



LIME MORTARS: TWO RECENT CASE STUDIES*

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Abstract

Over the last century, the increased use of portland cement-lime-sand mortars has led to a loss of empirical knowledge about workability, durability, and constructability issues related to lime-sand mortars by architects, conservators, scientists, and masons, especially in the United States. Recent published research has improved the knowledge base on the workability and durability of lime-sand mortars, but the requirements and limitations of lime-sand mortars related to constructability need to be relearned. This paper focuses largely on two recent case studies that included limited laboratory and field testing of lime putties for use in northern climates. Issues addressed include laboratory mortar compositional testing, mortar selection, carbonation rate, and the role of interfacing between materials suppliers, design professionals, contractors, and the individual masons on any particular project. The case studies provide two different approaches to the decision to use lime-sand mortars.

Keywords

lime, carbonation, constructability, mortar

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1 Introduction

The central business district of Chicago was decimated by the Great Fire of 1871. This loss, coupled with a rapid population increase fostered by transportation developments, led to unprecedented construction and density in the city. As Chicago architects and engineers experimented with new forms and designs, most notably skyscrapers, they relied on both traditional and new materials (Randall, 1999). As a result, late nineteenth century buildings in Chicago offer a juxtaposition between traditional and modern construction technology as the load bearing masonry buildings were replaced with steel buildings with masonry cladding.

This paper presents two recent case studies of preserving Chicago buildings using lime-sand mortars for partial repointing. In both cases, the mortar was supplied as pre-mixed lime putty and aggregate.

Lime-sand mortars have a long history of successful use. The renewed interest in this traditional material has revealed obstacles to high quality workmanship necessary for adequate performance [Sickles-Taves, 2002]. Although standards exist to ensure high quality work and adequate performance in masonry repair work, including the Brick Industry Association's Technical Notes and ASTM International's Standards and Guidelines, these standards do not fully address requirements for lime-sand mortars. This paper presents a synopsis of the investigation, limited testing, evaluation, and installation of lime-sand mortars. The following case studies offer insight into the complexities and variables that exist in selection of mortar materials for two older masonry-clad buildings in a northern climate when project limitations required a heavier reliance on in-situ trials for evaluation than extensive laboratory testing.

1.1 Case study 1

The first case study provides an example of a project where lime-sand mortar was selected based on the conditions observed on the building and the known performance characteristics of lime-sand mortars rather than an extensive testing program that was beyond the budget and scope of the investigation. The building dates from approximately 1871 and was constructed immediately after the Great Fire. This building is, therefore, among the oldest remaining structures in the downtown Loop area of Chicago.



Figure 1 View of north and west facades of building.

The commercial building was constructed with a wood structural system supplemented by isolated metal elements. The six story building is rectangular in plan and occupies a corner site. The original, north-facing, primary street facade is constructed of cast iron. As the downtown area developed, the

secondary facade faced the more prominent street to the west. In the 1920s, the original secondary brick facade was removed to provide larger punched window openings. It remains unclear if the original face brick was salvaged or replaced at this stage. Intermediate single headers laterally tie the face brick to the backup masonry. It is also unclear whether the current common backup brick is original or dates from the 1920s alteration. This facade remains today. In the 1980s, the structure underwent a major renovation and adaptive reuse. During this time, the design architect replaced the original wood structural system with a cast-in-place concrete structural system, using elements of the original wood structure as formwork for the concrete. Some wood structural elements remain in the building.

The current phase of work resulted from a routine inspection of the building facade, when isolated masonry repairs were deemed necessary based on external observations and a limited number of inspection openings. In general, conditions observed during the evaluation indicated distress consistent with restraint of structural and thermal movements. Offset cracking within sill areas, missing mortar, and step cracking primarily through mortar joints were identified in the corner bays.



Figures 2 and 3 Representative examples of cracked brickwork at corner (right) and joint conditions (left)

Based on the inspection, a multi-year, phased repair project was implemented. Previous repairs had included selective repointing of deteriorated mortar joints as well as abrasive cleaning that eroded the brick. The date of the previous repairs is unknown. The repointing mortar appeared to have a high proportion of portland cement content relative to lime, although chemical testing of the mortar was not performed. The previous repointing did not include sufficient joint preparation, and the mortar was placed directly over the existing mortar and, to some extent, over the face of the brick units.

