulfate $C_4A\bar{S}H_{12}$. Brownmillerite C_4AF, formed in the Prompt cement due to a high burning temperature, remains inert during hydration, as in Portland cements.

The Rosendale R116 sample (Fig. 4) exhibits a hydration mechanism different from the three European cements described above. Little C-A-H phase and ettringite are formed as evidenced by low intensities of their strongest diffraction maxima. The MgO (periclase) content is very high as one can see from a strong diffraction maximum at 42.9° 2θ (d_{200}=0.23 nm). The pattern for the Rosendale Mix cement is essentially identical to that of R116.

Strength Development

Strength development profiles of the two Roman cements investigated are shown in Fig. 5. Generally, they consist of three stages. Within the first six hours both pastes attain early strength which, however, is

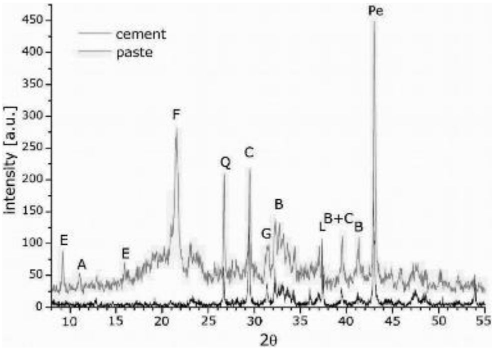

FIG. 4—*X-ray diffraction pattern of Rosendale cement R116 and its paste cured for four hours. Description of diffraction maxima as in Fig. 1.*

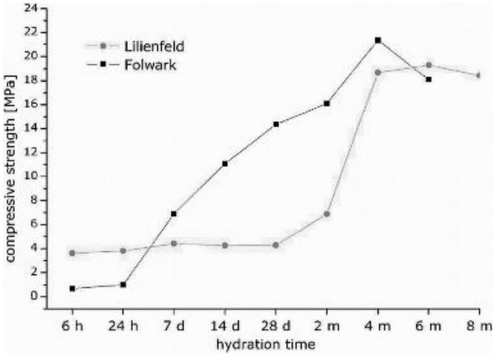

FIG. 5—*Strength development profiles of the pastes of two Roman cements studied.*

approximately five times higher for the Lilienfeld paste than for the Folwark. This first stage of hardening is followed by a dormant period which lasts in the case of the Lilienfeld cement studied for more than five weeks. In contrast, Folwark shows a negligible dormant period of no more than 24 hours. The dormant periods are followed by the accelerated strength gain to the same level of approximately 20 MPa.

Early hydration and the initial strength development coincide in the sulfate free cements with the formation of calcium aluminate hydrates C-A-H immediately after set. High content of these phases revealed in the Lilienfeld pastes results in a much higher strength when compared to the Folwark pastes in which C-A-H phases form less abundantly. The long-term strength correlates with the formation of calcium silicate hydrates—the C-S-H gel. As the latter is poorly crystallized and yields only an enhanced background in the X-ray diffraction, mercury porosimetry was used to follow the growth of the gel into the pore space of hardened cement pastes. Figure 6 compares the differential mercury intrusion curves, i.e., incremental pore volume intruded as a function of pore diameter for the pastes of Roman cements at two ages—four hours and six months. The MIP curve of the young paste exhibits a single, sharply defined peak at between 0.1 to 0.5 µm. The presence of the peak indicates a one-step intrusion of mercury into a capillary network connected to the specimen surface. It corresponds to the minimum throat dimension of this network—the threshold diameter according to Ref. [17]. The size of throats is clearly characteristic of the structure produced by the growth of the C-A-H phases in the pastes. For the long curing time of six months, the initial peak shifts to smaller pore sizes around 0.02 µm. It is assumed that the process involves blocking the larger pores by the formation of the C-S-H gel, as the pore sizes agree well with the "gel" porosity given in literature [18]. Furthermore, the gel formation is well visible on the SEM micrographs examples of which are shown in Fig. 7.

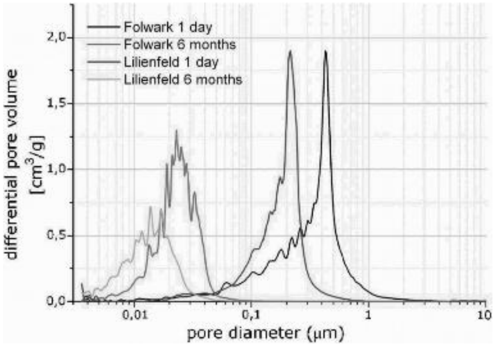

FIG. 6—*Pore size distribution of the pastes of two Roman cements at two ages—four hours and six months. (See color insert for color version of this figure).*

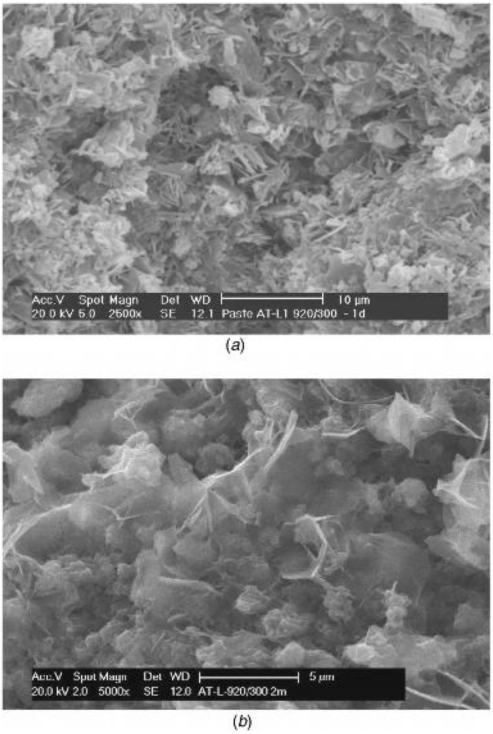

FIG. 7—*SEM micrographs of the pastes of Roman cements cured for one day (a) and two months (b).*

The formation of the C-S-H gel, correlating with the change in paste porosities, accounts for the long-term strength development by Roman cements. The process is, however, preceded by dormant periods of varying duration. The preparation of cements of a consistent grading should minimize any affect of particle size on the rate of hydration of the calcium silicates and further investigations are being carried out to clarify the mechanism accounting for the dormant periods.

Conclusions

Generally, the hydration of the Roman and American natural cements studied involves two principal reactions:

- formation of crystalline calcium aluminum oxide carbonate (or sulfate) hydroxide hydrates. They account for the initial fast setting of pastes and mortars, relatively high initial strengths (2–5 MPa) and a characteristic porosity having the threshold pore diameter between 0.1–0.5 μm.
- formation of a C-S-H gel of a dense microstructure. It accounts for a long-term strength development and a porosity concentrated around the threshold pore diameter of 0.02 μm.

In light of the above hydration mechanism, the two laboratory-burnt Roman cements and the Prompt cement are very similar, while the Rosendale cements show different hydration behavior. They yield very little of the C-A-H phases and their main crystalline components are inert in the early hydration process. The high amount of MgO (periclase) can have an influence on the hydration process which remains still to be elucidated.

The hydration mechanism described accounts for the main features of the European Roman cements—quick setting, combined with high initial and long-term strength. These features made them favored materials for economic and easy manufacture of the renders and stuccos for the exterior of buildings in the

19th and early 20th centuries and guide the present attempts to re-establish their manufacture and use in conservation practice.

Acknowledgments

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SUPPLEMENTAL MATERIALS

Designation: C 10 – 06

Standard Specification for Natural Cement[1]

This standard is issued under the fixed designation C 10; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification covers natural cement.

NOTE 1—Examples of typical past uses of natural cement include unit masonry mortar, cement plaster, grout, lime-wash, and concrete.

1.2 For properties where values are given in both SI and non-SI units, the values in SI units are to be regarded as the standard. Values in SI units shall be obtained by measurement in SI units or by appropriate conversion, using the Rules for Conversion and Rounding given in IEEE/ASTM SI 10, of measurements made in other units.

1.3 The text of this standard references notes and footnotes which provide explanatory material. These notes and footnotes (excluding those in tables and figures) shall not be considered as requirements of the standard.

2. Referenced Documents

2.1 *ASTM Standards:* [2]

C 109/C 109M Test Method for Compressive Strength of Hydraulic Cement Mortars(Using 2-in. or [50-mm] Cube Specimens)
C 114 Test Methods for Chemical Analysis of Hydraulic Cement
C 150 Specification for Portland Cement
C 151 Test Method for Autoclave Expansion of Hydraulic Cement
C 183 Practice for Sampling and the Amount of Testing of Hydraulic Cement
C 185 Test Method for Air Content of Hydraulic Cement Mortar
C 187 Test Method for Normal Consistency of Hydraulic Cement
C 188 Test Method for Density of Hydraulic Cement
C 191 Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle
C 204 Test Methods for Fineness of Hydraulic Cement by Air-Permeability Apparatus
C 219 Terminology Relating to Hydraulic Cement
C 305 Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency
C 465 Specification for Processing Additions for Use in the Manufacture of Hydraulic Cements
C 778 Specification for Standard Sand
C 786 Test Method for Fineness of Hydraulic Cement and Raw Materials by the 300-µm (No. 50), 150-µm (No. 100), and 75-µm (No. 200) Sieves by Wet Methods
IEEE/ASTM SI 10 Standard for Use of the International System of Units (SI): The Modern Metric System

3. Terminology

3.1 For definitions of terms related to this specification, see Terminology C 219.

4. Ordering Information

4.1 Orders for material under this specification shall include the following:

4.1.1 This specification number and date, and

4.1.2 Optional physical requirements as given in 7.2.

5. Additions

5.1 The cement covered by this specification shall contain no addition except as follows:

5.1.1 Water, or calcium sulfate, or both.

5.1.2 Processing additions used in the manufacture of the cement shall have been shown to meet the requirements of Specification C 465 in the amounts used or greater.

6. Chemical Requirements

6.1 Natural cements shall conform to the standard chemical requirements in Table 1.

7. Physical Requirements

7.1 Natural cements shall conform to the respective standard physical requirements prescribed in Table 1.

7.2 In order to match historic cements, at the option of the purchaser, the required values for % retention on the 300-µm (N0. 50), 150-µm (No. 100), and 75-µm (No. 200) sieves, or of air permeability fineness shall be agreed at time of placing the order.

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[1] This test method is under the jurisdiction of ASTM Committee C01 on Cement and is the direct responsibility of Subcommittee C01.10 on Hydraulic Cements for General Concrete Construction.

Current edition approved Sept. 1, 2006. Published September 2006. Originally approved in 1904. Last previous edition approved in 1976 as C 10 – 76.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

TABLE 1 Standard Requirements

	Applicable Test Methods	Requirements
Chemical Requirements		
Loss on ignition, max, %:	C 114	12
Insoluble residue, min, %:	C 114	2
Sulfur trioxide (SO_3), max, %:	C 114	3.0
Physical Requirements		
Autoclave length change, max, %:	C 151, as modified in 10.1.4	0.80
Fineness, m^2/kg or % retained:	C 204 or C 786	[A]
Time of setting, Vicat test[B]:	C 191	
Time in minutes, not less than		30
Air content of mortar[C], volume %:	C 185	
max		12
Compressive strength, min, MPa (psi):	C 109/C 109M, as modified in 10.1.7	
7 days		3.5 (510)
28 days		7.0 (1020)

[A] The fineness shall be chosen at the option of the purchaser as per 7.2.

[B] The time of setting is that described as initial setting time in Test Method C 191.

[C] Compliance with the requirements of this specification does not necessarily ensure that the desired air content will be obtained in concrete.

NOTE 2—If no data on historic cement fineness are available, the purchaser may wish to consider that previous editions of this specification from 1904 to 1976 required minimum values as follows:

1954-1976: Minimum 550 m^2/kg fineness (air-permeability method)
1937-1954: Maximum 15% retained on a 75-µm (No. 200) sieve
1904-1937: Maximum 10% retained on a 150-µm (No. 100) sieve, maximum 30 % retained on a 75-µm (No. 200) sieve

8. Acceptance and Rejection

8.1 Natural cement meets the strength requirements of this standard if the 7-day strength exceeds the minimum in Table 1. The cement also meets the strength requirements of this standard if the cement fails the 7-day strength minimum, but exceeds the 28-day strength minimum in Table 1.

8.2 If the cement fails an initial test for autoclave expansion, it meets the requirements of this standard if it passes on a second and third series of test specimens.

8.3 The cement shall be rejected if it fails to meet any of the requirements of this specification, subject to the provisions of 8.1 and 8.2.

8.4 Re-test cement remaining in storage for a period longer than six months after initial test. Reject it if it fails to meet any of the requirements of this specification at that time.

8.5 Tentative or provisional acceptance of the cement shall not deprive the purchaser of the right of rejection in the event final tests or retests fail to meet applicable requirements.

8.6 At the option of the purchaser, packages more than 2 % below the mass marked thereon shall be rejected and if the average mass of packages in any shipment, as shown by determining the mass of 50 packages selected at random, is less than that marked on the packages, the entire shipment shall be rejected.

9. Packaging and Package Marking

9.1 When the cement is delivered in packages, the words "Natural Cement," the name and brand of the manufacturer, and the mass of the cement contained therein, shall be plainly indicated on each package. Similar information shall be provided in the shipping documents accompanying the shipment of packaged or bulk cement. All packages shall be in good condition at the time of inspection.

10. Test Methods

10.1 Sample the cement and determine the properties enumerated in this specification in accordance with the following ASTM methods:

10.1.1 *Sampling*—Practice C 183.

10.1.2 *Chemical Analysis*—Test Methods C 114.

10.1.3 *Fineness*—One of the following test methods shall be used:

10.1.3.1 Test Method C 204. In this fineness determination, the specific gravity of natural cement shall be considered to be 2.90. Tests shall be made at a porosity of 0.530 ± 0.005. In case of dispute, the true specific gravity used shall be as determined in accordance with Test Method C 188.

10.1.3.2 Test Method C 786.

10.1.4 *Autoclave Expansion*—Test Method C 151 with the following modification:

10.1.4.1 The cement used in preparing the test specimens shall be a blend of 75 weight percent of the natural cement to be tested with 25 weight percent of portland cement conforming to the requirements of Type II cement in Specification C 150.

10.1.4.2 The natural cement and the portland cement shall be dry mixed to a uniform blend before water is added.

10.1.5 *Time of Setting*—Test Method C 191.

10.1.6 *Air Content of Mortar*—Test Method C 185. In this air content determination, the specific gravity of natural cement shall be considered to be 2.90. In case of dispute, the true specific gravity used shall be as determined in accordance with Test Method C 188.

10.1.7 *Compressive Strength*—The compressive strength shall be determined for mortar cubes prepared as follows:

10.1.7.1 The proportions shall be one part of cement to one part of standard sand by mass. The amount of mixing water is based on the amount of water required to produce a neat cement paste of normal consistency from the same sample of cement according to Test Method C 187. Calculate the percentage of water required as follows:

$$y = \frac{P}{3} + 6.5$$

where:

y = water required for the mortar as a percentage of the combined mass of cement and sand, and

P = water needed for normal consistency, percent by mass of cement.

10.1.7.2 The standard sand shall be 20-30 sand conforming to Specification C 778.

10.1.7.3 The mortar shall be mixed in accordance with Practice C 305. The quantities of materials to be mixed at one time in the batch of mortar for making six and nine test specimens shall be as follows:

	Number of Specimens	
	6	9
Cement, g	900	1335
Sand, g	900	1335
Water, mL	18y	26.7y

10.1.7.4 The 2-in. (50-mm) cube specimens shall be molded and tested in accordance with Test Method C 109/C 109M.

11. Keywords

11.1 hydraulic cement; natural cement; specification

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REPORT OF COMMITTEE C ON STANDARD SPECIFICATIONS FOR CEMENT.

GENERAL OBSERVATIONS.

1. These remarks have been prepared with a view of pointing out the pertinent features of the various requirements and the precautions to be observed in the interpretation of the results of the tests.

2. The Committee would suggest that the acceptance or rejection under these specifications be based on tests made by an experienced person having the proper means for making the tests.

SPECIFIC GRAVITY.

3. Specific gravity is useful in detecting adulteration or underburning. The results of tests of specific gravity are not necessarily conclusive as an indication of the quality of a cement, but when in combination with the results of other tests may afford valuable indications.

FINENESS.

4. The sieves should be kept thoroughly dry.

TIME OF SETTING.

5. Great care should be exercised to maintain the test pieces under as uniform conditions as possible. A sudden change or wide range of temperature in the room in which the tests are made, a very dry or humid atmosphere, and other irregularities vitally affect the rate of setting.

TENSILE STRENGTH.

6. Each consumer must fix the minimum requirements for tensile strength to suit his own conditions. They shall, however, be within the limits stated.

CONSTANCY OF VOLUME.

7. The tests for constancy of volume are divided into two classes, the first normal, the second accelerated. The latter should be regarded as a precautionary test only, and not infallible. So many conditions enter into the making and interpreting of it that it should be used with extreme care.

8. In making the pats the greatest care should be exercised to avoid initial strains due to molding or to too rapid drying-out during the first twenty-four hours. The pats should be preserved under the most uniform conditions possible, and rapid changes of temperature should be avoided.

9. The failure to meet the requirements of the accelerated tests need not be sufficient cause for rejection. The cement may, however, be held for twenty-eight days, and a retest made at the end of that period. Failure to meet the requirements at this time should be considered sufficient cause for rejection, although in the present state of our knowledge it cannot be said that such failure necessarily indicates unsoundness, nor can the cement be considered entirely satisfactory simply because it passes the tests.

STANDARD SPECIFICATIONS FOR CEMENT.

GENERAL CONDITIONS.

1. All cement shall be inspected.

2. Cement may be inspected either at the place of manufacture or on the work.

3. In order to allow ample time for inspecting and testing, the cement should be stored in a suitable weather-tight building having the floor properly blocked or raised from the ground.

4. The cement shall be stored in such a manner as to permit easy access for proper inspection and identification of each shipment.

5. Every facility shall be provided by the Contractor and a period of at least twelve days allowed for the inspection and necessary tests.

6. Cement shall be delivered in suitable packages with the brand and name of manufacturer plainly marked thereon.

7. A bag of cement shall contain 94 pounds of cement net. Each barrel of Portland cement shall contain 4 bags, and each barrel of natural cement shall contain 3 bags of the above net weight.

8. Cement failing to meet the seven-day requirements may be held awaiting the results of the twenty-eight day tests before rejection.

9. All tests shall be made in accordance with the methods proposed by the Committee on Uniform Tests of Cement of the American Society of Civil Engineers, presented to the Society January 21, 1903, and amended January 20, 1904, with all subsequent amendments thereto. (See addendum to these specifications.)

10. The acceptance or rejection shall be based on the following requirements:

NATURAL CEMENT.

11. *Definition.* This term shall be applied to the finely pulverized product resulting from the calcination of an argillaceous limestone at a temperature only sufficient to drive off the carbonic acid gas.

SPECIFIC GRAVITY.

12. The specific gravity of the cement thoroughly dried at 100° C., shall be not less than 2.8.

FINENESS.

13. It shall leave by weight a residue of not more than 10% on the No. 100, and 30% on the No. 200 sieve.

TIME OF SETTING.

14. It shall develop initial set in not less than ten minutes, and hard set in not less than thirty minutes, nor more than three hours.

TENSILE STRENGTH.

15. The minimum requirements for tensile strength for briquettes one inch square in cross section shall be within the following limits, and shall show no retrogression in strength within the periods specified: *

Age.	*Neat Cement.*	*Strength.*
24 hours in moist air		50–100 lbs.
7 days (1 day in moist air, 6 days in water)		100–200 "
28 days (1 " " " 27 " ")		200–300 "
	One Part Cement, Three Parts Standard Sand.	
7 days (1 day in moist air, 6 days in water)		25– 75 "
28 days (1 " " " 27 " ")		75–150 "

CONSTANCY OF VOLUME.

16. Pats of neat cement about three inches in diameter, one-half inch thick at centre, tapering to a thin edge, shall be kept in moist air for a period of twenty-four hours.

(*a*) A pat is then kept in air at normal temperature.

(*b*) Another is kept in water maintained as near 70° F. as practicable.

---

* For example the minimum requirement for the twenty-four hour neat cement test should be some specified value within the limits of 50 and 100 pounds, and so on for each period stated.

17. These pats are observed at intervals for at least 28 days, and, to satisfactorily pass the tests, should remain firm and hard and show no signs of distortion, checking, cracking or disintegrating.

PORTLAND CEMENT

18. *Definition.* This term is applied to the finely pulverized product resulting from the calcination to incipient fusion of an intimate mixture of properly proportioned argillaceous and calcareous materials, and to which no addition greater than 3% has been made subsequent to calcination.

SPECIFIC GRAVITY.

19. The specific gravity of the cement, thoroughly dried at 100° C., shall be not less than 3.10.

FINENESS.

20. It shall leave by weight a residue of not more than 8% on the No. 100, and not more than 25% on the No. 200 sieve.

TIME OF SETTING.

21. It shall develop initial set in not less than thirty minutes, but must develop hard set in not less than one hour, nor more than ten hours.

TENSILE STRENGTH.

22. The minimum requirements for tensile strength for briquettes one inch square in section shall be within the following limits, and shall show no retrogression in strength within the periods specified:*

Age.	*Neat Cement.*	*Strength.*
24 hours in moist air		150–200 lbs.
7 days(1 day in moist air, 6 days in water)		450–550 "
28 days(1 " " " 27 " ")		550–650 "

---

* For example the minimum requirement for the twenty-four hour neat cement test should be some specified value within the limits of 150 and 200 pounds, and so on for each period stated.

One Part Cement, Three Parts Standard Sand.

7 days (1 day in moist air, 6 days in water) 150–200 lbs.
28 days (1 " " " 27 " ") 200–300 "

CONSTANCY OF VOLUME.

23. Pats of neat cement about three inches in diameter, one-half inch thick at the centre, and tapering to a thin edge, shall be kept in moist air for a period of twenty-four hours.

(*a*) A pat is then kept in air at normal temperature and observed at intervals for at least 28 days.

(*b*) Another pat is kept in water maintained as near 70° F. as practicable, and observed at intervals for at least 28 days.

(*c*) A third pat is exposed in any convenient way in an atmosphere of steam, above boiling water, in a loosely closed vessel for five hours.

24. These pats, to satisfactorily pass the requirements, shall remain firm and hard and show no signs of distortion, checking, cracking or disintegrating.

SULPHURIC ACID AND MAGNESIA.

25. The cement shall not contain more than 1.75% of anhydrous sulphuric acid (SO_3), nor more than 4% of magnesia (MgO).

Submitted on behalf of the committee.

GEORGE F. SWAIN, *Chairman.*
GEORGE S. WEBSTER, *Vice-Chairman.*
RICHARD L. HUMPHREY, *Secretary.*

F. H. Bainbridge.
Booth, Garrett & Blair.
C. W. Boynton.
Spencer Cosby.
A. W. Dow.
L. Henry Dumary.
A. F. Gerstell.
Edward M. Hagar.
W. H. Harding.
Olaf Hoff.
Lathbury and Spackman.
Robert W. Lesley.
F. H. Lewis.
John B. Lober.
Andreas Lundteigen.
Charles F. McKenna.
W. W. Maclay.
Charles A. Matcham.
Spencer B. Newberry.
J. M. Porter.
Joseph T. Richards.
Clifford Richardson.
L. C. Sabin.
Harry J. Seaman.
S. S. Voorhees.

American Institute of Architects, W. S. Eames, *President.*
American Railway Engineering and Maintenance of Way Association, H. G. Kelly, *Vice-President.*

ADDENDUM.

ABSTRACT OF METHODS RECOMMENDED BY THE SPECIAL COMMITTEE ON UNIFORM TESTS OF CEMENT OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS.

SAMPLING.

1.—*Selection of Sample.*—The sample shall be a fair average of the contents of the package; it is recommended that, where conditions permit, one barrel in every ten be sampled.

2.—All samples should be passed through a sieve having twenty meshes per linear inch, in order to break up lumps and remove foreign material; this is also a very effective method for mixing them together in order to obtain an average. For determining the characteristics of a shipment of cement, the individual samples may be mixed and the average tested; where time will permit, however, it is recommended that they be tested separately.

3.—*Method of Sampling.*—Cement in barrels should be sampled through a hole made in the center of one of the staves, midway between the heads, or in the head, by means of an auger or a sampling iron similar to that used by sugar inspectors. If in bags, it should be taken from surface to center.

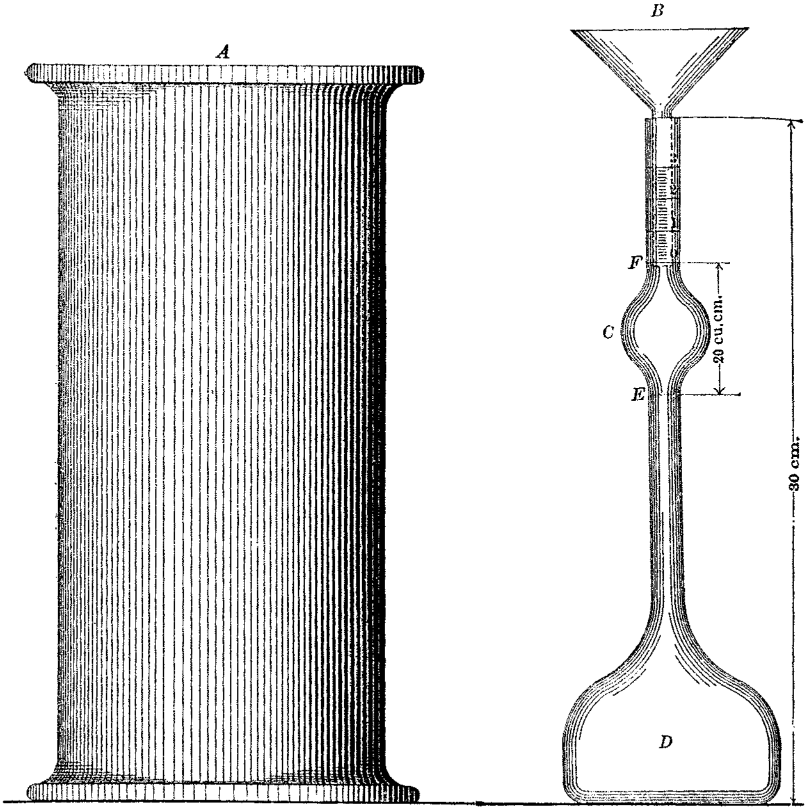
CHEMICAL ANALYSIS.

4.—*Method.*—As a method to be followed for the analysis of cement, that proposed by the Committee on Uniformity in the Analysis of Materials for the Portland Cement Industry, of the New York Section of the Society for Chemical Industry, and published in the *Journal* of the Society for January 15, 1902, is recommended.

SPECIFIC GRAVITY.

5.—*Apparatus and Method.*—The determination of specific gravity is most conveniently made with Le Chatelier's apparatus. This consists of a flask (*D*), Fig. 1, of 120 cu. cm. (7.32 cu. ins.) capacity, the neck of which is about 20 cm. (7.87 ins.) long; in the middle of this neck is a bulb (*C*), above and below which are two marks (*F*) and (*E*); the volume between these marks is 20 cu. cm. (1.22 cu. ins.). The neck has a diameter of about 9 mm. (0.35 in.), and is graduated into tenths of cubic centimeters above the mark (*F*).

6.—Benzine (62° Baumé naphtha), or kerosene free from water should be used in making the determination



LE CHATELIER S SPECIFIC GRAVITY APPARATUS.
FIG. 1.

7.—The specific gravity can be determined in two ways:

(1) The flask is filled with either of these liquids to the lower mark (*E*), and 64 gr. (2.25 oz.) of powder, previously dried at 100° C. (212° F) and cooled to the temperature of the liquid, is gradually introduced through the funnel (*B*) [the stem of which extends into the flask to the top of the bulb (*C*)], until the upper mark (*F*) is reached. The difference in weight between the cement remaining and the original quantity (64 gr.) is the weight which has displaced 20 cu. cm.

8.—(2) The whole quantity of the powder is introduced, and the level of the liquid rises to some division of the graduated neck. This reading plus 20 cu. cm. is the volume displaced by 64 gr. of the powder.

9.—The specific gravity is then obtained from the formula:

$$\text{Specific Gravity} = \frac{\text{Weight of Cement}}{\text{Displaced Volume.}}$$

10.—The flask, during the operation, is kept immersed in water in a jar (*A*), in order to avoid variations in the temperature of the liquid. The results should agree within 0.01.

11.—A convenient method for cleaning the apparatus is as follows: The flask is inverted over a large vessel, preferably a glass jar, and shaken vertically until the liquid starts to flow freely; it is then held still in a vertical position until empty; the remaining traces of cement can be removed in a similar manner by pouring into the flask a small quantity of clean liquid and repeating the operation.

FINENESS.

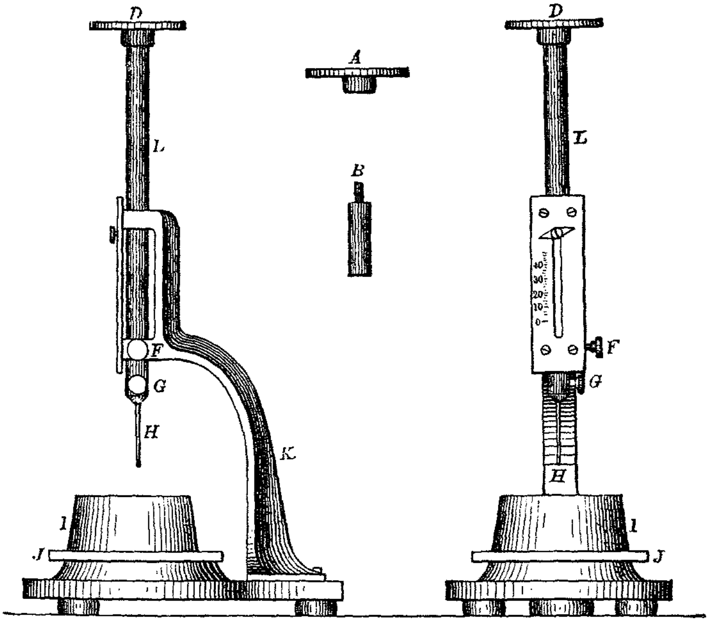
12.—*Apparatus.*—The sieves should be circular, about 20 cm. (7.87 ins.) in diameter, 6 cm. (2.36 ins.) high, and provided with a pan. 5 cm. (1.97 ins.) deep, and a cover.

13.—The wire cloth should be woven (not twilled) from brass wire having the following diameters:

No. 100, 0.0045 in.; No. 200, 0.0024 in.

14.—This cloth should be mounted on the frames without distortion; the mesh should be regular in spacing and be within the following limits:

No. 100, 96 to 100 meshes to the linear inch.
No. 200, 188 to 200 " " " "



VICAT NEEDLE.
FIG. 2.

15.—Fifty gram (1.76 oz.) or 100 gr. (3.52 oz.) should be used for the test, and dried at a temperature of 100° C. (212° F.) prior to sieving.

16.—*Method.*—The thoroughly dried and coarsely screened sample is weighed and placed on the No. 200 sieve, which, with pan and cover attached, is held in one hand in a slightly inclined position, and moved forward and backward, at the same time striking the side gently with the palm of the other hand, at the rate of about 200 strokes per minute. The operation is continued until not more than one-tenth of 1 per cent passes through after one minute of continuous sieving. The residue is weighed, then placed on the No. 100 sieve and the operation repeated. The work may be expedited by placing in the sieve a small quantity of large shot. The results should be reported to the nearest tenth of 1 per cent.

NORMAL CONSISTENCY.

17.—*Method.*—This can best be determined by means of *Vicat Needle Apparatus*, which consists of a frame (*K*), Fig. 2, bearing a movable rod (*L*), with the cap (*A*) at one end, and at the other the cylinder (*B*), 1 cm. (0.39 in.) in diameter, the cap, rod and cylinder weighing 300 gr. (10.58 oz.). The rod, which can be held in any desired position by a screw (*F*), carries an indicator, which moves over a scale (graduated to centimeters) attached to the frame (*K*). The paste is held by a conical, hard-rubber ring (*I*), 7 cm. (2.76 ins.) in diameter at the base, 4 cm. (1.57 ins.) high, resting on a glass plate (*J*). about 10 cm. (3.94 ins.) square.

18.—In making the determination, the same quantity of cement as will be subsequently used for each batch in making the briquettes (but not less than 500 grams) is kneaded into a paste, as described in paragraph 39, and quickly formed into a ball with the hands, completing the operation by tossing it six times from one hand to the other, maintained 6 ins. apart; the ball is then pressed into the rubber ring, through the larger opening, smoothed off. and placed (on its large end) on a glass plate and the smaller end smoothed off with a trowel; the paste, confined in the ring. resting on the plate, is placed under the rod bearing the cylinder, which is brought in contact with the surface and quickly released.

19.—The paste is of normal consistency when the cylinder penetrates to a point in the mass 10 mm. (0.39 in.) below the top of the ring. Great care must be taken to fill the ring exactly to the top.

20.—The trial pastes are made with varying percentages of water until the correct consistency is obtained

NOTE. The Committee on Standard Specifications inserts the following table for temporary use to be replaced by one to be devised by the Committee of the American Society of Civil Engineers.

PERCENTAGE OF WATER FOR STANDARD MIXTURES.

Neat	1-1	1-2	1-3	1-4	1-5	Neat	1-1	1-2	1-3	1-4	1-5
18	12.0	10.0	9.0	8.4	8.0	33	17.0	13.3	11.5	10.4	9.6
19	12.3	10.2	9.2	8.5	8.1	34	17.3	13.6	11.7	10.5	9.7
20	12.7	10.4	9.3	8.7	8.2	35	17.7	13.8	11.8	10.7	9.9
21	13.0	10.7	9.5	8.8	8.3	36	18.0	14.0	12.0	10.8	10.0
22	13.3	10.9	9.7	8.9	8.4	37	18.3	14.2	12.2	10.9	10.1
23	13.7	11.1	9.8	9.1	8.5	38	18.7	14.4	12.3	11.1	10.2
24	14.0	11.3	10.0	9.2	8.6	39	19.0	14.7	12.5	11.2	10.3
25	14.3	11.6	10.2	9.3	8.8	40	19.3	14.9	12.7	11.3	10.4
26	14.7	11.8	10.3	9.5	8.9	41	19.7	15.1	12.8	11.5	10.5
27	15.0	12.0	10.5	9.6	9.0	42	20.0	15.3	13.0	11.6	10.6
28	15.3	12.2	10.7	9.7	9.1	43	20.3	15.6	13.2	11.7	10.7
29	15.7	12.5	10.8	9.9	9.2	44	20.7	15.8	13.3	11.9	10.8
30	16.0	12.7	11.0	10.0	9.3	45	21.0	16.0	13.5	12.0	11.0
31	16.3	12.9	11.2	10.1	9.4	46	21.3	16.1	13.7	12.1	11.1
32	16.7	13.1	11.3	10.3	9.5						

	1 to 1	1 to 2	1 to 3	1 to 4	1 to 5
Cement	500	333	250	200	167
Sand	500	666	750	800	833

TIME OF SETTING.

21.—*Method.*—For this purpose the Vicat Needle, which has already been described in paragraph 17, should be used.

22.—In making the test, a paste of normal consistency is molded and placed under the rod (*L*), Fig. 2, as described in paragraph 18; this rod, bearing the cap (*D*) at one end and the needle (*H*), 1 mm. (0.039 in.) in diameter, at the other, weighing 300 gr. (10.58 oz.). The needle is then carefully brought in contact with the surface of the paste and quickly released.

23.—The setting is said to have commenced when the needle ceases to pass a point 5 mm. (0.20 in.) above the upper surface of the glass plate, and is said to have terminated the moment the needle does not sink visibly into the mass.

24.—The test pieces should be stored in moist air during the test; this is accomplished by placing them on a rack over water contained in a pan and covered with a damp cloth, the cloth to be kept away from them by means of a wire screen; or they may be stored in a moist box or closet.

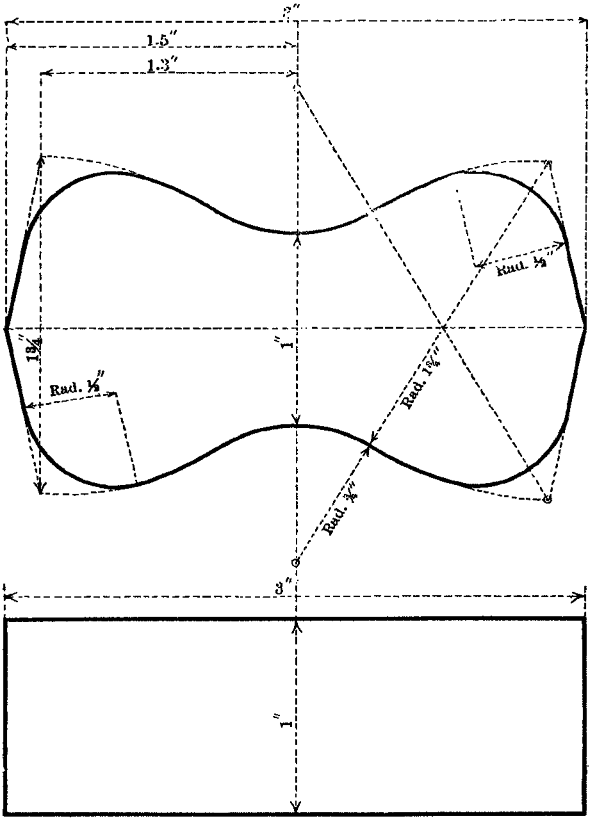
25.—Care should be taken to keep the needle clean, as the collection of cement on the sides of the needle retards the penetration, while cement on the point reduces the area and tends to increase the penetration.

26.—The determination of the time of setting is only approximate, being materially affected by the temperature of the mixing water, the temperature and humidity of the air during the test, the percentage of water used, and the amount of molding the paste receives.

STANDARD SAND.

27.—For the present, the Committee recommends the natural sand from Ottawa, Ill., screened to pass a sieve having 20 meshes per linear inch and retained on a sieve having 30 meshes per linear inch; the wires to have diameters of 0.0165 and 0.0112 in., respectively, *i. e.*, half the width of the opening in each case. Sand having passed the No. 20 sieve shall be considered standard when not more than 1 per cent passes a No. 30 sieve after one minute continuous sifting of a 500-gram sample.

28.—The Sandusky Portland Cement Company, of Sandusky, Ohio, has agreed to undertake the preparation of this sand and to furnish it at a price only sufficient to cover the actual cost of preparation.



DETAILS FOR BRIQUETTE.

FIG. 3.

FORM OF BRIQUETTE.

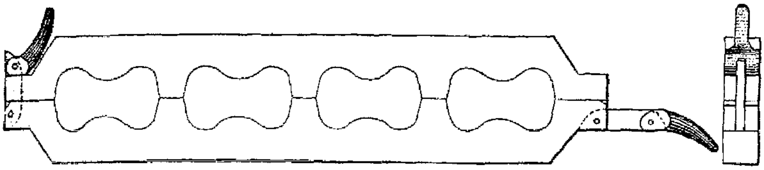
29.—While the form of the briquette recommended by a former Committee of the Society is not wholly satisfactory, this Committee is not prepared to suggest any change, other than rounding off the corners by curves of ½-in. radius, Fig. 3.

MOLDS.

30.—The molds should be made of brass, bronze or some equally non-corrodible material, having sufficient metal in the sides to prevent spreading during molding.

31.—Gang molds, which permit molding a number of briquettes at one time, are preferred by many to single molds; since the greater quantity of mortar that can be mixed tends to produce greater uniformity in the results. The type shown in Fig. 4 is recommended.

32.—The molds should be wiped with an oily cloth before using.



DETAILS FOR GANG MOULD.

FIG. 4.

MIXING.

33.—All proportions should be stated by weight; the quantity of water to be used should be stated as a percentage of the dry material.

34.—The metric system is recommended because of the convenient relation of the gram and the cubic centimeter.

35.—The temperature of the room and the mixing water should be as near 21° C. (70° F.) as it is practicable to maintain it.

36.—The sand and cement should be thoroughly mixed dry. The mixing should be done on some non-absorbing surface, preferably plate glass. If the mixing must be done on an absorbing surface it should be thoroughly dampened prior to use.

37.—The quantity of material to be mixed at one time depends on the number of test pieces to be made; about 1,000 gr. (35.28 oz.) makes a convenient quantity to mix, especially by hand methods.

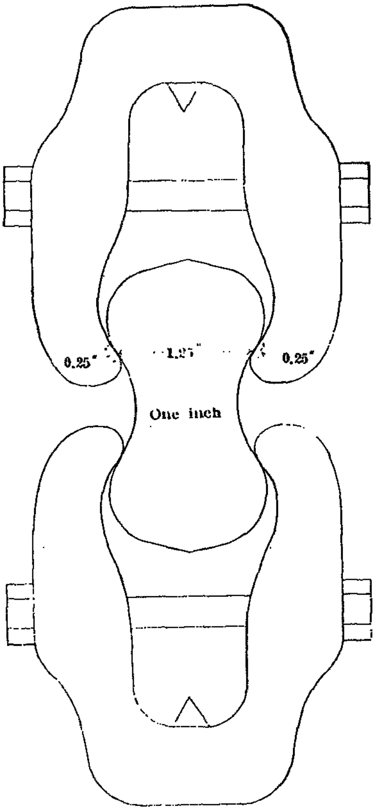
38.—*Method.*—The material is weighed and placed on the mixing table, and a crater formed in the center, into which the proper percentage of clean water is poured; the material on the outer edge is turned into the crater by the aid of a trowel. As soon as the water has been absorbed, which should not require more than one minute, the operation is completed by vigorously kneading with the hands for an additional 1½ minutes, the process being similar to that used in kneading dough. A sand-glass affords a convenient guide for the time of kneading. During the operation of mixing, the hands should be protected by gloves, preferably of rubber.

MOLDING.

39.—Having worked the paste or mortar to the proper consistency, it is at once placed in the molds by hand.

40.—*Method.*—The molds should be filled at once, the material pressed in firmly with the fingers and smoothed off with a trowel without ramming; the material should be heaped up on the upper surface of the mold, and, in smoothing off, the trowel should be drawn over the mold in such a manner as to exert a moderate pressure on the excess material. The mold should be turned over and the operation repeated.