The first phase of the repair project included repointing of the brick masonry and other limited masonry repairs at the end bays of the building. Lime-sand mortar was selected to repoint the brickwork on the masonry facade for a variety of reasons. While chemical testing was beyond the scope of the project, the existing setting mortar installed throughout the facade appeared to be portland cement-lime-sand mortar, as would have been typical of the 1920s facade recladding project [Kidder-Parker, 241–246]. The composition of the backup mortar was not determined and, as mentioned previously, may date from the original 1870s construction. Lime-sand mortar is consistent with Chicago building practices in the 1870s and was likely used at that time [Speweik, 1995].

Deterioration of the brick and damage resulting from previous cleaning had significantly compromised the fired skin of the brick, leaving them more susceptible to future damage. Further, crack patterns in the end bays strongly suggested that thermal movements and differential structural movements were the cause of mortar joint cracking within the spandrel sections of the wall. Given the size, scale, architectural details, and context of the building, introduction of expansion joints within the wall system

would have been visually intrusive. Yet, a means of addressing movements was desired to improve the serviceability of the facade. Lime-sand mortar was, therefore, selected to minimize potential future cracking of the masonry wall. If movement continued, the use of a lime-sand mortar would result in the preferential cracking of the mortar joints (sacrificial) rather than the fragile historic brick. The autogenous healing properties of lime-sand mortar was also desirable for this application since cracking of the mortar joints was likely to continue as a result of continued thermal and structural stresses. Despite limited cracking within the lime-sand mortar joints, the brick masonry would continue to function monolithically.

Specific training on the use and curing procedures of lime-sand mortars was required to ensure that the masons, who specialized in repair of historic masonry buildings, became familiar with the workability differences between a lime-sand mortar and a portland cement-lime-sand mortar. The training included a two-day, off-site training course where the masons were taught the history of mortar and differences in constructability and performance between a portland cement-lime-sand mortar and a lime-sand mortar. This training led to greater consistency in the work performed by the different masons on the project.

1.2 Case study 2

1.2.1 Background

The second case study provides an example of a project where lime-sand mortar was selected based on some laboratory testing as well as the conditions observed on the building and the performance characteristics of lime-sand mortars. This case study involves a building constructed in 1894. It is an early example of a Chicago School skyscraper, including the use of a steel structural system with masonry cladding. The building is seventeen stories tall and is constructed of clay brick with slip-glazed terra cotta decorative elements, including window surrounds, window lintels, window sills, and other elements at the lower and upper two floors. The face brick is laid with very narrow butter joints, ranging in width from less than 1/16 inch to 1/4 inch. Common brick masonry is used as backup behind the brick and terra cotta. The face brick is tied to the brick backup by blind headers. A terra cotta cornice at the top of the building was removed in the 1950s.



Figure 4 Overall view of south facade

Following an extensive inspection and investigation of the exterior facade, a multi-year facade restoration was implemented in 2002. The investigation included full documentation of the masonry and window conditions based on visual inspections, investigative probes, and partial disassembly of various components of the facade to evaluate and document concealed conditions. In addition, cleaning and material studies of the masonry were conducted.

The restoration included reconstruction of the cornice, facade cleaning, window restoration, and masonry repairs. Specifically, the masonry repairs included reconstruction of lintels, repair and replacement of deteriorated structural steel, repair of damaged and cracked terra cotta, and partial repointing of the brick and terra cotta masonry. The selection of mortar for repointing is discussed in detail below.

While the masons and contracting firm performing the work had a high degree of experience and skill in repairing historic terra cotta and brick skyscrapers, proper execution of the repairs at this building required additional training. All masons were trained in the use of lime-sand mortars by the mortar supplier. This training included both a workshop component and a refresher course on-site to identify specific issues related to this building. During the on-site course, various hand and power tools were tested for mortar removal. The goal was not to establish restrictive guidelines, but rather to establish a collaborative environment in which the preservation firm, contractor, and supplier worked together to identify a system of joint preparation that was cost-effective for the owner, yet caused no damage to the adjacent masonry.