41.—A check upon the uniformity of the mixing and molding is afforded by weighing the briquettes just prior to immersion, or upon removal from the moist closet. Briquettes which vary in weight more than 3 per cent from the average should not be tested.



FORM OF CLIP.
FIG. 5.

STORAGE OF THE TEST PIECES.

42.—During the first 24 hours after molding, the test pieces should be kept in moist air to prevent them from drying out.

43.—A moist closet or chamber is so easily devised that the use of the damp cloth should be abandoned if possible. Covering the test pieces with a damp cloth is objectionable, as commonly used, because the cloth may dry out unequally, and in consequence the test pieces are not all maintained under the same condition. Where a moist closet is not available, a cloth may be used and kept uniformly wet by immersing the ends in water. It should be kept from direct contact with the test pieces by means of a wire screen or some similar arrangement.

44.—A moist closet consists of a soapstone or slate box, or a metal-lined wooden box—the metal lining being covered with felt and this felt kept wet. The bottom of the box is so constructed as to hold water, and the sides are provided with cleats for holding glass shelves on which to place the briquettes. Care should be taken to keep the air in the closet uniformly moist.

45.—After 24 hours in moist air, the test pieces for longer periods of time should be immersed in water maintained as near 21° C. (70° F.) as practicable; they may be stored in tanks or pans, which should be of non-corrodible material.

TENSILE STRENGTH.

46.—The tests may be made on any standard machine. A solid metal clip, as shown in Fig. 5, is recommended. This clip is to be used without cushioning at the points of contact with the test specimen. The bearing at each point of contact should be ¼ in. wide, and the distance between the center of contact on the same clip should be 1¼ ins.

47.—Test pieces should be broken as soon as they are removed from the water. Care should be observed in centering the briquettes in the testing machine, as cross-strains, produced by improper centering, tend to lower the breaking strength. The load should not be applied too suddenly, as it may produce vibration, the shock from which often breaks the briquette before the ultimate strength is reached. Care must be taken that the clips and the sides of the briquette be clean and free from grains of sand or dirt, which would prevent a good bearing. The load should be applied at the rate of 600 lbs. per minute. The average of the briquettes of each sample tested should be taken as the test, excluding any results which are manifestly faulty.

CONSTANCY OF VOLUME.

48.—*Methods.*—Tests for constancy of volume are divided into two classes: (1) normal tests, or those made in either air or water maintained at about 21° C. (70° F.), and (2) accelerated tests, or those made in air, steam or water at a temperature of 45° C. (115° F.) and upward. The test pieces should be allowed to remain 24 hours in moist air before immersion in water or steam, or preservation in air.

49.—For these tests, pats about 7½ cm. (2.95 ins.) in diameter, 1¼ cm. (0.49 in.) thick at the center, and tapering to a thin edge, should be made, upon a clean glass plate [about 10 cm. (3.94 ins.) square], from cement paste of normal consistency.

50.—*Normal Test.*—A pat is immersed in water maintained as near 21° C. (70° F.) as possible for 28 days, and observed at intervals. A similar pat is maintained in air at ordinary temperature and observed at intervals.

51.—*Accelerated Test.*—A pat is exposed in any convenient way in an atmosphere of steam, above boiling water, in a loosely closed vessel.

52.—To pass these tests satisfactorily, the pats should remain firm and hard, and show no signs of cracking, distortion or disintegration.

53.—Should the pat leave the plate, distortion may be detected best with a straight-edge applied to the surface which was in contact with the plate.

A

TREATISE

ON

INTERNAL NAVIGATION.

EXPLAINING THE PRINCIPLES BY WHICH CANALS AND
THEIR APPENDAGES ARE LAID OUT, CONSTRUCTED AND KEPT IN REPAIR, TOGETHER
WITH OTHER INTERESTING AND
USEFUL MATTERS CONNECTED WITH THE SUBJECT;

COMPILED FROM THE LATEST AND MOST APPROVED AUTHORITIES:

TO WHICH IS ANNEXED,

THE

REPORT OF ALBERT GALLATIN

ON

ROADS AND CANALS.

BALLSTON SPA:
PRINTED BY U. F. DOUBLEDAY.
....
1817.

used for dragging the hoop and bag along the bottom, and for hauling the same up to the surface, when the man at the pole finds that the bag is full, he begins to pull instead of pushing by the pole; this is the employment at Woolwich of a great number of convicts, instead of their being transported Solid matters or rocks when they happen to need excavating, below the level that the water can be drawn off to, or the ebb of the tide, seem to require all the skill and resources of the engineer.

It may not be uninteresting to the reader, to learn the opinion which was entertained by the great *Brindley*, (who is emphatically stiled the father of British canals) on the subject of the improvement of river navigations. He was the greatest enthusiast, (says *Phillips*) in favor of artificial navigations that ever existed. "Having spoken upon various circumstances of rivers before a committee of the House of Commons, in which he seemed to treat all sorts of rivers with great contempt, a member asked him for what purpose he apprehended rivers were created? Mr. *Brindley*, considering within himself a moment, replied, "To feed navigable canals," see *Inland Navigation* by *J. Phillips*, pages 113–14.

CHAP. XIV.

WATER-CEMENTS. PUZZOLANA. TARRAS. BLACK OXIDE OF IRON. IRON ORES. WOOD-ASHES. COMPACT BASALT. CENDRÉE DE TOURNAY. LORIOT MORTAR. NOTE, ON WATER CEMENTS. BLACK OXIDE OF MANGANESE. MATERIALS IN THE UNITED STATES.

AS the construction of locks requires the use of mortar or cement, which will set, indurate or harden under water; a short account of *Water Cements*, may not be improper. Although a well made mortar, composed merely of sand and lime, if allowed to dry, becomes impervious to water, yet if the circumstances of the building are such as to render it impracticable to keep out the water, whether fresh or salt, a sufficient length of time, the use of common mortar must be abandoned; for lime and sand, if mixed together in any proportions, and put, while soft, into water, will, in a short time fall to pieces.

Among the nations of antiquity the Romans appear to have been the only people who practised building in water, and especially in the sea, to any great extent.—The bay of Baiæ, like our fashionable watering places, was the summer resort of all the wealthy of Rome; who, not content with erecting their villas as near the shore as possible, were accustomed to construct moles, and form small islands, in the more sheltered parts of the bay, on which, for the sake of the grateful coolness, they built their summer houses and pavillions. They were enabled to build thus securely in the water by the fortunate discovery, at the neighboring town of Puteoli, of an earthy substance, which, from this circumstance, was called *pulvis puteolanus*, (powder of Puteoli)

Puteolan powder, or as it is now denominated puzzolana, is a light, porous, friable mineral, of a red colour, and is generally supposed to derive its origin from concreted volcanic ashes, thrown out from Vesuvius, near to which mountain the town of Puteoli is situated. It seems to consist of a ferruginous clay, baked and calcined by the force of volcanic fire, and when mixed with common mortar, not only enables it to acquire a remarkable hardness in the air, but to become as firm as stone, even under water. The only preparation which puzzolana undergoes, to fit it for use, is that of pounding and sifting, by which it is reduced to a coarse powder; in this state being thoroughly beaten up with lime, either with or without sand, it forms a mass of remarkable tenacity, which speedily sets under water, and becomes at least as strong as good free-stone.

It has been before observed, that a composition of pure lime and sand alone will not harden under water, but limes containing a portion of clay possess this property in a considerable degree, and are therefore generally used in water building. The cement used by Mr. Smeaton, in the construction of the Eddystone lighthouse, was composed of equal parts by measure of slaked Aberthaw lime and puzzolana. The peculiar difficulties of this undertaking, exposed to the utmost violence of the sea, rendered these proportions advisable; but for works that are less exposed, such as locks and basons for canals, &c. the quantity of puzzolana may be considerably diminished. A composition of this kind, which has been found very effectual, is two bushels of slaked Aberthaw lime, one bushel of puzzolana, and three of clear sand; the whole being well beaten together will yield 4.67 cubic feet of cement.

The Dutch have practised building in water to a greater extent than any other nation of modern Europe; and to them is due the discovery of a cement admirably well adapted for this purpose, and called tarras or trass.—This is nothing more than wakke, or cellular basalt, and is procured chiefly from Bockenheim, Frankfort on the Maine, and Andernach, whence it is transported down the Rhine in large quantities to Holland. This substance being, by grinding and sifting, reduced to the consistence of coarse sand, is used in the composition of mortar, with the blue argillaceous lime from the banks of the Scheldt, in the following method. They take of the quick-lime about the quantity which will be wanted during a week, and spread it in a kind of bason in a stratum of a foot thick and sprinkle it with water. It is then covered with a stratum of about the same thickness of tarras, and the whole suffered to remain for two or three days; after which it is very well mixed and beaten, and formed into a mass, which is again left for about two days; it is then taken in small quantities, as it is wanted for daily consumption, which are again beaten previous to using. Thus is composed the celebrated tarras mortar with which the mounds and other constructions for the purpose of protecting the lowlands of Holland against the sea are cemented.

Tarras is frequently used in this country, being imported from Holland for that purpose. The proportions of the materials of the tarras mortar generally used in the construction of the best water works is the same as the Dutch practise. One measure of quicklime, or two measures of slaked lime in dry powder, is mixed with one measure of tarras, and both very well beat together, to the consistence of a paste, using as little water as possible. Another kind, almost equally good, and considerably cheaper, is made of two measures of slaked lime, one of tarras, and three of coarse sand; it requires to be beaten a longer time than the foregoing, and produces three measures and a half of excellent mortar. When the building is constructed of rough irregular stones, where cavities and large joints are to be filled up with cement, the pebble mortar may be most advantageously applied; this was a favorite mode of construction among the Romans, and has been used ever since their time in those works in which a large quantity of mortar is required. Pebble mortar will be found of sufficient compactness if composed of two measures of slaked argillaceous lime, half a measure of tarras, or puzzolana, one measure of coarse sand, one of fine sand, and four of small pebbles, screened and washed.

It is only under water that tarras mortar acquires its proper hardness; for if suffered to dry by exposure to the air, it never sets into a substance so firm as if the same lime had been mixed with good clean common sand, but is very friable and crumbly. Ash mortar is reckoned to be superior for works that are sometimes wet and sometimes dry, but tarras has the advantage when constantly under water. Tarras mortar when kept always wet, and consequently in a state most favorable to its cementing principle throws out a substance something like the concretions in limestone caverns called stalactites, which substance acquires a considerable hardness, and in time becomes so exuberant as to deform the face of the walls.

Although the cellular basalt is the only kind admitted into the preparation of Dutch tarras, yet it appears from some good experiments of Morveau on the subject, that the common compact basalt, if previously calcined, will answer nearly the same purpose.

In some parts of the Low Countries coal ashes are substituted for tarras with very good effect; of which the valuable *Cendrée de Tournay* is a striking instance. The deep blue argillo-ferruginous limestone of the Scheldt is burnt in kilns with a slaty kind of pit-coal that is found in that neighborhood. When the calcination of the lime is completed, the pieces are taken out, and a considerable quantity of dust and small fragments remain at the bottom of the kiln. This refuse consisting of coal ash mixed with about one fourth of lime dust, is called the cendrée, and is made into a mortar with lime in the following method. About a bushel of the materials is put in any suitable vessel, and sprinkled with water just sufficient to slake the lime; another bushel is then treated in the same way, and so on till the vessel is filled. In this state it remains some weeks, and may be kept for a much longer time if covered with moist earth. A strong open trough, containing about two cubic feet, is filled about two thirds full with the cement in the above state, and by means of a heavy iron pestle, suspended at the end of an elastic pole, is well beaten for about half an hour: at the end of this time it becomes of the consistence of soft mortar, and is then laid in the shade from three to six days, according to the dryness of the air. When sufficiently dry, it is beaten again for half an hour as before, and the oftener it is beaten the better will be the cement; three or four times, however, are sufficient to reduce the cement to the consistence of an uniform smooth paste; after this period it is apt to become refractory on account of the evaporation of its water, as no more of this fluid is allowed to enter the composition than what was at first employed to slake the lime. The cement thus prepared is found to posses the singular advantage of uniting in a few minutes so firmly to brick or stone, that still water may be immediately let in upon the work without any inconvenience, and by keeping it dry for 24 hours, it has nothing further to fear from the most rapid current.

A composition very similar to the preceding in materials, which are coal cinders and lime, though seldom prepared with any attention, is the blue mortar, commonly used in London for setting the coping of buildings, and other works much exposed to the weather.

Ash mortar is used in some parts of England. It is prepared by slaking two bushels of fresh burnt meagre lime, and mixing it accurately with three bushels of wood ashes: the mass is to lie till it is cold, and is then to be well beaten: in this state it will keep a considerable time without injury, and even with advantage, provided it is thoroughly beaten twice or thrice before it is used.

The scales, or black oxyd of iron, which are detached by hammering red hot iron, and are therefore to be procured at the forges and blacksmith's shops, have been long known as an excellent material in water cements; but we believe that Mr. Smeaton was the first person who made any accurate experiments on their efficacy, compared with other substances. The scales being pulverised and sifted, and incorporated with lime, are found to produce a cement equally powerful with puzzolana mortar, if employed in the same quantity. Induced by the success of these experiments, Mr. Smeaton substituted roasted iron ore for the scales, and found that this also gave to mortar the property of setting under water; it requires, however, to be used in greater proportions than either tarras or puzzolana; two bushels of argillaceous lime, two of iron ore, and one of sand being carefully mixed, produce 3. 22 cubic feet of cement fully equal to tarras mortar. If the common white lime is made use of, it will be advisable to employ equal quantities of all the three ingredients.

With respect to the water used in the preparation of water cements, that of rivers or ponds where it can be had easily, is to be preferred to spring water; but for works exposed to the action of the sea, such as piers, light-houses, &c. it is usually more convenient and equally advantageous in other respects to use salt water.

Pumice stone, brick, and tile dust, are also recommended for water cements, but their only advantage seems to be an absorbent quality, which causes the morter made with them to set sooner, and therefore acquire a greater hardness in the same time, than mortar composed of sand and lime alone, for they have no power of hardening under water.

The Loriot mortar is a composition which has acquired considerable celebrity in France, and has been employed in some large works. It was invented about 40 years ago by M. Loriot, who imagines that he has discovered the process used by the Romans. The principle of this invention consists in adding to any quantity of mortar made in the usual way with lime and sand, but prepared rather thinner than usual, a certain proportion of quick-lime, in powder. The lime powder being well incorporated with the mortar, the mass heats, and in a few minutes acquires a consistence, equal to the best Paris plaster, and is as dry at the end of two days, as an ordinary cement after several months. It also, when the ingredients are well proportioned, sets without any cracks. The quantity of lime powder to be added varies from 1-4 to 1-8 of the other materials, according to the qualities of the lime; too much burns and dries up the mass, and with too little it loses its peculiar advantages; thus the proportions, a point of the utmost importance, can only be determined by experiment. It is its speedy desiccation which rendered the Loriot mortar useful as a water cement, for under water it has only the common properties of a composition of lime and sand of equal solidity; indeed for this purpose various substances, commonly used in cements, are recommended to be added, such as brick and tile powder, and forge scales. The following is an approved receipt. One measure of bricks exactly pounded, two measures of fine river sand, old slaked lime in sufficient quantity to make a mortar in the usual manner and sufficiently liquid to quench the lime powder which is added in about the same quantity as the pulverised brick.

NOTE.

In addition to the water-cements above mentioned the compiler takes the liberty of extracting the following, on the subject, from *The Chemical Catechism*, by Samuel Parks, F. L. S. page 425.

"Mix four parts of gray clay, six of the black oxide of manganese, and ninety of good limestone reduced to fine powder; then calcine the whole to expel the carbonic acid. When this mixture has been well calcined and cooled, it is to be worked into the consistence of a soft paste with sixty parts of washed sand. If a lump of this cement be thrown into the water it will harden immediately. Such mortar, however, may be procured at a still less expense, by mixing with common quick-lime a certain quantity of what are called the *white* iron ores, especially such as are poor in iron. These ores are chiefly composed of manganese and carbon ate of lime, or chalk."

That all the materials for making the different kinds of water-cements, except puzzolana, and perhaps except cellular basalt, exist in great abundance, in the United States, there cannot be a doubt; and with respect to cellular basalt, with which the Dutch make the celebrated tarras mortar, it is very probable, considering the extent of our country, and the varieties of our soil, climate and mountains, that this also may be found: but the mineralogy of the United States is yet so imperfectly known, that this, at present, must rest in conjecture. We have, however, it is believed, all the kinds of lime-stone; and the State of New-York can furnish the several varieties, from the pure white lime of the bald mountain in Washington County, to the blue argillaceous and gray ferruginous kind, commonly known in the country by the name of *bastard limestone*. It is hardly worth while to remark, that we have forge scales, or the black oxide of iron in almost any quantities ; and iron ores exist in such abundance, that it would be superfluous to designate the places where they may be found. Several of the States produce pit coal in considerable varieties; and wood ashes are in great plenty, and of trifling value, in all parts of the country. The writer of this has, in his possession, a good specimen of the black oxide of manganese, brought from Bennington in the State of Vermont, where it is said to exist, in great quantities, and there is but little doubt, that it may also be found in various other parts of the United States. But perhaps the compact basalt would be the cheapest material for a water-cement that could be procured in the State of New-York : and we have enough of this material, in one place, to supply the United States. The well known rocks, or cliffs, called the *Pallissadoes*, which form a part of the west bank of the Hudson river, below the highlands, are entirely composed of compact basalt. This, when burnt like lime, and pulverised, communicates to the mortar with which it is mixed, the property of hardening under water. It may be pulverised by the rolling of a heavy circular stone with a horse, in the same manner as tanners grind bark ; or by the simple hydraulic machine, with which gypsum or plaster of Paris is broken into small fragments before it is ground.

Basaltes or basalt is of a gray, blue, or purplish black color, destitute of lustre or transparency, commonly presenting a texture composed of granular concretions, and is found in large masses of a regular form, generally columnar. According to *Klaproth*, it is composed of 44.5 silex, 17 alumine, 20 oxide of iron, 9.5 of lime, 2.6 of soda, and 6 manganese and water. See *Chemical Catechism* page 438.

Sect. V.—BRIEF OBSERVATIONS ON COMMON MORTARS, HYDRAULIC MORTARS, AND CONCRETES,

WITH SOME EXPERIMENTS MADE THEREWITH AT FORT ADAMS, NEWPORT HARBOUR, R. I. FROM 1825 TO 1838.

BY J. G. TOTTEN,
Lt. Col. of Eng. and Brevet Col. United States Army.

CHAPTER XXIII.

On Lime, Hydraulic Cement, Sand, Mortar making, Strength of Mortars and Grout.

During the progress of operations under my direction in the construction of Fort Adams, in Newport Harbour, Rhode Island, many experiments were made with mortars exposed in the air; giving, in some cases, results quite interesting. The results are too limited in number and restricted in variety, to justify the deduction of general principles; still they afford some hints that may be deemed worthy of being followed up.

The following tables contain these results in a very condensed form; but before giving the tables, it is proper to make some observations on the materials employed—the manner of using them, and the modes adopted of trying the relative strengths of the essays.

Lime.—Three kinds of lime were used, namely:

1st. "*Smithfield Lime.*"—From Smithfield, R. I. about fifteen miles from Providence. This is a very fat lime—slaking with great violence, when properly burned, and affording a large bulk of slaked lime.

2d. "*Thomastown Lime.*"—From Thomastown (Maine.) This is also a fat lime, at least so far as it has been tried at Fort Adams: but it is probable that some of the many varieties—including those of the neighbouring towns of Lincolnville, and Camden, may prove to be hydraulic. The richer varieties slake promptly, giving a large bulk of slaked lime.

3d. *Fort Adams Lime.* This is made from a ledge of whitish transition limestone found within the domain of the Fort. The stone is very fine grained and compact, exceedingly difficult to break, and crossed in all directions by three veins of whitish quartz. The ledge is a bed, or large nodule, in graywacke-slate. After calcination it yields, by sluggish slaking, a lime decidedly hydraulic. A little of this lime, after being slaked, was made into a cake of stiff hydrate; the excess of water being absorbed by bibulous paper: the cake was placed in the bottom of a tumbler and covered immediately with water. In about 7½ days, a wire $\frac{1}{24}$ of an inch in diameter, loaded to weigh 1 lb., made no impression on this hydrate.

Three modes of slaking the lime were tried in these experiments, namely:

1st. *Slaking by Sprinkling.*—In this mode, water, in quantity sufficient to slake the lime to dry powder, but not enough to afford moist powder, was sprinkled upon the lime. The lime was not made into mortar until it had become cold.

2nd. *Slaking by Drowning.*—In this mode, water enough was given, in the first place, to reduce the lime to a cream of such consistency as to afford mortar of proper "*temper*" for common use without any further addition of water, provided the mortar was made up immediately. If the making the mortar was delayed, a further supply of water became necessary.

3d. *Air-slaking.*—In this mode, lime, reduced to pieces about the size of a walnut, was left in the air to slake spontaneously.

These were the processes by which the lime used in the experiments was slaked: but by neither of these, nor by any modification recommended by others, or that we, ourselves, could devise, were we able to free the hydrate from an infinity of small particles of lime, that being imperfectly, or not at all, slaked in the first instance, it was almost impossible, by any amount of labour afterward, to break down and mix with the rest. The mortar mill, hereafter described, reduced these refractory particles better than any of the ordinary modes of acting upon lime; but not sufficiently, without an unwarrantable amount of labour. All other means having failed, resort was had, at last, for the mortar for the masonry of the Fort, to grinding the dry lime to a very fine powder between millstones. Lime thus ground gives a perfectly homogeneous mortar: and some partial experiments lead to the opinion that the gain in the quantity of lime available for mixtures with sand, will, nearly if not quite, compensate for the expense of grinding. So far as the mortar thus made has been tried, the results were favourable: but the experiments on the quantity and quality of lime thus treated, though they justify confidence, are not, yet, so conclusive as to warrant any positive assertions.

Hydraulic Cement.—Three kinds of hydraulic cement were employed—namely, a kind that will be here designated as *hydraulic cement A*, which was supplied from the State of New York—another kind, called *hydraulic cement B*, supplied from a different manufactory in the same State—and "*Roman (or Parker's) cement,*" imported from England.

The experiments will show a material difference in the respective qualities of these hydraulic cements. According to them, cement A was the best, cement B the next best, and the "Roman cement" the worst; but it must be remarked that the last mentioned had, no doubt, greatly deteriorated, from imbibing moisture during a long voyage, and long keeping in store; while there is reason to suppose that the two first mentioned had been calcined within a few weeks. Between these two, there was also a marked difference; but though the superiority of cement A was probably in part intrinsic, it was, no doubt, in part, to be ascribed to its greater freshness. These cements, therefore, should, in our tables, be compared with themselves under various combinations with other ingredients, rather than with each other.

This is perhaps the best place to mention a very certain and satisfactory mode of testing the hydraulic quality of lime or cement. It is derived from Raucourt's work on mortars.

Of the lime or cement to be tried, a cake of quite stiff hydrate must be made of a size to lie, without touching the sides, in the bottom of a tumbler: any excess of water should be absorbed from the cake by bibulous paper, until it will just support a wire $\frac{1}{12}$ of an inch in diameter loaded to weigh $\frac{1}{4}$ of a pound—this wire should barely make its impression. Noting the hour and minute of the watch, the cake, thus prepared, should be placed in the tumbler, and covered immediately with water. If the specimen be very hydraulic, it will set almost instantly; if not very hydraulic, it may require days, and if but slightly hydraulic, it may require weeks to harden. In order to have some invariable measure of what we call *setting*, we have always used a wire $\frac{1}{24}$ of an inch in diameter, loaded to weigh 1 pound.

With these two simple instruments, and these simple appliances, the comparative hydraulic qualities of limes and cements may be detected infallibly. It may not be strictly accurate to say that those cements which indurate most promptly under water will afford the strongest mortars in the air; although that has, for the greater part, appeared to be the case, in our experiments; still it is highly probable that such cements will be found among the best; it is, at any rate, amongst such that we should look when in search of mortars of superior excellence; and it is undoubtedly true, that when hydraulic qualities exist in lime, although in feeble proportion, the lime is essentially benefited. A simple means of testing hydraulic quality is therefore of value.

Our experience has, however, taught us one important caution in the use of this test; which is, to leave the cement in the water for a day or two, although it may have set in a few minutes. A cement was under trial which, at the expiration of 7 minutes had set so as to bear the small wire with the weight of 1 pound—and at the expiration of 15 minutes, with the weight of 2 pounds. In about two hours, however, it was entirely soft again, having been broken down by the slaking of some free lime that happened to be present, and which had not had time to slake before the hydraulic ingredients had indurated. After about fifteen hours it was taken out of the water, restored to the condition of stiff mortar, and again immersed. It now hardened very slowly, and was six days acquiring the test hardness. Such cements require peculiar treatment. It is evident that there is great hydraulic energy wasted in the first instance of immersion; because the subsequent swelling of the lime, breaks down the indurated mass; and, removing the hydraulic particles beyond the sphere of mutual action, prevents any useful effect from the remaining hydraulic power. The slaking the lime should, therefore, be complete before the cement is immersed. The best mode of slaking this lime has not been ascertained. Perhaps it would be best to sprinkle a little water on cement of this kind, leaving it for a few hours in the state of moist powder—perhaps leaving it exposed to spontaneous slaking for the requisite time—and perhaps throwing on a small quantity of water, in order to slake the lime, and then exposing the cement to heat for a short time, so as to drive off the water absorbed by the hydraulic constituents. This last mode is suggested by the following facts.

Some hydraulic cement A, which had been in a cask more than one year, on first opening the cask, hardened under water in three hours. After two or three days, it required five hours to harden; and after ten days, about nine hours—the cask being kept covered by the head lying loosely upon it. A little of this cement that had been out of the cask for more than a week, on being heated (but not to a red heat) for a few minutes, set under water in three hours. Some of the same cement that had been in the office, enclosed in paper, for about three weeks, required six hours to harden in water, while a little of it, after being kept on a red hot iron plate for about fifteen minutes, hardened in water in 45 minutes.

This power of restoring the energy of deteriorated cements may have many important applications.

Sand.

Several kinds of sand were used in the experiments, namely:

Sand No. 1.—This is the kind habitually used at Fort Adams in stone masonry. It is entirely free from dirt, and the particles, though not very sharp, are angular. Separated mechanically, it was found to consist, in 100 parts, in bulk, of

particles from	$\frac{1}{6}$ to $\frac{1}{12}$	of an inch	in diameter—	—about	10.00
do.	$\frac{1}{12}$ to $\frac{1}{24}$	do.	do.	do.	5.00
do.	$\frac{1}{24}$ to $\frac{1}{48}$	do.	do.	do.	48.00
do.	$\frac{1}{48}$ to dust			do.	45.00
do.	dust mostly silicious—no dirt			do.	4.50
100 parts in bulk producing				do.	112.50

Sand No. 2.—Is the above sand freed from particles larger than $\frac{1}{12}$ of an inch.

Sand No. 3.—Is the above sand freed from particles larger than $\frac{1}{48}$ of an inch.

Sand No. 4.—Is sand No. 2, pounded very fine after being freed from dust by washing.

Mortar Making.

With a view to a thorough incorporation of the constituents, at a small expense, and in order, at the same time, to break down the refractory particles of lime before mentioned, a mortar mill was constructed at the commencement of the works at Fort Adams in 1825, which has been in operation ever since.

The mill consists of a very heavy wheel about eight feet in diameter (having a tire one foot broad) moving in a circular trough fifteen inches wide at the bottom—the diameter of the circle being about twenty-one feet. The lime is slaked under the wheel, and ground until, with suitable additions of water, it has become a homogeneous paste sufficiently dilute to make mortar of the ordinary consistency. The requisite quantity of sand is then gradually sprinkled in, as the wheel is in motion. The draught is easy to the horse until near the last; when, for a few minutes, as he is giving the last turns, after all the sand has been thrown in, it is rather heavy.

It was found convenient to use three barrels of lime to each batch of mortar.

The three mortar mills of Fort Adams were competent to supply in one day 3077 cubic feet of mortar, at a total expense of $0.087 per cubic foot, viz.

105 casks of lime, at $1.52 per cask,	$ 159.60
2094 bushels of sand, at $0.04 per bushel,	83.76
Carting sand to mill, $0.12 for 20 bushels,	12.56
3 horses and 3 drivers, at $1.50 per day,	4.50
6 labourers, at $1.00 per day,	6.00
1 cooper at $1.00 per day,	1.00
Other small expenses say	0 58
Total cost of 3077 cubic feet of mortar	$ 268.00

or $0.087 per cubic foot. It appears that the expense of *making* the mortar was $12.08, being about $\frac{1}{3}$ of a cent for a cubic foot.

The proportions in the above mortar are about 1 of lime in paste to $2\frac{1}{2}$ of sand—should the proportion of lime be greater, the mortar will, of course, cost more.

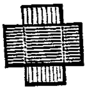
The above statement refers to mortar made without addition of any hydraulic substance. But such mortars are now never used at Fort Adams. Hydraulic cement, or burnt clay, or brick dust, or some other similar matter is added to every kind of mortar made at the work, in proportions varying with the purpose to which the mortar is to be applied. The poorest mortar we make contains 1 barrel of hydraulic cement to 3 barrels of unslaked lime and about 15 barrels of sand; the cement being added before the sand, and while the lime is being reduced under the wheel.

All the mortars used in the experiments in the tables, were made by hand with the trowel, with such exceptions, only, as are noticed.

Trials of the Strength of Mortars.

The strength of mortars as regards tenacity, was determined by measuring the force required to separate bricks that, having been joined by the mortar, had been left, for the desired length of time, in some place safe from frost or accident.

The bricks were joined in pairs, being crossed at right angles thus, so that, supposing each brick to be 4 inches wide, the surface of contact would be 16 square inches. The real surface, or surface of effectual contact, was, in every case, found by actual measurement. The mortar joint separating the bricks was made about $\frac{3}{8}$ of an inch thick: and, in order that this mortar should in all cases be equally consolidated, each pair of bricks was submitted to the pressure of 600 lbs. for 5 minutes, immediately after being joined.



An idea of the mode of separating the bricks may be got from fig. 9, Pl. II, where *a* and *b* represent two strong half-staples fastened to the floor: under these the ends of the lower brick are passed, while the ends of the upper brick are embraced by the piece of iron *c*, *c*, suspended from the steelyard *d*. The force needed to separate the bricks, is applied by pouring sand, at a uniform rate, into the bucket *e*. The weight of the sand and bucket, the mark on the beam where the weight was applied, and the weight of the *poise*, enable us to ascertain the force necessary to tear the bricks asunder. In the tables, the force required to separate the bricks is reduced to the proportional force required to tear up a surface of one square inch: so that if there were 16 square inches of actual contact, and the force used in separating the bricks was 1000 pounds, the table would represent the tenacity of the mortar by $62\frac{1}{2}$lbs.—equal to $\frac{1000}{16}$.

The hardness of the mortars was determined by ascertaining the weight, applied on a circular plane surface of 0.16 of an inch in diameter, (or .02008 of an inch area,) which the mortar would support. This mode of trial is represented in fig. 10, Pl. II. The circular surface at the extremity *a*, presses upon mortar still adhering to one of the bricks. The arms of the lever *b*, are of equal length, so that the upward force at *c* is equal to the pressure at *a*. The force is applied by means of a steelyard and sand, as in the preceding case.

The experiments were generally made with several pairs of bricks, and a mean was taken of the results; unless it had obviously been subjected to some accident or disturbance, being made to contribute to the mean. Very few results were rejected. There could be only as many trials of *tenacity*, in each particular experiment, as there were pairs of bricks. But for *hardness*, it was often possible to make a considerable number of distinct trials on the same surface of mortar: on the other hand, it would sometimes happen that the surface would be left too ragged and uneven for this trial: and in several instances this test seemed to be entirely inapplicable—the mortar beginning to yield with light weights, and continuing to yield more and more as the weight was increased, the whole effect being a gradual crumbling. In a great majority of cases, however, the effects were sufficiently decided to leave no doubt as to the moment when the power prevailed over the resistance—and sufficiently consistent to afford useful comparisons.

The method, just described, of trying the strength of mortars, was adopted in the Fort Adams experiments, on account of the facility of application. There was, in the first instance, no purpose of extending the experiments beyond what was deemed indispensable to a proper choice, and judicious application of materials, in the construction of a work of some magnitude, then being begun. One series of experiments, however, involved another and another, until the series became extended and the experiments too numerous and valuable, not to make it desirable that subsequent ones should be comparable with them, and, consequently, the same mode of test was continued.

It is probable that the method followed by Genl. Treussart, of making rectangular prisms of mortar, and subjecting them to fracture by weights suspended from the middle, is the best mode. It, at any rate, has the advantage of allowing mortars made in different places, and at distant times to be compared. This mode was adopted in some of the later trials at Fort Adams.

The following table exhibits the mean results of all the experiments made from 1825 to 1832; comprising seven series. The time of exposure of the 1st series was 5 months; of the 2nd. series, 10 months; of the 3rd, 10 months; of the 4th, 5 months; of the 5th, 10 months; of the 6th, 25 months; and of the 7th, 11months. In the 1st series, there were 2 pairs of bricks to each experiment; in the 2nd, 3 pairs; in the 3rd, 3 pairs; in the 4th, 1 pair; in the 5th, 4 pairs; in the 6th, 2 pairs; and in 7th, 3 pairs.

The first column prefixes a number to each kind of mortar, for convenient reference; the 2nd column expresses the nature, or composition of the mortar; the 3rd column, whether the bricks were *wet* or *dry* when joined together; the 4th, the number of series of which the results are a mean as to *tenacity*; the 5th, the *tenacity*, as expressed by the number of pounds required to tear open a joint of one inch square; the 6th, the number of series of which the results are a mean as to *hardness;* and the 7th, the number of pounds required to force into the mortar a circular plane surface of 0.16 of an inch in diameter.

Table No. LXV.

No.	Nature and Composition of the mortar.	Bricks wet or dry.	Tenacity.		Hardness.		Remarks.
			Number of series affording the mean.	Mean tenacity.	Number of series affording the mean.	Mean hardness.	
1	New York Hydraulic cement B, alone	W	1	32.6			
2	do. do. do. A, alone	W	5	56.2	4	1053	
3	Roman cement (Parker's English) alone	W	1	18.5	1	260	
4	do. (do.) alone	D	1	22.6	1	412	
5	Lime alone	W	1	10.5	1	98	
6	Hydraulic cement A in powder 1 Sand No 3 .50	W	1	61.9	1	1055	
7	Cement A do. 1 Sand the same 1	W	6	40.3	5	993	
8	Cement A do. 1 Sand the same 1.50	W	5	33.1	4	918	
9	Cement A do. 1 Sand the same 1.50	D	2	30.4	1	765	
10	Hydraulic cement A in powder 1 Sand No. 3 2	W	3	17.5	3	670	
11	Cement A do 1 Sand the same 3	W	3	19.8	2	367	
12	Cement A do. 1 Lime slaked to powder .50 Sand the same 1.50	W	2	29.6	3	573	
13	Cement A do. 1 Lime the same .50 Sand No. 2 2	W	4	20.1	3	509	
14	Cement A do. 1 Lime the same 1 Sand No. 2. 2	W	4	28.3	3	778	
15	Cement A do. 1 Lime the same 2 Sand No. 2 4	W	4	17.1	3	545	
16	Cement A do. 1 Lime the same 2 Sand No. 2 6	W	4	16.2	3	267	
17	Cement A do. 1 Lime in paste, .50 Sand No. 2 1.50	W	1	44.4	1	765	
18	Cement A 1 Lime in paste .50 Sand No. 2 1.50	D	1	54.7	1	915	
19	Cement B do. 1 Sand No. 3 1	W	2	18.9			
20	Cement B do. 1 Sand No. 2 1.50	W	1	23.4			
21	Cement B do. 1 Sand No. 2. 2	W	2	14.7			

Table No. LXV—Continued.

No.	Nature and Composition of the mortar.	Bricks wet or dry.	Tenacity.		Hardness.		Remarks.
			Number of series affording the mean.	Mean tenacity.	Number of series affording the mean	Mean hardness.	
22	Cement B do. 1 Lime in powder slaked . .50 Sand No. 2 2	W	2	17.5			
23	Cement B do. 1 Lime the same 1 Sand No. 2 2	W	2	19.1			
24	Hydraulic cement B in powder 1 Lime slaked in powder 2 Sand No. 2 4	W	2	18.1			
25	Cement B 1 Lime the same 2 Sand No. 2 6	W	2	15.0			
26	Roman cement 1 Sand No. 2 .50	W	1	19.2	1	397	
27	Roman cement 1 Sand No. 2 1	W	1	16.8	1	309	
28	Roman cement 1 Sand No. 2 1.50	W	1	13.3	1	286	
29	Roman cement 1 Lime in paste 0.50 Sand No. 2 1.50	W	1	26.7	1	471	
30	Roman cement 1 Lime in paste 0.50 Sand No. 2 1.50	D	1	29.1	1	787	
31	Lime in powder 1 Sand No. 3 3.50	W	3	12.3	1	159	
32	Lime in powder 1 Sand No. 3 6	W	1	5.6	1	107	
33	Lime in paste 1 Sand No. 3 .50	W	1	14.3	1	208	
34	Lime in paste 1 Sand No. 3 1.50	W	3	15.4	2	275	
35	Lime in paste 1 Sand No. 3 3	W	4	12.8	2	146	Made with a hoe.
36	Lime in paste 1 Sand No. 3 2.50 *a* 3	W	6	14.3	3	202	Made in mortar mill.
37	Lime in paste 1 Sand No. 3 2.50 *a* 3	D	5	14.9	4	254	do. do.
38	Lime in paste 1 Sand No. 1 2.50 *a* 3	W	1	13.7	1	217	do. do.
39	Lime in paste 1 Sand No. 1 2.50 *a* 3	D	1	16.2	1	200	do. do.
40	Lime in paste 1 Sand No. 1 2	W	1	33.8	1	242	Lime different.
41	Lime in paste 1 Sand No. 1 2	D	1	26.6	1	231	

Observations on the Experiments of Table No. LXV.

1st. Generally, within the limits of the experiments, *a mortar made of lime and sand, or of hydraulic cement and sand, or of hydraulic cement, lime and sand—whether it was cement A, or cement B, or Roman cement, was the stronger, as the quantity of sand was the less.* In 24 comparisons, 3 exceptions.

In 13 comparisons of *tenacity*, 2 exceptions.

In 11 comparisons of *hardness*, 1 exception.

2nd. *It appears that with cement A, or cement B, any addition of sand weakens the mortar.* In all the cement experiments, except one, composed of Roman cement 1—sand ½ (No. 26,) the cement alone, was stronger than when mixed with sand in any proportion whatever. Cement A (No. 6,) would seem to be another exception, but it is not; the strength of cement A, alone, as given in No. 2, is the average of five results with different specimens of cement, some of which were of inferior quality; while the result given in No. 6 is of one trial only, and that of a cement proving to be the best used; the particular result of No. 2 which corresponds with No. 6—that is to say, which was afforded by the same specimen of cement, gave for *tenacity* 74.7 lbs. and for *hardness* 1063 lbs., while No. 6 shows a *tenacity* of 61.9 lbs. and a hardness of 1055 lbs.

3rd. *It appears that when cement mortars are not required to be the strongest that can be made—a little lime may be added, without great loss of tenacity, and, of course, with a saving of expense.*

4th. *Mortar made in the mortar-mill was superior to mortar made by being mixed, in the common mode, with the hoe.*

5th. *When the bricks were dry and the mortar more fluid than usual, the mortar was better, both as to* TENACITY *and* HARDNESS*—in five cases out of seven, than when the bricks, being wet, were put together with mortar of common consistence.*

In the next table there is a comparison of the three kinds of lime—of the three modes of slaking, of various proportions of sand—of the effect of wet and of dry bricks on the mortar, &c.

In most cases six pairs of bricks were put together at the same time, and of the same materials; of which three pairs were separated after about 6 months, and the remainder after the lapse of 4 years and 5 months.

Table No. LXVI.

Showing the tenacity and hardness of mortars variously composed after exposure in the air.

No.	Nature and composition of the mortar.	Bricks wet.				Bricks dry.				Remarks.
		Tenacity per square inch.		Hardness.		Tenacity. per square inch.		Hardness.		
		After 6 months.	After 4 years and 5 months.	After 6 months.	After 4 years and 5 months.	After 6 months.	After 4 years and 5 months.	After 6 months	After 4 years and 5 months	
		lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	
1	*Paste of Smithfield lime slaked by* DROWNING 1 Sand No. 2 1	20.4	42.8	119	220					There are two kinds of Fort Adams lime in the table. The first, A, was imperfectly calcined: the second B, was thoroughly burned.
2	Lime the same 1 Sand No. 2 2	15.2	18.8	130	297					
3	Lime the same 1 Sand No. 2 3	12.6	16.6	182	232					
4	Lime the same 1 Sand No. 2 4	13.2	16.4	85	203					
5	*Paste of Thomastown lime slaked by* DROWNING 1 Sand No. 2 1	11.3	38.3	216	300		40.3		355	
6	Lime the same 1 Sand No. 2 2	17.1	38.3	123	273		39.1		310	
7	*Paste of Thomastown lime, slaked by* DROWNING 1 Sand No. 2 3	24.7	27.6	265	240		38.0		220	
8	Lime the same 1 Sand No. 2 4	15.1	21.7	214	210		35.4		203	
9	*Paste of Fort Adams lime* A *slaked by* DROWNING 1 Sand No. 2 1	13.4	21.9	105	273		34.0		186	
10	Lime the same 1 Sand No. 2 2	9.9	18.8	68	175		22.5		110	
11	Lime the same 1 Sand No. 2 3	12.6	22.7	75	93		22.8		187	
12	Lime the same 1 Sand No. 2 4	9.6	11.5	92	93		21.4		102	
13	*Paste of Thomastown lime, slaked by* SPRINKLING 1 Sand No. 2 1	26.8	49.1	259	798		40.6		787	
14	Lime the same 1 Sand No. 2 2	26.4	35.6	225	666		57.3		370?	
15	Lime the same 1 Sand No. 2 3	26.3	37.0	285	392		26.2		625	
16	Lime the same 1 Sand No 2 4	25.2	31.0	289	313		38.0		347	
17	*Paste of Fort Adams lime* B *slaked by* SPRINKLING 1 Sand No. 2 1	32.9	47.8	446	900		56.7		620	

Table No. LXVI. Continued.