Given the softness of the brick and the narrow mortar joints, joint preparation presented a great risk of damage to the brick and terra cotta units. A joint preparation manual was created to assist the masons in deciding which joints to prepare and repoint, and which joints not to repoint if preparation would have likely led to damage of the masonry units. In general, the decision whether to repoint was based on the location of the joint, its proximity to embedded structural steel elements, the condition of the existing mortar, the width of the joint, and the ability to prepare the joints adequately without causing damage.

Since the bond between the mortar and the brick was intact at many locations, repointing of selected joints/areas was performed. The corner bays typically had a greater level of mortar distress, and joints in these areas were prepared and repointed to the greatest extent possible. The following rules were presented to the masons in a training booklet:

- No power tools were permitted to remove mortar from head joints.
- Special grinding blades, 0.04 inch thick, were used to prepare bed joints greater than 1/16 inch wide.
- Mortar joints at reveal courses were not prepared because preparation would have led to damage of the brick. The joints are protected from the elements by the geometry of the facade, and there was no embedded steel at this location.



Figure 5 Sample of instructions from joint preparation guide

Given the presence of mild steel J-hooks and anchors attaching the terra cotta, all joints between the terra cotta units were repointed to limit water infiltration and subsequent corrosion of the terra cotta anchors.

1.2.2 Laboratory analysis

To supplement the close-up inspections, selected materials testing was also conducted. At an inspection opening where brick had been previously removed, unexposed mortar adhered to the face brick surface was removed and tested. Mortar was also removed from the backup brick masonry. The face brick mortar was pigmented brown to match the face brick. The backup mortar was not pigmented. As part of the investigation, the mortar was tested according to ASTM C 1324, Standard Test Method for Examination and Analysis of Hardened Masonry Mortar. Test results are provided in Table 1.

Table 1 Analytical data for mortar samples

Calculated	Face Brick Mortar	Backup Mortar
Soluble Silica, %	0.53	1.52
Calcium oxide, %	16.58	9.33
Magnesium oxide, %	10.10	6.46
Magnesium hydroxide, %	3.0	0.4
Insoluble residue, %	44.49	68.48
Losses on ignition, %		
to 110° C	1.48	0.81
from 110 ° to 550 ° C	12.81	5.27
from 550 ° to 950 ° C	11.98	9.10
Fe ₂ O ₃ , %	3.97	--
Hydrated lime, %	36.52	21.67
Volumetric ratio, Lime: sand	1 : ² / ₃	1 : ¹ / ₂

The face brick and backup brick mortars were similar mixes that were determined to be non-hydraulic lime-sand mortars with a high lime-to-aggregate ratio. The aggregate in both the face brick and backup masonry mortars contained very fine, predominantly quartz aggregate. The face brick mortar had a high percentage of iron oxide pigment.

Brick was tested according to ASTM C 67 Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile for hot and cold water absorption. Table 2 summarizes the results.

Table 2: Absorption and saturation coefficients of brick

Brick Sample No.	24 hr. Absorption (% wt)	5 hr. Boiling Absorption (% wt)	Saturation Coefficient
1	6.0%	8.0%	0.75
2	7.2%	9.2%	0.77
3	7.2%	9.3%	0.77
4	7.6%	9.7%	0.78
<u>5</u>	<u>7.2%</u>	<u>9.3%</u>	<u>0.78</u>
<i>Average</i>	7.0%	9.1%	0.77
<i>Standard Deviation</i>	0.6%	0.6%	0.01

The brick had a moderately high water absorption rate and a moderate saturation coefficient. The brick was also tested for compressive strength according to ASTM C 67. Table 3 summarizes the compressive strength results.

Table 3 Compressive strength of face brick

Brick Sample No.	Stress (psi)
1	4,760
2	5,260
3	7,150
4	2,830
5	6,321
6	3,697
7	5,004
<u>8</u>	<u>5,243</u>
<i>Average</i>	5,033
<i>Standard Deviation</i>	1,360

The brick had a moderate average compressive strength with high variability, which is consistent with brick of this era.