No.	Nature and Composition of the mortar.	Bricks wet.				Bricks dry.				Remarks.
		Tenacity per square inch.		Hardness.		Tenacity per square inch.		Hardness.		
		After 6 months.	After 4 years and 5 months.	After 6 months.	After 4 years and 5 months.	After 6 months.	After 4 years and 5 months.	After 6 months.	After 5 years and 5 months.	
		lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	
18	Lime the same 1 Sand No. 2 2	33.1	54.5	228	600		52.4		507	
19	Lime the same 1 Sand No. 2 3	28.9	43.1	221	327		51.8		266	
20	Lime the same 1 Sand No. 2 4	23.5	30.4	254	258		52.6		233	
21	*Paste of Smithfield lime* AIR SLAKED 1 Sand No. 2 1		22.4		126					
22	Lime the same 1 Sand No. 2 2		9.9		85					
23	*Paste of Thomastown lime* AIR SLAKED 1 Sand No. 2 1				372					
24	Lime the same 1 Sand No. 2 2		6.0		203					
25	*Paste of Fort Adams lime* B AIR SLAKED 1 Sand No. 2 1		29.2		664					*Equal, lime 1 Cement 0.33 Sand 5.00 do. 50 Lime 1 Cement 0.33 Sand 5.50
26	Lime the same 1 Sand No. 2 2		21.6		281					
27	*Paste of Fort Adams lime* B *slaked by* DROWNING 1 Brick dust 0.40 Sand No. 2 1.40	16.3		104						
28	Lime the same 1 Dust of burnt clay .50 Sand No. 2 .50	17.5		168						
29	*Paste of Thomastown lime slaked by* SPRINKLING 1 Brick dust 2	35.0		360						
30	*Paste of Thomastown lime slaked by* DROWNING, measured before slaking 1 Sand No. 2 5	12.2	18.5	102	263		22.5		192	
31	Lime the same* 1 Cement A .33 Sand No. 2 5.50	15.4	23.1	165	192		42.6		230	
32	*Paste of Fort Adams lime* B *slaked by* DROWNING, measured before slaking 1 Sand No. 2 5	25.7	48.8	130	650		17.8		652	
33	Lime the same* 1 Cement A .33 Sand No. 2 5.50	22.7	46.7	194	849		46.2		303	
34	Cement A in powder 1 Sand No. 2 1.50	63.3	72.4		1508	467	88.4		1659	

Observations on the experiments of Table No. LXVI.

1st. *Within the limits of the experiments, whatever was the mode of slaking, or the kind of lime, the mortar was the stronger as the quantity of sand was less.*

The lime being measured in paste, the proportions were 1 of lime to 1 of sand; 1 of lime to 2 of sand; 1 to 3, and 1 to 4 of sand.

In all the corresponding trials of the table,

1 lime in paste, to 1 sand, gave the strongest mortar in 35 cases of tenacity, and in 13 cases of hardness.

1 lime in paste, to 2 sand, gave the strongest mortar in 3 cases of tenacity, and in 1 case of hardness.

1 lime in paste, to 3 sand, gave the strongest mortar in 2 cases of tenacity, and in 2 cases of hardness.

1 lime in paste, to 4 sand, gave the strongest mortar in 0 cases of tenacity, and in 1 case of hardness.

2d. *Slaking by* DROWNING, *or using a large quantity of water in the process of slaking, affords weaker mortar than slaking by* SPRINKLING.

In 24 corresponding cases of the table—The quantity and quality of the materials being alike: and there being no other difference than in the modes of slaking the lime.*

Lime slaked by SPRINKLING, gave the best mortar in 22 cases of tenacity, and in 24 cases of hardness.

Lime slaked by DROWNING, gave the best mortar in 2 cases of tenacity, and in 0 case of hardness.

The average strength in all the 24 cases in which the lime was slaked by *drowning* was, as to tenacity, 23.79 lbs., and as to hardness, 187.00 lbs.

While the average strength in all the 24 cases in which the lime was slaked by *sprinkling* was, as to tenacity, 38.63 lbs., and as to hardness 417.33 lbs.

The relative tenacity then is as 1 to 1.62; and the relative hardness as 1 to 2.23.

3d. *The experiments with air* SLAKED LIME, *were too few to be decisive—but the results were unfavourable to that mode of slaking.*

Average strength of the mortar made of *air-slaked* lime as to tenacity 20.80 lbs., and as to hardness 202.18 lbs.

Average strength of the corresponding mortars made of lime slaked by *drowning*, as to tenacity 27.10 lbs., and as to hardness 207.50 lbs.

Average strength of the corresponding mortars made of lime slaked by *sprinkling*, as to tenacity 46.70 lbs., and as to hardness 533.83 lbs.

4th. *The mortars were very materially stronger at the end of* 4 *years and* 5 *months, than at the end of the first half year.*

Of the 26 mortars which enter into this comparison, the average strength at the end of 6 months was, as to tenacity, 22.54 lbs., and as to hardness 166.33 lbs., and at the end of 4 years and 5 months it was, as to tenacity, 35.45 lbs., and as to hardness 367.37 lbs.

The relative tenacities being as 1 to 1.57, and hardness as 1 to 1.97 lbs.

5th. *Brick dust, or the dust of burnt clay, improves the quality of mortars both as to tenacity and hardness.*

6th. *Hydraulic cement added, even in small quantities, to mortars, improves their quality sensibly.*

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* Except in their being two different burnings of Fort Adams lime

7th. *The tenacity of mortars seems to have been increased by using dry bricks, and making the mortar a little more fluid than usual. But the hardness of the mortars was rather the greatest when* WET BRICKS *were used.*

In 21 corresponding instances, *wet bricks* and mortar of common consistency gave the best results, as to tenacity, in 5 instances; and, as to hardness, in 12 instances. *Dry brick* and mortar more fluid, gave the best results as to tenacity in 16 instances; and as to hardness, in 9 instances.

Table No. LXVII.

Trials in December, 1836, of mortars made in December, 1835. The results show the weights in pounds required to break prisms of mortar 2 inches square, 6 inches long and 4 inches in the clear between the supports.

No. of the comparison.	Sand No. 2.	Lime { slaked to powder with 1-3 of its bulk of water, measured in paste.	Cement A, cask No. 1, measured in paste.	Lime from the same barrel.							Lime slaked with water enough to make a thin paste—and made into mortar after 12 hours.		Lime from the same barrel.			
				Mortars made with the least possible quantity of water	Mortars made rather thin.	Mortars made with equal parts of water and bitter-water.	Mortars made with bitter-water alone.	Mortars made of cement A, cask No. 2, which required much more time to set under water than cask No. 1.	Mortar made of calcined clay instead of cement A, cask No. 1.	Mortar made of sand No. 4, instead of sand No. 2.	Stone Lime.	Shell Lime	Lime slaked with ¼ its bulk of water, after being kept sealed hermetically in a jar 3 months.	Lime slaked to cream at first, and kept in that state in a keg under ground for 3 months.	Lime allowed to slake spontaneously for 3 months.	Lime slaked to powder with 1-3 its bulk of water and kept dry in a tight keg for 3 months.
1	1		½	497	370	323										
2	1		¾	562	502											
3	1		1	655	525	703	206									
4	1		1¼	782	516											
5	1		1½	707	721	1125	483									
6	1		1¾	783	712											
7	1		2	844	694	984	452									
8	1	1	¼		117			103	115	197						
9	1	⅓	½		351		220									
10	1	1	½		155			164	178	211						
11	1	1	¾		337			173	155	412						
12	1	½	1		469		295									
13	1	1	1		426			178	206	328						
14	1	1	1¼		328			305	187	469						
15	1	1	1½		295		295	267	206	426						
16	1	1	1¾		337			305	206	351						
17	1	1	2					548		511						
18	1	1	3		417		454	455								
19	1	1	4		389		455	520		806						
20	1	1	5		492		548	530		633						
21	1	1	6		576		553	649		862						
22	1	1									206	141	401	286	253	286
23	2	1									155	129	412	225	244	
24	3	1									122	173	356	160	159	244
	4	1									131	89	286	169	150	220

Observations on Table No. LXVII.

It results from this table, and from the tables from which it has been abridged, 1st. *That in mortars of cement and sand (no lime) the strength is generally greater as the quantity of sand is less.* In 33 comparisons, 12 exceptions.

2nd. *That in mortars of sand, cement and lime—the lime remaining the same in quantity, the mortars were stronger as the quantity of sand was less in proportion to the cement.* In 57 comparisons, 10 exceptions.

3rd. *That in mortars of cement, sand and lime—the quantities of cement and sand being the same—the mortars were stronger as the quantities of lime were less.* In 52 comparisons, 15 exceptions.

4th. *That mortars made of cement and sand were materially stronger when the least possible quantity of water was used, than when the mortars were made thin.* In 14 cases, 1 exception.

5th. *That mortars made of cement and sand with the least possible quantity of water, were stronger when kept in a damp place, than when kept in a dry one.* In 7 comparisons, 1 exception. The experiments did not prove this to be true with reference to mortars made thin. These results were afforded by the experiments but are not included in the above table.

6th. *That in mixtures of lime and sand in various proportions, the mortar was generally stronger as the lime was slaked with less water.*

The average strength of several trials with 0.30 of water being represented by 80—with .40 of water, it was 98—with .60 of water, it was 72—with .80 of water, it was 60, and with 1.00 of water, it was 57. These results were afforded by the experiments, though not included in the table.

7th. *That mortars of lime and sand are materially improved by the addition of calcined clay, but not so much as by the addition of cement A.*

8th. *That sand freed from dust by washing and then pounded fine, gives much better mortars, than a sand composed of particles of every size from dust (no dirt) up to grains $\frac{1}{12}$ of an inch diameter.* In 21 comparisons, 2 exceptions.

9th. Many experiments were made to ascertain whether of two cements of the same manufactory, the difference being, probably, only difference of age, that cement which sets the quickest under water will give the strongest mortars in the air after a considerable lapse of time. The results leave the matter in doubt. The quick cement sometimes giving stronger mortars, and sometimes weaker.

10th. Of lime kept for three months after being slaked, before being made into mortar—the lime slaked into powder by sprinkling one-third of its bulk of water, gave the strongest mortar—represented by 250 lbs.; the lime slaked into cream gave the next strongest mortar—represented by 210 lbs., and the lime slake spontaneously during three months, the weakest mortar, represented by 202 lbs. All these mortars being much inferior to that made of the same lime which had been carefully preserved from slaking by being sealed hermetically in a jar—this last mortar being represented by 364 lbs. It must be remarked here that this result is very extraordinary for fat lime and sand; and it is probable this particular barrel of lime was somewhat hydraulic.

11th. Mortars of cement and sand in which bitter-water alone was mixed (Bitter-water being the mother water after the separation of muriate of soda from sea water,) were weaker than those in which water, or a mixture of equal parts of water and bitter-water, was used. But a mixture of equal parts of water and bitter-water gave much better mortar than water alone—the strongest composition we had, being cement 1½, sand 1, and equal parts of water and bitter-water. In 8 comparisons, 2 exceptions.

The trials that afforded the two exceptions were with mortars containing a smaller proportion of cement than the six others. These facts seem to show that the addition of bitter-water, within certain limits, improves the cement, but that beyond these limits it is injurious; and that where the proportions of cement are great, an increased addition of bitter-water may be advantageous. These particular experiments were made in consequence of finding that the addition of a little bitter-water hastened the setting of cement A when immersed.

12th. *Mortars of cement and sand are injured by any addition of lime whatever, within the range of the experiments; that is to say from sand* 1, *lime* $\frac{1}{8}$, *and cement* $\frac{1}{2}$; *to sand* 1, *lime* 1, *and cement* 2. No exceptions in 67 comparisons.

13th. *Stone-lime, in the proportions tried, gives better mortar than shell-lime, as* 153 *to* 133: but some previous trials had afforded results slightly the best with shell-lime.

Table No. LXVIII.

Trials made in June, 1836, *of mortars made in September*, 1835.

The results show the weights, in pounds, required to separate each inch square of surface of bricks joined by mortars. The object is to compare grout with mortar.

No.	Sand No. 2.	Lime slaked to powder and measured in paste.	Cement A.		Mortar.	Grout.
1	2	1		Lime and cement the same.	30.12	17.19
2	2	1	$\frac{1}{8}$		33.33	17.84
3	2	1	$\frac{1}{4}$		31.35	15.13
4	2	1	$\frac{1}{2}$		32.14	25.14
5	2	1	$\frac{3}{4}$		41.06	21.42
6	2	1	1		39.64	34.68
7	2	1		Lime and cement the same.	22.94	23.08
8	2	1	$\frac{1}{8}$		23.38	14.22
9	2	1	$\frac{1}{4}$		27.07	12.67
10	2	1	$\frac{1}{2}$		29.93	16.96
11	2	1	$\frac{3}{4}$		33.79	22.71
12	2	1	1		36.69	19.75

Observations on Table No. LXVIII.

In order to compare the strength of grout with that of mortar, bricks were joined (as before described) with the mortar given in the table—there being four pairs to each kind of mortar. To obtain similar joints of grout, bricks were supported on their ends and edges, in a box large enough to contain all, in such a way as to admit the proper quantity of grout to flow in between each pair. The box was not disturbed until the grout had become quite stiff, when it was first laid on one side, and then taken to pieces. The excess of grout was carefully cleared away from the bricks, which were removed without injury to any of the pairs, and put away by the side of the bricks joined with mortar.

It will be seen that, in every case but one, the grout was much inferior to the mortar. The average strength of all the mortars in the table is 31.78, and the average strength of all the grouts is 20.06

Changes of bulk on slaking lime—making mortar, grout, &c.

A great many measurements were made of the changes of bulk in the operations of slaking lime, making mortars, &c., and the results, as might be expected, varied with the qualities of the lime. The following condensation of the results may be useful.

						trials.	varying from
1 lime and	$\frac{1}{3}$	water made,	as a mean,	2.25	of powder.	27	1.56 to 2.97
1 do.	$\frac{2}{3}$	do.	do.	1.74	do.	4	1.55 to 1.83
1 do.	$\frac{3}{4}$	do.	do.	1.81	do.	4	1.63 to 1.95
1 do.	1	do.	do.	2.06	do.	4	1.77 to 2.39
1 do.	2.54	do.	do.	2.68	of thin paste.	3	2.50 to 2.82
			Slaked by drowning.				
1 do.	1.70	do.	do.	1.98	do.	6	1.73 to 2.36
			Slaked by sprinkling.				

Lime in powder.	Water.					
1	0.40	made,	as a mean,	0.66 thick paste.	2	0.65 to 0.67
1	0.50	do.	do.	0.76 thinner paste.	19	0.67 to 0.94

1 lime air-slaked gave, as a mean,	1.84	powder	3	1.37 to 2.41

1 of air slaked lime in powder and 0.50 water made, as a mean, 0.75 thin paste, 2 trials varying from .70 to .80.

1 of lime (quick) pounded to powder, made 0.90 of powder, 1 trial.

1 of lime slaked to powder, kept dry for 3 months, still measured 1.00, 1 trial.

Sand.	thin paste.	cement.		mortar.	trials.	varying from.
1	52	00	made, as a mean,	1.17	13	1.06 to 1.21
1	58	0.125	do.	1.25	23	1.70 to 1.50
1	55	0.25	do.	1.37	3	1.29 to 1.54
1	61	0.35	do.	1.43	3	1.38 to 1.57
1	72	0.50	do.	1.60	2	1.50 to 1.70
1	1.00	0.125	do.	1.78	1	
1	1.00	0.25	do.	1.85	1	
1	1.00	0.50	do.	2.18	1	
1	1.10	0.75	do.	2.14	1	
1	1.40	0.25	do.	2.20	1	
1	1.28	1.00	do.	2.36	1	
1	1.00		do.	1·71	1	
1	2.00		do.	2.14	1	

1	50	00	do.	0.32	water,	made	1.27	grout.
1	50	0.062	do.	0.45	do.	do.	1.50	do.
1	50	0.125	do.	46	do.	do.	1.55	do.
1	50	.25	do.	51	do.	do.	1.66	do.
1	50	.375	do.	52	do.	do.	1.78	do.
1	50	.50	do.	61	do.	do.	1.88	do.

202	of mortar	with 87	of water	made	290	of grout.
213	do.	87	do.	do.	305	do.
430	do.	180	do.	do.	604	do,
467	do.	201	do.	do.	660	do.
430	do.	180	do.	do.	620	do.
495	do.	176	do.	do.	664	do.
553	do.	180	do.	do.	711	do.

CHAPTER XXIV.

Observations and experiments on Concrete, &c.

It was ascertained, by careful measurement, that the void spaces, in 1 bulk of sand No. 1, taken from the middle of the heap, amounted to 0.33: the cementing paste, whatever it may be, should not be less therefore, than one-third the bulk of this sand. Taking one bulk of cement A, measured in powder from the cask, and a little compacted by striking the sides of the vessel, water was added till the consistence was proper for mortar: 0.35 of water was required to do this, and the bulk of the stiff cement paste was 0.625. To obtain, at this rate, an amount of cement paste equal to the voids (0.33) in the sand, will require, therefore, 0.528 cement in powder, and 0.185 of water, or

Dry sand,	1.000	making a bulk of 1.000 of mortar.
Cement in powder,	.528	
Water,	.185	

It is by no means certain that a mortar composed on this principle will be the most tenacious that can be made—on the contrary our experiments indicate that the mortar would be stronger with a smaller proportion of sand; but possessing the minimum quantity of cementing constituent, which is by far the most expensive ingredient, it affords the cheapest admissible mortar, made of cement and sand; and as it was probable, that it would shrink very little on drying, it was tried as a *pointing* for exposed joints, and also as *stucco*, and it answered very well for both purposes—becoming very hard, and never showing the slightest crack. An excess of cement, and a very *slight excess of water*, above the stated proportions, should be allowed for imperfect manipulation, because the proportions suppose every void to be accurately filled.

Extending the application of this principle to concrete—experiment showed that one bulk of stone fragments (nearly uniform in size, and weighing about 4 oz. each) contains 0.482 of void space. To convert this bulk of stones into concrete, we, in strictness, need use no more mortar than will fill this void space; and to compose this mortar we need use no more cement than is necessary to occupy, in the state of paste, the voids in 0.482 of sand. This concrete would therefore be composed as follows:

Stone fragments about 4 oz. each,	1.000	making a bulk of 1.000 of concrete.
Sand No. 1 . .	.482	
Cement in powder, .	.255	
Water, . .	.089	

Obtaining thus a cubic yard of concrete by the use of one-fourth of a cubic yard of cement in powder, (about one and a half bbls.)

But the above fragments were of nearly equal size, and of a form approaching the spherical: affording more void space than if they had been more angular, and had varied in size from about six oz. to less than one oz. such as would commonly be used. We have found that clean gravel, quite uniform in the size of the pebbles, which were about half an inch in average diameter, afforded voids to the amount of 0.39. And Mr. Mary, a French Engineer, used pebbles, probably mixed of coarse and fine, of which the voids were 0.37. The above allowance of 0.482 for void space is therefore quite large.

In all cases of the composition of concrete, the quantities expressed above, should be ascertained by actual measurement of the particular cement, sand and fragments, or pebbles, that are to be used. No better mode of measuring the void spaces, will be found, probably, than measuring the quantity of water that can be poured into a vessel already filled with stone fragments, pebbles, or sand, as the case may be.

Although the hydraulic property of cement will be the cause, in all cases of its use in concrete, it may happen that the cement at hand is more energetic than is actually necessary, and that the concrete would fully accomplish the object in view, even if it should be two or three weeks in becoming hard and impervious to water. Under such circumstances lime may take the place of part of the cement, with great economy. The lime may be added either in the state of powder that has been slaked some time, or in the state of paste: but in either case, the previous slaking must be complete.

The mortar is to be made first, and then the pebbles, or broken stones, may be mixed therewith by turning them over several times with the shovel.

When it is to be deposited under water, it is still a disputed point whether the concrete, prepared as above, should be used immediately, or be left in heaps to stiffen to such a degree as to require the use of pickaxes to break down the heaps: but, in works out of water, there can hardly be a case in which it will not be best to place it at once in its allotted space, where it should be compacted by ramming till none of the stone fragments project above the common surface. One or two trials will show how much mortar over and above the strict proportion is necessary in each case.

In circumstances where ramming cannot be applied, as when depositing concrete in deep water, the concrete should be more yielding and plastic —containing a larger proportion of mortar, and the mortar should be rammed before being deposited, in order thoroughly to imbed the larger constituents.

In many situations where concrete may be resorted to with great advantage, the economy need not stop at the above proportions. This substance may be rammed between, and upon, stones of considerable size—the only indispensable precaution being, to make sure that the stones are perfectly clean, are well imbeded in the concrete, and are far enough apart to permit the full action of the rammer between them.

The following case occurred at Fort Adams in October, 1836.

The proportions adopted were, *fragments of granite*, of

nearly uniform size, and about 5 oz. each,	1.000	Bulk of concrete, a little more than 1.000.
Sand No. 1	0.500	
Cement A, in powder,	0.280	
Water rather more than	0.100	

Experiment gave 16.683 as the number of cubic feet of concrete made by 1 barrel of cement—187 barrels were consumed which afforded 115.52 cubic yards of concrete. There were also used, 11.29 struck Winchester bushels of sand, and 22.58 struck Winchester bushels of granite fragments.

187	barrels of cement at $2.45	$ 458.15
1129	struck bushels of sand at $.0.37	41.77
2258	do. granite fragments at $0.04	90.32
	Carried over,	$ 590.24

Brought over,	$ 590.24

There were 151 days labour, applied to making mortar—making concrete—depositing the concrete in its proper place, ramming it into a compact mass, and doing all other work required in the operation.

151 days at $ 0.92.	138.92
Supervision	10.00
Cost of 115.52 cubic yards,	$ 739.16

Cost of one cubic yard $ 6.40

Springs of water flowed over this work continually; and were allowed to cover each day's work. The next morning the concrete was always found hard and perfectly set.

Had we dispensed with one half of the cement used, and used in lieu thereof, as much paste of lime, as the cement dispensed with would have furnished of paste of cement, the cost would have been materially reduced, and the work have been still very hydraulic, and very strong. In that case, the bulk would not have been altered, but would have been as before, 115.52 cubic yards. We should have used 93½ bbls. of cement less than we did: and, as cement, in passing to the state of paste, diminishes in bulk in the proportion of 1 to .625, we should have used 93.5×.625 equal to 58.43 barrels of paste of lime. Saving, thereby, the difference between the cost of 93.5 barrels of cement and 58.43 barrels of paste of lime.

93.5 barrels of cement at $ 2.45	$ 229.07
58.43 do. of paste of lime at $ 0.60	36.06
Amount saved	$193.01

$ 739.16, less $ 193.01, equal $ 546.15; the cost of 115.52 cub. yards.
Cost of one cubic yard $ 4.73.

Another Instance.

Proportions—Clean gravel,	1.000	Bulk of concrete about 1.15
Sand No. 1,	.530	
Cement A, in powder,	.430	
Water about,	.140	

This was rammed into a mould of the capacity of 13.786 cubic feet.

Cement A,	4.35 struck bushels	at $ 0.59		cost $ 2.57
Sand No. 1, washed	5.44	do.	" 0.04	.22
Gravel	10.00	do.	" 0.04	.40
Cost of all the labour,				1.03
Total cost of 13.786 cubic feet,				$ 4.22

Being $ 0.306 per cubic foot, or $ 8.26 per cubic yard.

This became very hard, and is a very good substitute for stone, in certain applications.

Another Instance.

Proportions—Clean gravel,	1.000
Sand No. 1,	.625
Cement A, in powder,	.333
Water, about	.125

This was rammed into a mould of the capacity of 7.812 cubic feet; and the whole cost was $ 2.15, being $ 0.276 per cubic foot, or $ 7.45 per cubic yard.

This became a hard mass, but the concrete was rather too incoherent to make the best factitious stone.

Another case.

In this instance, a box containing 7.812 cubic feet was filled, first, with pieces of a stone of slaty structure—laying the pieces on their beds; a grout was then poured in, until all the interstices were filled. The composition of grout was as follows.

Washed sand No. 1,	1.000
Cement A in powder,	1.000
Water,	.910

The whole cost was $2.40—being $0.31 per cubic foot—or $8.37 per cubic yard.

This mass became hard, but was not so strong as those made of mortar instead of grout.

Numerous objects have, at different times, been moulded at Fort Adams, with analogous compositions, and always with success. Sometimes concrete was used, the entire mass being rammed into the mould: at other times the mortar without the fragments was used *as mortar*; bricks, or fragments of stones, being laid therein, in successive strata, until the mould was filled. Shafts of columns—the Doric echinus, abacus, &c., thus formed many years ago, resist the climate well, although less perfect than we should now be able to produce.

All our experiments concur in showing that much sand weakens cement mortar essentially; at least when exposed to the air. The improvement to be applied to the foregoing proportions should consist therefore, if the expense be no objection, in increasing the quantity of cement—taking care to keep the quantity of water as low as possible, in order to retain the shrinkage of the indurated mass at a minimum. It is surprising how much water may be driven out of an incoherent and apparently half-dry heap of cement-mortar, by hard ramming: and it is still more surprising, after the exact quantity necessary to saturation has been supplied, how small a quantity of water will suffice to convert a dry and powdery heap, if well worked, into a thin paste. Cements vary in their capacity for water: hence the dose of water is a matter that must be established by experiment in each case. The true quantity for concrete, and moulded objects in air, is that which, with hard ramming, affords a stiff paste, with a *little* free water on the surface: a state to which it can be brought with difficulty under the trowel or under the shovel. More water than this is attended with the double disadvantage of lessening the density of the mortar when dry, and of causing cracks by the shrinkage. If the quantity of water be thus regulated, the quantity of cement may be increased at pleasure, but the expense will increase rapidly with every addition of cement. In the first concrete above, the bulk of the dry cement is about one half the bulk of the sand, and the expense per cubic yard is $6.40; make the dry cement to equal the sand in bulk, and the expense per cubic yard will be about $10.00, all other proportions remaining, as they ought, the same.

In the preceding proportions it has been supposed that the concrete was to be used in the air, and that nothing would prevent the free use of the rammer. But if the concrete is to be deposited under water beyond the reach of this instrument, there should be a change of the proportions; and the quantity of mortar should be so increased that the fragments will be certain to be severally imbedded therein from their own weight, the gentle operation of the rake and other leveling instruments, and the pressure of the superincumbent concrete. Attention must be paid to the constituents of the mortar, in reference to hydraulic energy, also, especially in running water: this mortar must not only be very hard after a time—it must become hard speedily; and to attain this end, the materials at command may demand proportions quite different from those required to fill the voids in the sand.

The following instances are derived from the practice of the French.

M. Mary, Engineer des Ponts et Chausseés, states that he ascertained the voids between the stones to be .37 of the whole bulk—that filling .90 parts of a box with stones, .10 parts+(.37×.90=.33)=.43 parts of mortar would be required, in theory, to fill the box: but he found that the box was more than full, showing that some of the mortar designed to occupy the voids did not reach them, from imperfect manipulation. Instead of .90 parts, he then filled .87 parts of the box with stones, which required that the mortar should amount to .13+ (.37×.87=.32) =.45 parts of mortar; and this he found filled the box very exactly. He also found that the transportation of the concrete, in wheelbarrows, from the mortar bed to the place where it was to be deposited, produced agitation enough to settle all the stones to their places, and bring the excess of mortar to the top. M. Mary is not aware that so large a proportion of stones had been employed any where else than at Pont-de-Remy, at Abbeville, and at the upper dam of Saint Valery; but at these places, no disadvantage resulted from the quantity, and the concrete was impervious to water. The mortar mixed with these stones was composed of 0.22 parts of feebly hydraulic lime measured in paste—0.225 of sand—and 0.225 of brick, or tile, dust (''*cement.*'') The proportions of this concrete were therefore, as follows:

	Stones,	.87	Total bulk 1.000
	Sand,	.225	
	Brick, or tile dust,	.225	
	Feebly hydraulic lime in paste	.22	
	Water,		
Or—	Stones,	1.000	1.15
	Sand,	.259	
	Brick or tile dust,	.259	
	Feebly hydraulic lime in paste,	.253	
	Water,		

At the lock of Haningue the cube of concretes was composed as follows:

Pebbles,	.69	Bulk 1.00
Sand,	.40	
Hydraulic lime in paste,	.22	
Water,		

As to this case M. Mary observes that it is probable the pebbles were a mixture of coarse and fine gravel; because, with these quantities, in order to make up the cube of 1.00, the void spaces could amount to only about .09. This would be about 13 per cent. only of the measure of the pebbles, instead of 37, found by M. Mary, himself, in the case stated above. Expressing, as in the other cases, the proportions used at this lock, in parts of the measure of pebbles—it would stand thus,

Pebbles,	1.00	Bulk 1.45
Sand,	.58	
Hydraulic lime in paste,	.32	

To found the pier of the suspension bridge communicating between la Grève and l'ile de la Cité, at Paris, a concrete was used which was much more hydraulic than those just mentioned. It was thus composed:

Fragments of Buhrstone,	1.00	Resulting bulk 1.50
Sand,	.50	
Factitious puzzolana of M. St. Leger,	.25	
do. hydraulic lime do. (unslaked)	.25	
	2.00	

This concrete was placed in a bed eight feet thick, which, owing to a flood in the Seine, was about six weeks in being deposited. Masonry was begun upon it in eight days after its completion, and in six weeks it had the whole pier to support; and before the concrete was four months and a half old it sustained the weight of the pier of the bridge, and of the proof load, without the least appearance of subsidence.

At the Saint Martin canal, where great quantities of concrete were used, the proportions were:

Pebbles,	1.00	Bulk 1.63
Sand,	1.00	
Hydraulic lime	.33	

In another case, these proportions were used, viz:

Siliceous pebbles,	1.00	Bulk 1.34
Tile dust and brick dust,	.28	
Fat lime made from chalk used at the moment of slaking—measured as quicklime,	.56	
Water, more or less,	.53	

Another case.

Rounded gravel about the size of a hazle-nut,	1.000	Bulk 1.15
Mortar, . .	0.500	

The mortar being composed of brick-dust,	1.00
Slaked lime, in powder,	1.00
Sea-sand,	1.00

After three months immersion in salt water, this concrete sustained a pressure on one end of the mass of 260,000 pounds per square foot of surface without impression. On being broken up, it showed that the gravel was well imbedded in mortar. The void space in the gravel was found to measure 0.35.

Another.

The aqueduct of Guétin, which conducts the Loire canal across the Allier, is composed of 18 arches of 53½ feet span, and of 17 piers of 9.84 feet in thickness. Immediately at one end of the aqueduct are three connected locks, whereof the mass forms the left buttress of the bridge.

The right buttress and its wing-walls, the 17 piers, and the three connected locks, are built on a general "*radier*" or platform, 1594 feet long, 57.42 feet wide, and 5.41 feet thick; on the upper and lower sides of the platform are two guard walls 6.56 feet thick, and 14.76 feet deep—these walls, like the rest of the platform, rising to within 1.64 feet of the level of the water in the river in its lowest state.

The whole of the guard walls, as well as the lower layer of the platform for a thickness of 3.28 feet, were formed of concrete deposited in the water. The concrete used amounted to near 22,000 cubic yards.

The operation of depositing the concrete was confined to the 4 or 5 months between the spring and autumn floods; and at the end of the second season it supported the superstructure above described.

The following is the composition of the concrete:

Stone fragments,	1.000
Mortar,	1.000

The mortar was composed of sand,	1.50
Hydraulic lime measured in powder,	1.00
Artificial puzzolana of M. St. Leger,	0.50

And the puzzolana was formed by calcining, at a heat not great, a mixture of four parts of earthy clay measured in paste, and one part of fat lime measured in the same way—the mixed pastes being formed into small prisms, dried in the sun, calcined and pulverised.

In order to obtain some evidence of the actual strength of concrete, and to compare several varieties of compositions, the experiments contained in the following table were made at Fort Adams: some prefatory remarks are necessary in relation to them.

The *cement* was obtained by taking several casks of hydraulic cement A, of nearly equal energy—emptying them into one heap on the floor, and after mixing the contents intimately, returning the cement into the casks, and heading them all tightly, until they were severally wanted. As the casks were opened, in succession, for use, the quality of the mixture was tried with the test wire, and was found to be very uniform—about half an hour being required for the setting. This cement had been on hand about four months.

The *lime* used was Fort Adams' unground lime. It was slaked to powder by the affusion of one-third its bulk of water, and allowed to stand several days. As it was about to be used, it was reduced to paste and passed through a hand paint-mill, by which it was made very fine. It should be borne in mind that this lime is slightly hydraulic.

The *sand* used was sand No. 1

The larger constituents of the concrete were of four kinds, viz: 1st. *granite fragments,* angular, average weight of each 4 oz.; 2d, *brick fragments,* angular, average weight 4 oz.; 3d. *stone-gravel,* made up of rounded pebbles from ½ to ¾ of an inch in diameter; and, 4th. *brick gravel,* composed of angular fragments of bricks from ½ to 1 inch in their greatest dimensions. All were perfectly free from dirt, and were drenched with water before mixing them with the mortar.

The measure of the void spaces in the granite and brick fragments was .48; and of the stone gravel and brick gravel, .39.

One set of experiments was made by using, in each case, a measure of mortar equal to the measure of void space—and another set, by using two such measures of mortar.

The mortar was made witn as small a quantity of water as possible. On this account, the mixture of the constituents was probably somewhat imperfect; and to this may, in part, be attributed the irregularities observable in the results. The concrete, before ramming, was quite incoherent, especially when only one measure of mortar was used. It was, in every case, consolidated by ramming into boxes that afforded rectangular prisms of concrete 12 inches by 6 inches by 6 inches.

The prisms were made in December 1836, and being kept in a damp place, safe from frost and accident, were broken in June, July, and August following. In breaking the prisms the two edges of the supports were 9 inches apart, leaving $1\frac{1}{2}$ inch resting at each end: weights were applied, by adding about 60 lbs. at a time, to a scale-pan suspended from a knife edge which bore on the middle of the prism.

Table LXIX.

Trials made in June, July and August, 1837, of the strength of concretes made in December 1836. The results show the weight in pounds required to break prisms of concrete 12 inches by 6 inches by 6 inches—the distance between the supports being 9 inches.

No.	Composition of the Concrete.	Mortar No. 1. Cement A. 1.00 Sand No. 1. 0 Lime 0	Mortar No. 2. Cement A. 1.00 Sand No. 1. .50 Lime 0	Mortar No. 3. Cement A. 1.00 Sand No. 1. .50 Lime .25	Mortar No. 4. Cement A. 1.00 Sand No. 1. 1.00 Lime 0	Mortar No. 5. Cement A. 1.00 Sand No. 1 1.00 Lime .25	Mortar No. 6. Cement A. 1.00 Sand No. 1. 1.50 Lime 0	Mortar No. 7. Cement A. 1.00 Sand No. 1 1.50 Lime .25	Mortar No. 8. Cement A. 1.00 Sand No. 1. 2.00 Lime 0	Mortar No. 9. Cement A. 1.00 Sand No. 1. 2.00 Lime .25
1	Granite fragments, with 1 measure of mortar	4973	4142	2778	3989	2721	2045	2056	lost	1574
2	do. with 2 do.	4068	4983	5064	4088	5366	1547	3537	1643	1972
3	Brick fragments, with 1 measure of mortar	3242	2117		4127	3254	1788	2136	1567	3649
4	do. with 2 do.	2805	5047	2826	4232	1178	3655	3856	2320	4803
5	Stone gravel, with 1 measure of mortar	1097	1049	1240	1256	1066				
6	do. with 2 do.	2347	4247	2655	1295	3351				
7	Brick gravel with 1 measure of mortar	5437	6183	3088	lost	4726				
8	do. with 2 do.	6025	5712	5480	3142	2699				
9	Stone fragments, grouted,	3278	1846	2012	1158	1178				
10	Brick fragments, grouted,	1634	2305	2869	2726	2770				

Observations on the experiments given in the above table.

It is to be regretted that such discrepancies are to be noted in the table. They are ascribable, in the first place, as suggested above, to the difficulty of bringing the mixture always to the same condition as regards the dissemination of the ingredients, when worked in so dry a state; but, probably, chiefly to the difficulty of filling the moulds always with equal accuracy, and ramming every part with equal force, when using so incoherent a mortar, united with so large a proportion of very coarse ingredients.

Notwithstanding these discrepancies, however, several deductions may be fairly drawn from the table, which, if confirmed by future trials, will be useful.

1st. *When the mortar was made of cement, sand, and lime, or of cement and sand without lime, the concrete was the stronger as the sand was less in quantity* In 50 comparisons 19 exceptions. *But there may be* 0.50 *of sand and* 0.25 *of lime without sensible deterioration; and as much as* 1.00 *of sand and* 0.25 *of lime, without great loss of strength.*

2d. *A mortar of cement and sand does not seem to be improved by the addition of lime, while the bulk of sand is only equal to, or is less than, the bulk of cement; but as the quantity of sand is further increased, the mortar appears to be more and more benefitted by the addition of a small quantity of lime.*

3d. *Two measures of mortar, in concrete, are better than one measure; that is to say, a quantity of mortar equal to the bulk of the void space does not give as strong a concrete as twice that quantity of mortar.* In 30 comparisons, 7 exceptions. Nevertheless, the strongest example was with one measure of mortar, and it is not unlikely that the deficiency of strength in the other cases resulted from the difficulty of causing all the voids to be accurately filled, when the mortar was a minimum, and the space into which it was forced so small. It is not improbable that the voids may be perfectly occupied, even with one measure of mortar, when the mass of concrete is large enough to permit the full effect of the rammer.

4th. The results of the experiments recommend the several compositions of the table, in the following order, namely:

1.	Brick gravel,	with 2	measures of mortar,	No. 8.
2.	do.	with 1	do.	7.
3.	Brick fragments,	with 2	do.	4.
4.	Granite fragments,	with 2	do.	2.
5.	do.	with 1	do.	1.
6.	Brick fragments,	with 1	do.	3.
7.	Stone gravel,	with 2	do.	6.
8.	Brick fragments, grouted			10.
9.	Stone fragments, grouted			9.
10.	Stone gravel,	with 1	measure of mortar	5.

5th. *It appears that the best material to mix with mortar to form concrete, is quite small, angular, fragments of bricks: and that the worst is small, rounded, stone-gravel.*

6th. *Grout, poured amongst stone, or brick fragments, gave concretes inferior to all, but one, of those obtained from mortars.*

A piece of sound and strong *red sand-stone*, 12 inches by 4 inches by 4 inches, required a weight of 3673 pounds to break it—there being 9 inches between the supports. According to the formula $P = R.\frac{ab^2}{c}$,* prisms of

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* In this formula P is the weight causing fracture, c the distance between the supports, a the breadth, and b the depth of the prisms.

this stone of the size of our prisms of concrete, would require the weight of 12,396 lbs. to break them; whence it appears that the strongest prism under trial, was, after eight months exposure, half as strong as this sand stone.

CHAPTER XXV.

Some recent experiments with Mortars made of Lime and Sand.

There will be presented, in conclusion, some experiments, made very recently at Fort Adams, with lime mortars without cement; they were instituted in reference to the best proportions of lime and sand, and also to a comparison of coarse and fine sand, and salt and fresh water.

In making these, a cask of fresh Smithfield lime, of the best quality, was taken, and the lumps broken into pieces of about the size of a pigeon's egg. These being carefully screened, in order to get rid of all dust and fine lime, and carefully intermixed, in order to obtain uniformity of quality throughout, were slaked by the affusion of water to the amount of one third the bulk of lime. When cold, the slaked lime was returned to the barrel, which was carefully headed and put in a dry place; and on all occasions of withdrawing a portion of this lime for use, the cask was carefully re-headed.

The sands used were those described in page 4, as sand No. 1, sand No. 2, sand No. 3, and sand No. 4.

In making the mortars, just enough water was added to the slaked lime taken from the cask, to make a stiff paste. This paste being passed through a hand paint mill, which ground it very fine, was mixed, by careful manipulation, with the due proportions of sand. Much care was bestowed upon the operation of filling the prism-moulds with mortar; and each prism was submitted to a pressure of 600 lbs. for a few minutes, that is to say while the succeeding prism was being formed.

About one week was consumed in preparing the prisms—namely, from the 7th to the 15th of May, 1838. And they were broken on the 1st of July, 1838, making the average duration of the experiment, 50 days.

Three prisms were made of each composition. But, on the principle that there are several causes which tend to make a prism weaker than it should be, and few or none that tend to make it stronger, only the maximum result of eaoh experiment is given in the following table.

It may, however, be well to state that precisely the same inferences are deduceable, if the mean of the results be taken instead of the maximum.

Table No. LXX.

Trials made on the 1st of July, 1838 of the strength of the mortars made between the 7th and 15th of May, 1838 (50 days.) The results show the weights, in pounds, required to break prisms of mortar 6 inches long, by 2 inches by 2 inches: the distance between the supports being 4 inches, and the power acting midway between the supports.

Composition of the mortars.	Sand No. 1.—Lime. Fresh water.	Sand No. 2.—Lime. Fresh water.	Sand No. 3.—Lime. Fresh water.	Sand No. 4.—Lime. Fresh water.	Sand No. 1.—Lime. Salt water.	Sand No. 3.—Lime. Salt water.
Lime in stiff paste 1—Sand 0	262½					
do. 1 do. ¼	224	220½	248½	353½	192½	234½
do. 1 do. ½	213½	234½	234¼	241½	210	199½
do. 1 do. 1	248½	220½	227½	234½	178½	178½
do. 1 do. 2	164½	199½	161	178½	140	178½
do. 1 do. 3	157½	189	185½	157½	119	119
do. 1 do. 4	126	227½?	157½	136½	101½	154

Observations on the experiments of table No. LXX.

1st. Within the limits of the experiments, the mortar was the stronger as the quantity of sand was the less—in 96 comparisons, 12 exceptions.

2nd. Although the above inference is derived from the whole range of the table, still, when the quantity of sand was less than the quantity of lime, the weakening effect of the sand on the mortar was not very sensible. And it would seem from table No. LXV. that from one-fourth to one-half of sand may be slightly beneficial.

3rd. It appears that coarse sand, or, rather, sand composed of coarse and fine particles, (sands No. 1 and 2,) is a little inferior to sand that is all fine (sands No. 3 and 4;) in 36 comparisons, 16 exceptions; and also that sand reduced by pounding to a fine powder (No. 4,) afforded some of the best results of the table. It is to be regretted that no experiments were instituted in order to compare sand all coarse, with sand all fine.