Table 4 Absorption and saturation coefficients of terra cotta

Terra Cotta Sample No.	24 hr. absorption (% wt)	5 hr. boiling absorption (% wt)	Saturation Coefficient
1	2.8%	8.5%	0.33
2	5.9%	10.2%	0.58
3	7.2%	11.9%	0.60
4	7.0%	10.9%	0.64
5	9.1%	13.5%	0.67
Average	6.4%	11.0%	0.56
Standard Deviation	2.3%	1.9%	0.14

The terra cotta had moderately high water absorption values with a high degree of variability, also consistent with terra cotta of this era.

1.2.3 Test program: background

Given the significance of the building, the sensitive nature of the materials, and the desire to limit accelerated deterioration, a testing program was developed to evaluate variables for the installation and long-term performance of the masonry system in general and, specifically, the mortar. Though a more extensive test program was considered, financial and schedule limitations necessitated a greater emphasis on in-situ evaluations and low-technology laboratory testing.

Project requirements dictated that the bulk of the masonry repairs be completed in a single construction season. Since the contract for the restoration work was awarded near the end of the construction season in 2003, the in situ testing program was initiated during the end of the 2003 construction season and the laboratory work commenced on a separate schedule.

The program consisted primarily of in-situ testing that was incorporated into the mock-up portion of the project. In addition, empirical laboratory testing was conducted to evaluate curing characteristics of the mortar under various environmental conditions.

Given the extent of repointing work, an entire construction season (approximately April to November in Chicago) was necessary to complete the scheduled repairs. Most available historic reference materials on the use of lime-sand mortars do not address the use of those mortars in northern climates such as Chicago. Therefore, references to new construction were considered.

The Brick Industry Association Technical Note 1 – All Weather Construction largely serves to establish the minimum standards for masonry construction. It identifies cold temperatures as a significant threat to durability of masonry construction. Specifically, the technical note states “Mortar which freezes is not as weather-resistant or as watertight as mortar that has not been frozen. Furthermore, significant reductions in compressive and bond strength may occur.” The technical note continues “Mortar having a water content over 6 to 8 percent of the total volume will experience disruptive expansive forces if frozen due to the increase in volume of water when it is converted to ice. Thus, the bond between the unit and the mortar may be damaged or destroyed.” [BIA, 1992, 4].

The technical note offers a number of solutions to construction during cold temperatures, including heating the building materials, using a brick with a lower initial rate of absorption, or using mortar with a lower water content. If construction occurs when the temperatures are less than 25 degrees

Fahrenheit, the masonry wall should be protected from freezing temperatures for 48 hours. Other sources provide similar limitations and recommendations for cold weather masonry work.

The porosity of the existing brick could not be changed, water content of the repointing mix could not be changed because it was based on matching the appearance of the original mortar, and the cost and complexity of the project would increase significantly if the contractor was required to heat the exterior of the façade. Therefore, the more realistic approach would be to end construction at a safe date, at least 48 hours prior to the first freezing temperatures.

In order to identify reasonable weather restrictions for the repair work, historic weather data was reviewed. Tables 5 and 6 provide recent and average weather data for Chicago [www.wunderground.com].

Table 5 Average monthly temperature data for Chicago

Month	Average temperature° F	
	High	Low
October	63	42
November	48	32
December	34	19
January	29	13
February	33	17
March	46	29
April	59	39

Table 6 Earliest freezing temperatures for Chicago, Illinois

Year	Date of Freezing Temperature (Low Temperature °F)				
	1 st	2 nd	3 rd	4 th	5 th
1999	24 Oct (30)	3 Nov (30)	25 Nov (30)	28 Nov (28)	29 Nov (28)
2000	11 Nov (30)	13 Nov (30)	14 Nov (30)	15 Nov (24)	16 Nov (30)
2001	20 Nov (30)	10 Dec (30)	11 Dec (30)	18 Dec (30)	20 Dec (28)
2002	1 Nov (26)	2 Nov (28)	3 Nov (28)	17 Nov (30)	18 Nov (28)
2003	7 Nov (28)	8 Nov (24)	9 Nov (27)	10 Nov (30)	13 Nov (30)

Typically, construction in Chicago continues until daytime temperatures become too cold to work efficiently. Typically, this occurs between mid-November and early December, as shown in Table 5. Reviewing the low temperature for the last five years, provided in Table 6, work would have to end by October 22 to provide at least 48 hours of cure prior to freezing temperatures. In order to avoid temperatures less than 25 degrees Fahrenheit, construction would have to end the first week in November. Reviewing all the data provided in both Tables 5 and 6, consistent freezing temperatures do not occur until the end of November or early December. This is typically when masonry work ends in Chicago.

After closely reviewing the recommendations, we determined that the BIA recommendations may be of limited value since they refer to new construction using portland cement-lime-sand mortars rather than repair of historic buildings using lime-sand mortars.

1.2.4 In-situ mortar evaluation and selection

Based on the analysis conducted during the investigation, the original pointing mortar was a highly-pigmented, dolomitic lime-sand mortar with very fine aggregate. The source of the dolomitic lime was likely a locally-available limestone. The original pointing mortar had performed well. Only a relatively

small percentage of the facade had been repointed using a highly-pigmented cement-rich mortar applied as a thin coating over mortar joints, with minimal joint preparation, and, to some extent, over the face of the brick.

A limited study, which involved joint preparation and installation of repointing mortar, assessed both a dolomitic lime-sand mortar and a calcium-rich lime-sand mortar during the fall of 2003 and the early winter of 2003–2004. The goals of the trial installations were an in-situ evaluation and comparison of both types of mortar. Initially, the trial installation was used to evaluate and compare the dolomitic and calcium lime-sand mortars that had been in service through one winter season. For this study, the joints in sections of brick masonry approximately two square feet in area were prepared and pointed. Two trial locations were selected, one on the south facade and one at the southeast corner, at the third floor of the building.

Observations during installation, following initial curing, and periodically through the winter and following spring were performed prior to implementation of the repointing portion of the restoration. The following observations were made, which were consistent for both mortars:

1. Using a premixed mortar resulted in a consistent, uniform color and texture of the mortars.
2. No shrinkage cracks were observed in the mortars.
3. The mortar appeared to be well adhered to the adjacent brick masonry.
4. No distress was observable in the mortars.
5. No erosion or cyclic freeze-thaw damage was observed in the mortars.

Based on the limited natural weathering of these in-situ mock-ups and previous experience on other projects, a calcium-rich lime-sand mortar was selected for repointing.

1.2.5 In-situ mortar installation - weather constraints evaluation

As discussed above, special cold weather recommendations exist for masonry construction when the temperatures are less than 40 degrees Fahrenheit. Restrictions imposed by local ordinances, economics of the project, and the desire of the owner to complete the facade restoration in one construction season necessitated further study of the relationship between temperature during installation and durability of the mortar. Previous research on mortars used in northern climates have relied on portland cement-lime-sand mortars or hydraulic lime-sand mortars [Fontaine, 1998].

A limited study was initiated to identify a reasonable end date for installation of masonry repairs. The field testing that compared the performance of a dolomitic lime-sand mortar and a high-calcium lime-sand mortar was expanded to identify reasonable weather constraints. The dolomitic lime-sand mortar was chosen for the study since it more closely matched the chemical composition of the original mortar, and the high-calcium lime-sand mortar was chosen based on previous experience with this material. The mortars comply with ASTM C 1489. For this study, the joints in sections of brick masonry approximately two square feet in area were prepared and pointed. Two trial locations were selected: one on the south facade and one at the southeast corner, at the third floor of the building. Three trials were conducted at each location. For each trial, a total of four, two square foot areas were repointed. The trials were conducted at various times in the fall and early winter, at approximate six week intervals. Table 7 provides the dates for the pointing trials and some weather data.

Table 7 Dates and Weather Data of Pointing Trials

Trial #	Date (2003)	Temperature ° F	
		High	Low
1	19 August	82	64
2	1 October	54	36
3	21 November	51	43

Observations during installation, following initial curing, and periodically through the winter and following year were similar to those observations that compared the dolomitic lime putty with the high-calcium lime putty.