4th. It appears that the mortars made with salt water—that is to say, the water of the ocean, was decidedly weaker than those made with fresh water; 1 exception in 12 comparisons. The aggregate strength of all the prisms made of coarse sand and salt water was 2674 lbs.; while the aggregate strength of the corresponding prisms of coarse sand and fresh water was 3174 lbs. And the aggregate strength of all the prisms of fine sand and salt water was 2800lbs. while the aggregate strength of the corresponding prism of fine sand and fresh water was 3346 lbs.

DESCRIPTION OF THE PLATES.

PLATE I.

Fig. 1. *a*, *a*, Prism of mortar under trial.

b, *b*, Iron stirrups, supporting the prism.

c, *c*, Iron collar, embracing the prism.

d, *d*, Iron link, to which the ropes of the scale-pan are fastened.

e, *e*, check, against which the collar rests when on the middle of the prism.

f, *f*, Timber, to which the stirrups are attached.

g, Scale pan, in which the weights to break the prism are put.

Fig. 2. *h*, Interior of the furnace.

i, Door of the furnace.

k, *k*, Chimney

l, Register.

m, *m*, Arches, under the hearth, in which the fuel is placed.

n, *n*, Conduits, to lead the flame and a current of air into the furnace.

Fig. 3. *o*, Plan of lime kiln.

p, *p*, Nut of the kiln.

q, *q*, Steps descending to the doors of the kiln.

r, Steps, up which the materials are carried to the top of the kiln.

s, *s*, Doors of the kiln.

t, *t*, Portions of spherical arches leading to the doors of the kiln.

PLATE II.

Figs. 4, 5, 6, 7 and 8, represent Mr. Petot's "*curves of energy*" of fat lime, hydraulic lime—plaster-cements—calcareous puzzolanas, and clay.

Fig. 9. *a*, *b*, Half staples, driven into the floor.

f, *g*, A pair of bricks united by mortar.

c, *c*, Iron piece, embracing the ends of the upper brick, and suspended from the steelyard.

d, Steelyard.

e, Bucket, into which sand flowed from the trough.

h, Trough.

i, Floor.

Fig. 10. *a*, *b*, *c*, Iron lever, with a steel point at *a* to impress the mortar *f*, on the brick *g*.

d, Steelyard, connected with the lever *a*, *b*, *c*, at *c*.

e, Iron rod, from which the steelyard is suspended.

h, *h*, Uprights, supporting the rod *e*.

i, Uprights of iron, supporting the fulcrum of the lever *a*, *b*, *c*.

FINIS.

Plate 1.

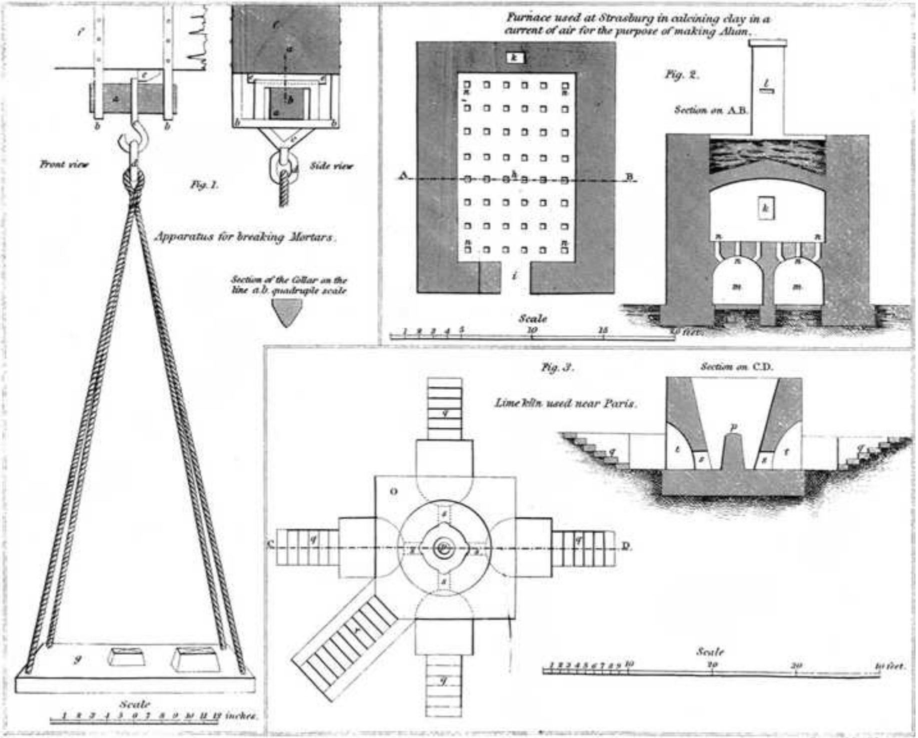


Fig. 1.
Apparatus for breaking Mortars.
Front view
Side view
Section of the Collar on the line a.b. quadruple scale
a
b
c
e
g
Scale
1 2 3 4 5 6 7 8 9 10 11 12 inches.
Fig. 2.
Furnace used at Strasburg in calcining clay in a current of air for the purpose of making Alum.
Section on A.B.
A
B
h
i
k
l
m
n
Scale
1 2 3 4 5 10 15 20 feet.
Fig. 3.
Lime kiln used near Paris.
Section on C.D.
C
D
O
p
q
r
s
t
Scale
1 2 3 4 5 6 7 8 9 10 20 30 40 feet.

Plate II.

Fig.4.

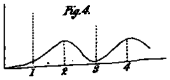


Fig.5.

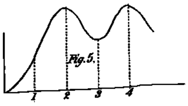


Fig.6.

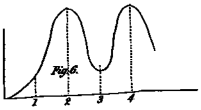


Fig.7.

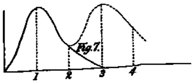


Fig.8.

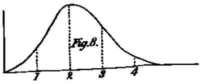


Fig.9.

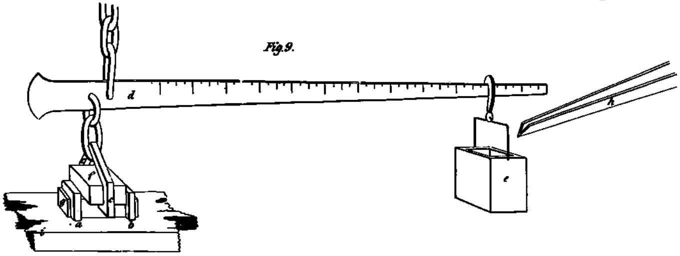
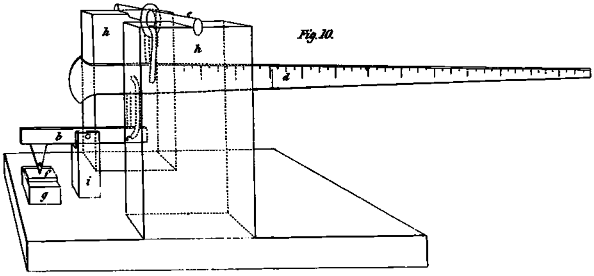


Fig.10.



ERRATA.

PAGE.
8. Line 29 from top—for *Berard*, read *Brard*.
26. Table 4, last column—for 22 lbs, read —22 lbs.
33. Table 8, No. 3—for 1 day required to harden in water, read 1½ day.
35. 8th line from bottom—for *pharmaciеur* read *pharmacien*.
37. Table 9, last column, 2 lines from bottom—for 197 lbs., read 187 lbs.
42. Line 6 from top—for *one-fifth*, read *one and a half grammes*.
44. Table 10, No. 5—for 1 day, read 15 days.
" " No. 10—for 24 days, read 25 days.
45. Line 3 from top—erase the *;* after the word lime.
49. Table No. 11, No. 2—for 3-10 of pipe clay, read 2-10.
" Line 5 from bottom—for 1-10 read 2-10.
57. Table No. 14, 8th column—for 96 read 396.
" " " for 3*d* read *d*.
" " 11th " for 86 read 385.
61. Line 14 from top—insert the word *the*, before the word *three*.
" Line 4 from bottom—for *table* read *tables*.
" Bottom line—insert the word *good*, before *resistance*.
65. Line 3rd from bottom—erase *up*.
66. Last line in the note—for 194 lbs., read 191 lbs.
76. Table No. 22, No. 12—for *dust of clay No*. 9, read *dust of clay No*. 8.
77. Line 20 from bottom—for *Haquenau*, read *Haguenau*.
78. Table No. 23, No. 9—for *same clay with* 1-6 *do*., read *same clay with* 1-4 *do*.
" " " 6, in last column but one—for 15, read 25.
80. Table No. 24, Nos. 15 and 16—for *Kilbsheim clay*, read *Kolbsheim clay*.
84. Line 13 from top—for *vigorously*, read *rigorously*.
85. Line 15 from bottom—for *the bad mortar*, read *the last mortar*.
90. Line 15 from top—for *are as follaws*, read *cost as follows*.
91. Line 12 from top—for *preparation*, read *proportion*.
101. Table No. 28, No. 15, last column—for 405, read 385.
105. Line 24 from bottom—for *attach*, read *attacks*.
107. Line 20 from top—insert the word *dissolved*, after the word *had*.
" Line 6 from bottom—for *nearly*, read *merely*.
109. Line 17 from top—insert the word *always* after the word *not*.
110. Line 2 from top for *thorough*, read *thoroughly*.
" In the table, last column—for 0.3500, read 0.3300.
112. Line 2 from top—for *lamelleo*, read *lamelles*.
122. Line 6 from top—for *poured*, read *formed*.
129. Line 10 from top—for *mortars*, read *matters*.
" Line 11 " " "
" Line 17 " for *difficult*, read *different*.
133. Line 13 from bottom—for *le mortar que*, read *le mortier qui*.
134. Line 9 from top—for *that the lower*, read *the lower*.
136. No. 3 of table 32—for 1 *of lime and* 1 *of sand*, read 1 *of lime and* 2 *of sand*.
137. Table No. 33, No. 1—for 50 lbs., read 55 lbs.
" " When 22 lbs. occurs in the table, it should be preceded by the negative sign.
138. Line 6 from bottom—for *Table No*. VI, read *Series No*. 6.
139. Table No. 34, last column—for 10, read —22.
142. Table No. 35, No. 4—for 262 lbs, read 242 lbs.
143. Line 21 from top—for *shows*, read *shew*.
146. Line 2 from bottom—for *Article* XIII., read *Chapter* XIII.
" Bottom line—for *Article*, read *Chapter*.
147. Top line—for *Article*, read *Chapter*.
149. Line 16 from top—for XXVII, read XXXVII.
156. Line 7 from bottom—insert the word *in* after the word *cement*. and erase the comma.
157. Line 2 from top—for *should*, read *would*.

PAGE.	
160.	Line 18 from bottom—for *pieces*, read *piers*.
"	Line 17 " do do
161.	Line 9 from bottom—for *least*, read *last*.
164.	Line 12 from top—substitute for *or*, the words *such as*.
"	Line 16 " substitute for *wrong*, the word *advantageous*.
168.	Line 7 " for *amelioracion*, read *amelioration*.
"	Line 7 " for *work*, read *works*,
177.	Line 22 from bottom—for *trass*, read *copper*.
180.	Table 48, last line—for *calcined*, read *melted*.
"	Line 4 from bottom, and in every other case where the word occurs—for *plastic cements*, read *plaster-cements*.
184.	Line 27 from bottom—insert the words *stone of the*, before the word *Pouilly*.
189.	Table 51, 3d column—for 54, read 51. 4th column, for 51, read 54.
190.	Line 5 from top—for *cases*, read *causes*.
"	Table 52, 7 line from top—for *one-half of quartzose sand*, read *one of quartze sand*, and in the last column, for 12.31, read 13.31.
"	Line 10 from bottom—for *Biard*, read *Brard*.
198.	Line 16 from bottom—for 76.00, read 74.00.
211.	Line 9 from top—for *that of* 1-5 *of clay*, read *as much as* 1-5 *of clay*.
213.	Line 16 from top—for *Rine de Geir*, read *Rive-de-Gile*.
219.	Table 57, column 3—for *clay from Bidoreau*, read *clay from Bedouan*.
222.	" 60, column 4—for 0.159, read 0.059.
"	" " 5—for 0.019, read 0.059.
223.	Table 61, column last—for 19, read 79.
225.	Table 63, No. 17—for *minerals*, read *mineral*.
226.	Table 64, No. 10—for 09.4, read 59.4.
"	" No. 53—for 293.8, read 239.8.
227.	Bottom line—for *three*, read *thin*.
229.	Line 16 from bottom—for *instance*, read *instants*.
232.	Line 10 from top—insert the words *each result*, before the word *unless*.
233.	No. 19—for *Sand, No.* 3, read *Sand, No.* 2.
239.	No. 9, 3d column—for $\frac{1}{3}$, read $\frac{1}{8}$,
242.	Line 25 from bottom—for 1.70, read 1.10.
244.	Line 8 from bottom—for 11.29, read 1129.
"	" 7 " for 22.58, read 2258.
"	" 4 " for $0.37, read $0.037.
247.	Line 16 from bottom—for *Haningue* read *Huningue*.

STP1494-EB/Mar. 2008

HANDBOOK

OF

RAILROAD CONSTRUCTION;

FOR THE USE OF

AMERICAN ENGINEERS.

CONTAINING THE

NECESSARY RULES, TABLES, AND FORMULÆ

FOR THE

LOCATION, CONSTRUCTION, EQUIPMENT, AND MANAGEMENT OF
RAILROADS, AS BUILT IN THE UNITED STATES.

With 158 Illustrations

BY

GEORGE L. VOSE,
CIVIL ENGINEER.

"Rules themselves oblige us to reflect, that we may see whether we have not departed from them." — Napoleon.

BOSTON AND CAMBRIDGE:
JAMES MUNROE AND COMPANY.
1857.

CHAPTER XI.

MASONRY.

STONES.

262. THE varieties of this material most commonly used in engineering operations are granites, limestones, sandstones, slates, brick, and artificial stones; the latter being made by compounding clays, limes, and cements.

Rock taken from the surface, which has been exposed to the atmosphere, is of an inferior quality to that found at a depth where it has been exposed to a strong pressure; and is consequently denser. Therefore, in opening a quarry it is advisable to excavate upon a hill-side and come at once to the sound stone. Rock is generally found in beds, divided by joints or seams, at which the natural adhesion is broken and the layers are easily separated. When the quarry shows no natural line of separation, one may be produced by drilling a line of holes at equal distances from each other, into which conical steel pins are driven, and the stone splits; the pins being placed in the plane of the required seam.

263. Stone is used almost entirely to resist a compressive strain; as in the voussoirs of an arch, or in the courses of a pier. The resistance of stone to crushing, is as follows:—

	Pounds per square inch.
Granite	10,000 to 16,000
Limestone	12,000 to 14,000
Sandstone	10,000
Marble	9,000 to 14,000
Firm, hard burned brick	2,600
Yellow burned brick	1,500
Red brick	1,200
Pale-red brick	900
Chalk	750

264. When stone cannot be found, brick forms an excellent substitute; being made from clay earths, which can be found in almost any locality. Bricks are well fitted for nice work, are cheap, and easy of transport. The French, at Algiers, have used concrete, rammed in boxes so as to make large cubes and other shapes. The structures built of this material are found to be very nearly if not quite as strong as those of natural rock.

LIMES, CEMENTS, MORTARS, AND CONCRETES.

265. Nothing is more important in the construction of masonry than good cement; and generally, no part of construction is intrusted to more ignorant persons. Under the above head are to be considered limes, cements, sands, common hydraulic mortar, and concrete.

266. Lime is obtained by burning off the carbonic acid from the pure limestones; when it is put up in air tight barrels and is unslacked lime. Natural cements are composed of pure lime mixed with argyle magnesia, iron, and manganese. Artificial cements are prepared by mixing with pure lime, calcined clay, forge scales, powdered bricks which are underburnt, and other materials of like nature. Cements made thus artificially, are as good as those naturally hydraulic.

Lime is termed rich, poor, hydraulic, and eminently hydraulic, according to its properties.

Rich or fat limes are those which double their volume in slacking and dissolve in fresh water to the last particle. They absorb about 300 per cent. of their weight of water.

Poor limes do not much increase their volume, do not dissolve completely, and absorb 200 per cent. of water.

Hydraulic limes set in fifteen or twenty days after immersion, and continue to harden as they grow older. After one year their consistency is about that of hard soap.

Eminently hydraulic limes set in five or six days, and continue to harden.

Limes are said to set when they will bear, without depression, a rod of $\frac{1}{20}$ of an inch diameter loaded with ten or twelve ounces.

NOTE. — The following test was applied to every tenth cask of Rosendale cement used upon the masonry of the United States Dry Dock at the Brooklyn (N. Y.) Navy Yard. Cakes two inches in diameter and three fourths of an inch in thickness, after being immersed five days, were required to bear a rod of one twenty-fourth of an inch diameter loaded with fifty lbs. Two bricks united with the cement and immersed five days, were required to resist one hundred lbs. before separating. The following shows the progress of hardening. The force required to thrust a rod one twenty-fourth of an inch in diameter through a cake three fourths of an inch in thickness, was, after

24 hours,	65 lbs.
48 "	70 "
72 "	75 "
15 days,	150 "
50 "	390 "

SAND.

267. Sand is the product of the decomposition of granitic and schistose rocks, and weighs, per unit of bulk, somewhat less than one half of the rock producing it; owing to the spaces between the grains. The amount of lime necessary

to fill these spaces must be known before we can form a solid mass with the least lime. The amount of void may be found by filling a measure with sand, and then pouring in water: the volume of water is that of the spaces. In pebbles of one half inch in diameter the void amounts to about one half, in gravel about five twelfths, in common sand two fifths, and in very fine sand, one third. Clean sharp sand obtained from the beds of rivers is the best for mortars.

268. In mixing the ingredients for mortar, the lime is first spread on a platform and wet by sprinkling with water, which causes it to give off a great deal of heat and vapor, and fall into a powder. The sand is then applied, and the whole brought with water to a consistent paste.

The proportions for common mortar for dry work are

Sand, . .	7½ to 2
Lime, . . .	1

It is well always to use a small quantity of cement; the parts which have in practice been found perfectly satisfactory are

Cement, . . .	1
Lime, ...	3
Sand, . . .	6

For hydraulic mortar the following proportions have been used with success: —

Cement, . . .	2
Sand, ...	3

269. Concrete is made by mixing broken stone, brick, or shells, with cement mortar; it is used for foundations, backing of arches, and for making artificial stone. The common proportions are

Cement, . .	1 or 2
Sand, . . .	1½ or 3
Broken stone, .	5 or 10

The cement and sand are first mixed as for cement mortar; the broken stone is added and the whole well mixed and immediately applied before it has time to set. Both concrete and cement mortar should be made as required for use, and in no case applied after standing over three hours.

FLASHING MORTAR.

270. Flashing consists of a thin coat of cement mortar made with a very large part of cement. It is used to protect the face of walls exposed to the wet; such as the top of arches. Stone liable to disintegration may be protected by flashing.

POINTING MORTAR.

271. Pointing is used to protect the joints of masonry, and is made by mixing cement and sand with a minimum of water. The joint is first cut out to the depth of from one half to one inch, carefully brushed clean, moistened with water, and filled with the mortar, which is well rubbed with a steel tool. To give architectural effect, plaster of Paris (Gypsum) is sometimes used in pointing.

GROUT.

272. Grout is thin-tempered mortar, composed almost entirely of cement and water. It is run into the joints, and is useful in filling crevices in masonry which cannot be filled with mortar.

STP1494-EB/Mar. 2008

American Cements . .

BY

Uriah Cummings.

BOSTON:
ROGERS & MANSON.
1898.

STATISTICS.

From the year 1818, when the Rock cement industry was first established in this country, until 1882, no public statistics were kept to show the extent and growth of this branch of the building trade.

Since 1882, however, such records have been faithfully kept by the United States Geological Survey, Washington, D. C., and have been published yearly in *Mineral Resources of the United States*, which is issued by the Survey.

The author has prepared several of these yearly reports, and, having a natural taste in that direction, he has let no opportunity pass to add to his little storehouse of knowledge concerning the statistics of the Rock cement industry from the date of its birth in this country near the little village of Fayetteville, in Onondaga County, N. Y., in the year 1818 until the present time.

During the past thirty years the author has been adding little by little to the items bearing on this subject, either by correspondence or in conversation with the oldest persons engaged in the industry, by gathering bits of family history, and in ways too numerous and uninteresting to record.

The difficulties encountered in the compilation of these statistics during the period named have been much greater than would readily be believed by a person who has never attempted such work.

Information seemingly reliable would accumulate in the course of years, and be found at last to bear but a slight resemblance to the truth.

But by dint of persistent effort and careful gleaning and sifting, the author has been enabled to form a table covering the entire history of the industry in this country, which he feels assured will be accepted as being practically accurate, and in the entire absence of any other known effort in the same direction, authoritative.

Production of Rock cement in the United States during the time since the industry was established in 1818 to Jan. 1, 1897.

TIME.	Years.	No. of barrels.
To 1830	12	300,000
To 1840	10	1,000,000
To 1850	10	4,250,000
To 1860	10	11,000,000
To 1870	10	16,420,000
To 1880	10	22,000,000
1880	1	2,030,000
1881	1	2,440,000
1882	1	3,165,000
1883	1	4,190,000
1884	1	4,000,000
1885	1	4,100,000
1886	1	4,186,152
1887	1	6,692,744
1888	1	6,253,295
1889	1	6,531,876
1890	1	7,082,204
1891	1	7,451,535
1892	1	8,211,181
1893	1	7,411,815
1894	1	7,563,488
1895	1	7,741,077
1896	1	7,970,450
Totals	79	151,990,817

The following table gives the number of barrels of Portland cement imported into the United States, and the number of barrels of that class of cement manufactured in this country during the years named.