1. No shrinkage cracks were observed in the mortars.
2. The mortar appeared to be well adhered to the adjacent brick masonry.
3. No distress was observable in the mortars.
4. No erosion or cyclic freeze-thaw damage was observed in the mortars.

The first freezing temperature in Chicago was on 23 November 2003, 48 hours after the third trial installation. Although this study included only a limited sampling, the mortar samples installed in the second half of November were performing adequately after a nearly a year, even after being subjected to freezing temperatures shortly after installation.

1.2.6 Laboratory testing- depth of carbonation

To supplement the in situ testing, limited concurrent laboratory testing was conducted to evaluate depth of carbonation and the impact of freezing temperatures on depth and rate of carbonation of the lime in the mortars under consideration. Previous literature suggested the importance of carbonation in lime-sand mortars [Cazalla, 2000]. Two-inch mortar cubes were made from the premixed mortar, using the same mix formulation selected for repointing and setting of the masonry units, except the laboratory mix contained no pigments. No additional water was added to the mortar mix.

Eight sets of mortar cubes were made and each set underwent freezing temperatures (approximately 10 degrees Fahrenheit) in a freezer once for a four-hour duration at various times after preparation. The mortar samples were not saturated or set in water during the freezing period. It was not the goal of the limited test to establish mortar durability in freezing temperatures, but rather to try and ascertain if a single freezing cycle affected mortar curing. Except for the time when the cubes were frozen, they were all cured in the same environment. While the temperature was not regulated, the temperature and humidity remained relatively consistent in an indoor environment (approximately 65 degrees Fahrenheit with 50 percent relative humidity).

Table 8 identifies the group of mortar cubes and time at which each set was exposed to freezing temperatures. Mortar cube set A was not subjected to freezing temperatures.

Table 8 Dates of trials

Set	Point at freeze
A	No freezing
B	24 Hours
C	48 Hours
D	72 Hours
E	96 Hours
F	1 Week
G	2 Weeks

The mortar cubes were broken at various times and the depth of carbonation was measured using a phenolphthalein solution as an indicator. Table 9 provides the results from the first month.

Table 9 Depth of carbonation

Set	Depth of Carbonation (inches)		
	2 weeks	3 weeks	4 weeks
A	0.14	0.13	0.16
B	0.04	0.19	0.21
C	0.09	0.16	0.20
D	0.09	0.22	0.18
E	0.08	0.19	0.18
F	0.13	0.16	0.20
G	n/a	0.12	0.19

After two weeks, the depth-of-carbonation testing suggested that mortar cubes that were exposed to a freezing temperature for a limited duration during the first week had less depth of carbonation than the cubes that did not experience any freezing temperatures during the first week. After three weeks, however, this difference was no longer observable. Further, depth-of-carbonation in the mortar cubes in Group F was not significantly different than that in Group A. This limited study suggests that a single unexpected freeze after one week of installation does not noticeably affect the rate of carbonation. In addition, the difference in carbonation rate caused by a single limited exposure of the mortar to freezing temperatures in the first week after mortar installation is not noticeable after three weeks. This testing was very limited in nature and was of an empirical, rather than a rigorous scientific, nature because of limited time and budget. In addition, no effort was made to emulate actual conditions in the wall. The samples were not saturated with water prior to freezing. While achieving the longest period of time possible after setting mortar and before freezing temperatures occur is desirable, limited duration freezing temperatures that can occur in Chicago in late October or early November may not dramatically impact the depth of carbonation.

2 Conclusion

The experience and limited trials and tests presented in these case studies suggest that restrictions in the industry standards for a portland cement-lime-sand mortar may be appropriate for a lime-sand mortar used for repointing; since none of the installed mortar samples were exhibiting distress after one year. The success of the trial may be a result of the forgiving nature of lime-sand mortars, the low water content of the premixed repointing mortar, and the narrow joint width of this particular project. The limited nature of the testing suggests that further analysis should be conducted. The limited trials and laboratory tests did not take into account the microstructure of the cured mortar, or durability over many years.

The authors anticipate periodically reviewing the condition of the mortar at the project in the future. These case studies represent only a starting point for evaluating the performance of lime-sand mortars and appropriate specification requirements.

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