YEARS.	Imported.	Domestic.
1878	92,000	28,000
1879	106,000	39,000
1880	187,000	42,000
1881	221,000	60,000
1882	370,406	85,000
1883	486,418	90,000
1884	585,768	100,000
1885	554,396	150,000
1886	650,032	150,000
1887	1,070,400	250,000
1888	1,835,504	250,000
1889	1,740,356	300,000
1890	1,940,186	335,000
1891	2,988,313	454,813
1892	2,440,654	547,440
1893	2,674,149	590,652
1894	2,638,107	798,757
1895	2,997,395	990,324
1896	2,989,597	1,543,023
Total	26,567,681	6,804,009

PRODUCT OF ROCK CEMENT IN UNITED STATES, 1895 AND 1896.

STATE.	1895.			1896.		
	Number of works.	No. of Barrels.	Bulk Value at Mills.	Number of works	No. of Barrels.	Bulk Value at Mills.
Georgia. . . .	1	8,050	$6,038	1	12,700	$9,525
Illinois	2	491,012	171,854	2	544,326	217,731
Ind. and Ky. . .	14	1,703,000	681,400	15	1,636,000	654,400
Kansas	2	140,000	56,000	2	125,567	50,226
Md. and W. Va. .	4	242,000	116,700	5	271,500	125,175
Minnesota . . .	2	73,772	33,621	2	83,098	38,549
New Mexico . .	1	5,000	6,000	1	idle	....
New York . . .						
Erie County . .	4	556,754	269,089	4	550,851	275,426
Onondaga Schoharie } Co.	10	152,973	77,974	10	204,375	92,450
Ulster County .	15	3,230,000	1,938,031	15	3,426,692	2,056,015
Ohio.	3	38,060	22,836	3	28,565	17,139
Pennsylvania . .	5	600,895	300,447	6	608,000	304,000
Texas	1	10,000	17,000	1	12,000	18,000
Virginia . . .	2	13,050	7,830	3	16,776	10,566
Wisconsin . . .	1	476,511	190,604	1	450,000	180,000
Total . . .	67	7,741,077	$3,895,424	71	7,970,450	$4,049,202

The foregoing tables afford a wide field for speculation as to the uses to which this enormous amount of cement has been applied.

One can hardly realize the value of the properties which have been constructed with mortars and concretes made with this cement.

Among those which seem most prominent to the mind may be mentioned the almost innumerable number of tunnels, bridges, culverts, and buildings connected with the 235,000 miles of railroad track in this country, the improvements made in all cities in the line of waterworks, in the construction of aqueducts, reservoirs, and dams, and in the street pavements, concrete foundations, sewers, and sidewalks.

The amount of American Rock cement which has been used in the construction of cisterns by the farmers and planters of this country, and in the villages having no waterworks, is almost inconceivable.

We append hereto a list of a few of the notable engineering and architectural structures which have been laid in American Rock cement.

It is difficult, if not impossible, to estimate the cost of these improvements, the permanence and stability of which depend so much on the cement used in their construction.

Important as these structures may be, they are absolutely insignificant when compared with the immense body of work done with American Rock cements, of which no complete record can ever be made.

STRUCTURES LAID IN AMERICAN ROCK CEMENT.

CUMBERLAND, MD., CEMENT.

Washington, D. C.—Boundary Sewer, Bureau of Engraving and Printing, New Patent Office, National Museum, New Pension Office, New Navy, State, and War Department, New Library Building, Tiber Sewer.

Federal Buildings.—Pittsburgh and Harrisburg, Penn., Baltimore, Md.

U. S. Government Work.—Kanawha River Locks, W. Va.

Bridges in Pennsylvania.—Altoona, Columbia, Harrisburg, Millersburgh, Johnstown, Williamsport.

Centennial Buildings in Philadelphia, Penn., and Johns Hopkins Hospital Building, Baltimore, Md.

ROUND TOP CEMENT, HANCOCK, MD.

Washington, D. C.—United States Capitol, Washington Monument, War, State, and Navy Building, Washington and Potomac Tunnel, New Washington Reservoir, Boundary Sewer 2½ miles long, 20 ft. internal diameter, Long Bridge over the Potomac River, and Cabin John Bridge, which is the largest stone arch in existence. It was built by General Meigs in 1866, and has one span of 220 ft., with a rise of 57 ft. 3 ins., and is 20 ft. wide. This bridge is only exceeded in the world's history by a bridge built in 1377 by Barnabo Visconti over the Adda at Frezzo, Italy, which was destroyed in a local war in 1416. It was a segmental arch, with a span of 237 ft. and a rise of 68 ft.

Baltimore, Md. — Gunpowder Waterworks, City Hall Building, Gas Works.

HOWARD CEMENT, CEMENT, GA.

Two bridges across Tennessee River at Chattanooga, Tenn.; Kimball House, Atlanta, Ga.; Georgia Central Railroad Bridge at Columbus, Ga.; Fulton County Jail and Seaboard Air Line Depot, Atlanta, Ga.; Times Building, Chattanooga, Tenn.; the Vanderbilt residence, Biltmore, Asheville, N. C.

JAMES RIVER CEMENT, GLASGOW, VA.

Waterworks in Virginia.— Richmond, Lynchburgh, Staunton, Charlottesville, Liberty, Lexington, Danville, also in Durham, N. C.

Richmond, Va.— New City Hall, Church Hill Tunnel, bridges across James River at Snowden and Joshua Falls, high bridge at Farmville, Va., Washington Monument foundations, Capitol Square, Richmond, Va.

HOWE'S CAVE, N. Y., CEMENT.

State Capitol Building, Albany, N. Y.; Federal Building, Albany, N. Y. *Waterworks* at Albany, N. Y., at Plattsburgh, N. Y., at New Milford, Conn., at Cobleskill, N. Y., at Ware, Mass. County Court House, Scranton, Penn. Used exclusively in the walls of the Hotel Holland, Fifth Avenue and 30th Street, New York City, and in the Postal Telegraph Building, New York City.

BUFFALO, N. Y., CEMENT.

In City of Buffalo.— Iroquois Hotel, Niagara Hotel, Buffalo Library, St. Louis Church, Church of the Seven Dolors, Board of Trade Building, Bank of Buffalo, Bank of Commerce, German Insurance Building, Erie County Penitentiary, Erie and Niagara Elevators, Trunk Sewer, and Hertel Avenue Sewer, both 8 ft. diameter, New York State Asylum, Inlet Pier and Waterworks tunnel under the Niagara River, one of the most difficult under-water constructions in the world; Buffalo General Hospital, Erie County Almshouse, Buffalo Medical College.

Towers of Suspension Bridge, Minneapolis, Minn.; Kokomo Gas

Works, Kokomo, Ind.; Court House, Dansville, Ill.; Court House, Hamilton, Ont., State House of Correction, Ionia, Mich.; piers of Erie Railway Bridge, Portage, N. Y.; Soldiers' Home, Bath, N. Y.

Federal Buildings. — Post-offices, Buffalo, N. Y.; Cleveland, Ohio, Pittsburgh and Alleghany, Penn.

U. S. Government Work. — Falls of St. Anthony; Mississippi River, Minn.; Rock Island Arsenal, Rock Island, Ill.

The dams in the Missouri River at Great Falls, Mont.

AKRON, N. Y., CEMENT.

Bridges. — Railroad bridge over the Hudson River at Poughkeepsie; cantilever and suspension at Niagara Falls, N. Y.; Connecticut River, Windsor Locks, Conn.; Mississippi River at Burlington, Iowa, at St. Louis, Mo.; Red River at Fulton, Ark.; great viaduct over the Cuyahoga River at Cleveland, Ohio; waterworks tunnel under Lake Michigan at Chicago, Ill.; elevated tracks and bridge over the Genesee River at Rochester, N. Y.; waterworks reservoir, Buffalo, N. Y.; City and County Hall, Buffalo, N. Y.; Grand Central Depot, New York, N. Y.

UTICA, ILL., CEMENT.

Chicago Buildings.— Armour & Dole Elevators, Central Elevators A and B, Hough & Galena Elevators, Chicago Board of Trade, Pullman Works, Rialto Office Building, Pullman Office Building, Rookery Office Building, Home Insurance Building, Chicago Public Library Building, Woman's Temple, Illinois Steel Company, South Chicago.

Indianapolis, Ind.— Big Four Round House, Home Brewing Company Building, Park Theatre, New Hospital, Indiana State Prison, Michigan City, Ind.

Kansas City, Mo.— Y. M. C. A. Building, Keith & Perry Building.

Saint Joseph, Mo.— United States Government Building.

Omaha, Neb.— New York Life Insurance Building, City Hall, Paxton House, Murry House, Millard House.

Denver, Col.— State House, Union Depot, The Windsor, The Albany, The Equitable Insurance Company Building.

Pueblo, Col.— Opera House, Board of Trade Building, Union Depot.

Des Moines, Iowa.— State Capitol, Y. M C. A. Building, Dam in Des Moines River.

St. Paul, Minn.— Ryan Hotel, New York Life and Germania Life Insurance Company Buildings, Manhattan Building, Pioneer Press Building, Globe Building, Lowery Arcade, Union Depot, Gas Works, Endicott Arcade, Germania Bank Building.

Minneapolis, Minn.— Union Depot, New York Life Insurance Building.

Duluth, Minn.— Hotel Saint Louis, Spalding House, Board of Trade Building, Court House and Jail.

MANKATO, MINN., CEMENT.

Federal Buildings at Duluth, St. Paul, and Mankato, Minn.; Ashland, Wis.; Fort Dodge, Cedar Rapids, and Sioux City, Iowa; Fremont, Neb.; Sioux Falls, So. Dak.; Fargo, No. Dak. Bridge across Mississippi River at Redwing, Minn.; across the Blue Earth River at Mankato, Minn. State Insane Asylum, Independence, Iowa, and at Fergus Falls, Minn. Railroad Bridge crossing the Mississippi River at Plattsmouth, Neb. Waterworks, Minneapolis, Minn. Irrigation Canals at San Bernardino and Riverside, Cal., and State Capitol Building at St. Paul, Minn.

CUMMINGS CEMENT, AKRON, N. Y.

Federal Buildings.—Jackson, Tenn.; Macon, Ga.; Aberdeen, Miss.; Waco, Tex.; Port Royal, S. C.; Clarksburg, W. Va.; Harrisonburg, Va.; Detroit, Mich.; Youngstown, Ohio.

United States Government Work.— Sacket's Harbor, N. Y., and Buffalo Harbor, Buffalo, N. Y.

Trumbull County Court House, Warren, Ohio; Dana's Music Hall, Warren, Ohio; Otis Steel Company and Cleveland Rolling Mill Company Buildings, Cleveland, Ohio; New City Hall, Goodale Block, Burdick Block, Flower Block, Watertown, N. Y.; Herrin & Sons Paper Mills and Dam, Great Bend, N. Y.; Dexter Paper Company Buildings and stone arch raceway, Dexter, N. Y.; Globe Paper Mills, Brownville, N. Y.; Bridge at Black River, N. Y.; Ursuline Convent of the Sacred Heart Buildings, and the Episcopal Church Building, Youngstown, Ohio; the Great Eads Bridge, St. Louis, Mo.; County Alms House, Rome, N. Y.; Diamond Match Company Buildings, Oswego, N. Y.; Faxton Hospital, Utica, N.Y.; Hoosac Tunnel, Mass.; Niagara Falls Paper Company Buildings, Niagara Falls, N. Y.; Erie County Savings Bank Building, Buffalo, N. Y.; City and County Hall, Buffalo, N. Y.; waterworks standpipe at Delphos, Ohio, and Akron, N. Y.; reservoir waterworks, Fredonia, N. Y.; Atlanta Brewing Company, Atlanta, Ga.; Chattanooga Brewing Company, Chattanooga, Tenn.; Sebald Brewing Company, Middletown, Ohio; Gerst Brewing Company, Nashville, Tenn.; Brenner Brewing Company, Covington, Ky.; old and new Croton Aqueducts, New York (613,000 barrels); Grand Central Depot, New York, N.Y.; N. Y. C. & H. R. R. bridge over the Hudson River at Albany, N. Y. Waterworks dam at Willimantic, Conn.; the great International bridge crossing the Niagara River at Buffalo, N. Y., and the suspension and cantilever bridges at Suspension Bridge, N. Y.

Buildings in New Castle, Penn.—The New Castle Steel and Tin Plate Company (largest tin mill in the world), the New Castle Wire Nail Company, Shenango Valley Steel Company, New Castle Tube Company, Arethusa Iron Works, Atlantic Iron and Steel Company, Shenango Glass Company, Lawrence Glass Company, New Castle Water Company, Pearson Building, Boyles' Block, St. Cloud Hotel.

Heavy stone masonry on the new Erie Canal improvements, and for concrete pavement work, over 125,000 barrels yearly.

FORT SCOTT, KAN., CEMENT.

Federal Buildings.—Kansas City, Mo.; Atchison, Fort Scott, Salina, Fort Leavenworth, Fort Riley, Kan.; Camden, Ark.; Pueblo, Col.; Fort Crook, Neb.

Buildings in Kansas City, Mo.—New England Life, New York Life, Insurance Buildings, Union Depot, Kansas City Journal, Board of Trade, American National Bank, Hotel Brunswick, Coates House, Public Library, Gibraltar, Massachusetts, Nelson, Bayard, Baird, Peet Bros., Kansas City Star, and Waterworks Buildings. The Dold, Fowler, Allcutt, and Armour Packing Company Buildings.

State Capitol Buildings at Topeka, Kan., and Austin, Tex., County Court Houses, Fort Worth and Dallas, Tex.; Warrensburg, Chillicothe, and Clinton, Mo.; National Soldiers' Home, Leavenworth, Kan.; Union Depot, Omaha, Neb.

Waterworks. — Lamar, Boonville, and Kansas City, Mo.; Parsons, Coffeyville, St. Mary's, and Horton, Kan.; Yocum and Cisco, Tex.; Missouri River Bridge, Jefferson City, Mo.

MILWAUKEE, WIS., CEMENT.

Minneapolis, Minn. — Stone arch bridge over Mississippi River, Hennepin County Court House and City Hall, dams and retaining walls of the St. Anthony's Falls Water Power Company, the Exposition Building, Guaranty Loan and Trust Building, Union Depot.

St. Paul, Minn. — Ramsey County Court House and City Hall, Robert Street Bridge, and the Chicago and Great Western Railway Bridge over the Mississippi River, Globe Building.

United States Government Locks at Sault Ste. Marie, Mich.

Milwaukee, Wis. — City Hall, City Library, Pabst Building.

Omaha, Neb. — Bee Building, City Hall, American Waterworks' Basins.

Duluth, Minn. — Masonic Temple, Lyceum Building, Union Depot.

Chicago, Ill. — Chamber of Commerce, Rookery Building, Home Insurance Building, C. B. & Q. General Office Building.

Federal Buildings. — Milwaukee, Wis.; Omaha, Neb.; and Duluth, Minn.

LOUISVILLE, KY., CEMENT.

UNITED STATES-GOVERNMENT WORK.

Locks and Dams. — On Muskingum River; Muscle Shoals, Tennessee River; Warrior River; Kentucky River; Kanawha River; Big Sandy River; Illinois River; Ohio River below Pittsburgh; Monongahela River, Pittsburgh; Sault Ste. Marie; Canal around Falls of the Ohio at Louisville.

Custom Houses. — Cincinnati, Ohio; St. Louis, Mo.; Louisville, Ky.; Memphis, Tenn.; Chattanooga, Tenn.

Bridges. — P. H. R. R. connecting bridge over the Ohio at Pittsburgh; B. & O. R. R. bridge over the Monongahela above Pittsburgh; P. H. R. R. at Steubenville, Ohio; N. & W. R. R. at

Kenova, W. Va.; L. & N. R. R. at Cincinnati, Ohio; C. & O. R. R. at Cincinnati, Ohio; Suspension Bridge at Cincinnati, Ohio; Cincinnati & Newport Bridge at Cincinnati; Pennsylvania R. R. Bridge at Louisville, Ky.; Kentucky & Indiana Bridge at Louisville, Ky.; Louisville & Jeffersonville Bridge at Louisville, Ky.; L. & N. R. R. at Henderson, Ky.; I. C. R. R. at Cairo, Ill.; K. C. & M. R. R. at Memphis, Tenn.; Tennessee River Bridge at Chattanooga; Eads Bridge at St. Louis; Merchants Bridge at St. Louis; C. B. & Q. R. R. Bridge at Alton, Ill.; C. B. & Q. R. R. Bridge at Bellefontaine, Mo.; C. B. & Q. R. R. Bridge at Leavenworth, Kan.; Illinois Central R. R. Bridge at Yazoo River, Miss.; Northern Pacific R. R. Bridge at Minneapolis, Minn.; N. C. & St. L. R. R. Bridge at Bridgeport, Tenn.; Bridge over Missouri River at Sioux City, Iowa; Railroad Bridges at Dubuque, Davenport, Clinton, Fort Madison, Burlington, and Keokuk, Iowa.

Waterworks, Dams, etc.—Chattahoochee River Dam, Columbus, Ga.; Hot Springs Waterworks Dam, Hot Springs, Ark.; Little Rock, Ark., Dam; Covington, Ky., Reservoir; Nashville, Tenn., Reservoir; Minneapolis, Minn., Waterworks; St. Anthony Falls Tunnel; St. Louis, Mo., Waterworks; Little Falls, Minn., Dam.

Public Buildings.—State House, Indianapolis, Ind.; State House, Springfield, Ill.; State House, Lansing, Mich.; State House, Atlanta, Ga.; State House, Austin, Texas.

Tunnels.—Tunnel under Chicago River, Chicago, Ill.; Cleveland Waterworks Tunnel; Sanitary Drainage Canal, Chicago, Ill.; Sea Wall Foundation Lincoln Park, Chicago, Ill.; Lake Shore Drive Sea Wall, Chicago, Ill.; Palmer House Gas Receiver, Chicago, Ill.; Farwell Block, Chicago, Ill.; Dock, San Diego, Cal.

ROSENDALE, N. Y., CEMENT.

New York, N. Y.—High Bridge, Harlem River; New York & Brooklyn Bridge; Washington Bridge, Harlem River; Madison Avenue Bridge, Harlem River; Second Avenue Bridge, Harlem River; American Museum of Natural History; Astoria Hotel—Largest in the World; Washington Life Insurance Building; Columbia College—New Buildings; New Park Row Office Building—Thirty Stories; New York University Buildings; Astor's New Exchange Court Building; Post-Office; Custom House; Equitable

Building; Mutual Life Insurance Building; Public School Buildings; New York Athletic Club Building.

Boston, Mass. — Subway; State House, Bulfinch Front; Tremont Temple; Parker House Extension; Suffolk Bank Building; Austen & Doten Warehouse; Brookline Sewer Work; Metropolitan Sewerage Extension; Metropolitan Water Board — Nashua Aqueduct; Sewer Department; Water Board Department; Paving Department; Sudbury Building; Warren Chambers; Metropolitan Warehouse Company; Conduit Work by West End Street Railway Company; Boston Electric Light Company; Edison Electric Company; West End Power Station, Charlestown; Edison Power Station, Atlantic Avenue; Union Terminal Station.

Pittsburgh, Penn. — Post-Office; Court House; Carnegie Mills; Davis Island Dam; Monongahela Bridge.

Washington, D. C. — Capitol; Bureau of Engraving and Printing; New Patent Office; New Pension Building; Navy, War, and State Department Building; Washington Waterworks; Treasury Building.

United States Government Work. — Fortifications: Fort Delaware; Fort Montgomery; Fort Jackson; Fort Adams; Fort Sumter; Fort Trumbull; Fort Taylor; Fort Warren; Fort Jefferson; Fort Wadsworth; Fort Preble; Fort Monroe; Fort Hamilton; Fort Washington; Fort Knox; Fort Morgan; Governor's Island; Tybee Island; Amelia Island; Fisher's Island; Garden Keys; Hawkins' Point; Pensacola; North Point; San Francisco; Gull Island; Sandy Hook; Newport Harbor; Plattsburgh; Portland, Me.; Key West; Finn's Point.

Navy Yards. — Brooklyn; Norfolk.

Rivers. — Allegheny; Ohio; Kanawha.

Dams and Waterworks. — New Haven, Conn.; Holyoke, Mass.; Mechanicsville, N. Y.; Rochester, N. Y.; Pottstown, Penn.; Pen Yan, N. Y.; Canandaigua, N. Y.; Dunnings, Penn.; Kittanning Point, Penn.; New Milford, Conn.; New York City, Jerome Park Reservoir; Boston, Mass.

South Carolina Cotton Mills. — Spartan Mills, Spartansburgh; Pacolet Mills, Pacolet; Pelzer Mills, Pelzer; Clifton Mills, Clifton; Columbia Mills, Columbia; Reedy River Mills, Mauldins; D. E. Converse Mills, Glendale; Union Mills, Union; Pelham Mills, Mauldins; Fingerville Manufacturing Co., Fingerville.

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