

**Shrinkage in lime stucco:
Does “banking” mortar help mitigate
shrinkage?**

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Submitted in partial fulfillment of the requirement for the degree
Master of Science in Historic Preservation

Graduate School of Architecture, Planning and Preservation

Columbia University

(May 2016)

ABSTRACT

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One of the most common problems with lime stucco, used in building conservation, is shrinkage during the early stages of curing. In most situations, shrinkage is seen as cracking and/or separation from the underlying masonry wall. According to much of the published literature, shrinkage in lime-based materials is often associated with the amounts of both water and aggregate that are used in the mix. Early manuals of practice and historical builders’ notes suggest that lime mortars (and therefore stuccos) should not be used right after they are made, and that instead they should be kept for a period of time prior to application.

In traditional construction, numerous practices were developed, sometimes based on the specific needs of a given site. Some of these practices were passed down without a complete understanding of the underlying principles. It has been said that the “banking” of lime mortar will help mitigate shrinkage in stucco. This was based on the belief that short-term storage of the components (lime putty and sand) would somehow cause them to be in a more stable state to be used than as freshly mixed materials. Interviews with practicing masons as well as a literature review show that although “banking” has been in practice for centuries, there is a lack of research of the actual mechanism and its specific effect in mitigating shrinkage problems.

This thesis has explored the practice of “banking” and the role it plays in mitigating shrinkage. A series of laboratory experiments was developed to study selected parameters: type of lime, amount of sand and amount of water. With “banking” as central procedure in the research, variations in these parameters were tested to better understand if the practice will have effect in one mix and not another, or if the practice will affect all mixes. Although the mechanism of “banking” mortar for a relatively short period of time is not well understood, observations derived from this research support the masons’ belief that “banking” helps mitigate shrinkage.

ACKNOWLEDGEMENT

This thesis would have not taken shape without the close guidance and sheer dedication from my advisor, Professor Norman R. Weiss. I would like to thank him for his wise guidance and enthusiasm in supporting and developing my thesis from the beginning until the very end. I would also like to thank my readers, Professors George Wheeler and John Walsh for being very critical in giving feedback.

My deepest gratitude goes to Jo Thwaites from the Historic Royal Palaces, UK, for her continual support and more importantly, for the platform she had provided for me to explore my questions and ideas in the initial development of my thesis. I would also like to thank three wonderful conservation masons, Manjit Phul, Emma Carr and Keiran from Sally Strachey Historic Conservation Ltd. UK, for spending their time and energy in answering my questions and giving guidance in the execution of my initial mini experiment.

Thank you to my parents, Borhanuddin Mohd Ali and Sabrina Sabri, and my family for their endless prayers and words of encouragements. My appreciation also goes to my sisters - Azimah Borhanuddin, Sarah Yoon and Pui Yu Chan, and all of my classmates for their endless support and keeping me sane through this process.

Last but not least, I would like to dedicate this thesis to my husband, Jefriman Johari, for believing in me, and for his unconditional love and selfless encouragements. I love you.

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1.0 Introduction

1.1 Nomenclature

Lime stucco was commonly applied to masonry substrates to produce a uniform building surface that is aesthetically pleasing. (It was also applied to frame houses to imitate the look of masonry.) It not only acts as a coating material for exterior building surfaces, but can serve as a protective material that defends the substrate from accelerated deterioration. Lime stucco is cheaper and easier to produce and replace as compared to many building materials.

It is widely seen on historic buildings, not only in North America, but also all across the globe, where it is referred to by many names. In the UK and European countries, lime stucco is known as lime render, while the term lime stucco there refers more specifically to sculptural finishes that were made with lime. In other parts of the world, such as South East Asia, lime stucco or lime render is known as lime plaster.

In the American context, plaster is typically used as a finish for interior walls, and is generally composed of a mixture of sand, lime, and water. The term stucco is used for the finishes of exterior walls, applied over unfinished walls made of stone, brick, tile, concrete or wood.¹ In most modern construction, however, stucco is commonly made of cement, sand and water.

¹ Oswald Constantin Hering, *Concrete And Stucco Houses: the Use of Plastic Materials In the Building of Country And Suburban Houses In a Manner to Insure the Qualities of Fitness, Durability And Beauty*. Rev. ed. (New York: R. M. McBride & Company, 1922), pp. 11-12

1.2 Use of lime stucco

Working with lime is said to go back as far as 4000 B.C.² The use of lime as a binder spans the globe from the construction of the Great Wall of China, to temples in Asia, and cathedrals in Europe. Lime became one of the most important building materials, and it was not until the end of the nineteenth century that it began to be replaced by high-strength clinkered cement as the main binder used in construction industry.^{3,4}

Today, it is imperative to recognize the importance of lime as a repair material for historic buildings. These buildings were often built without any damp proof courses, and are not rigid structures. Lime is a material known for its remarkable mechanical properties and permeability. When applied as mortar or stucco, it allows buildings to move and ‘breathe’. Through its pore structure, lime is able to readily absorb and release moisture when it is needed, protecting the wall and its masonry units from frost damage.⁵ It is only in recent years that water vapor transmission of lime-based materials has been measured in scientific studies.⁶

Another important role that lime mortar plays in the protection of the building fabric is that it is a sacrificial material, because most frequently lime mortar is weaker than the masonry units. Lime’s ability to deform over time allows the building to move as the result of ground settlement and thermal expansion, thus preventing severe cracks and structural damage.

² Robert S. Boynton, *Chemistry and Technology of Lime and Limestone*, 2nd ed. (New York: John Wiley & Sons, 1980), pp. 441-442

³ Boynton, *Chemistry and...*, p. 442

⁴ Paul Livesey, “Building limes in the United Kingdom,” *Construction Material*, 164:CM1, 2009. p. 13

⁵ Livesey, *Building limes...*, p. 17

⁶ Jacob, Judith, and Norman R. Weiss. “Laboratory measurement of water vapor transmission rates of masonry mortars and paints”. *APT Bulletin* 21.3/4 (1989): p. 68

While working on a conservation project of a listed building in Kuala Lumpur, Malaysia, the author encountered great challenges in working with lime stucco, primarily as the result of a lack of knowledge and skills among local masons. Observations made on a number of restoration projects throughout Malaysia showed that this lack of understanding of materials and techniques, as well as poor workmanship in the preparation and application process, had led to failures that ranged from cracks in the newly applied stucco, to separation from the underlying masonry wall.

1.3 Practice of “banking”

In 2015, the author was engaged in a summer internship with Historic Royal Palaces in London, working with experienced conservation masons on the facade conservation of the Banqueting House, Whitehall. For any lime putty-based materials, the masons would set the mix aside for a number of days before applying it as pointing mortars, mortar repairs or stucco finishes. This “banked” mortar was claimed to be better than the freshly-mixed mortar, providing better performance. “Banking”, a term used in a 1998 publication by an experienced UK bricklayer, Gerard Lynch (1998), referred to the practice of storing mortar made of non-hydraulic lime putty, traditionally called “coarse stuff”.

This was explained in his paper as follows:

The quickest and most practical method for gauging and mixing, which achieves full integration of all the ingredients, was, and remains, slaking to a medium or coarse powder, screening and sieving the aggregates, mixing and 'banking' as a damp coarse stuff. For increased storage times, one can only be talking about pure or non-hydraulic lime, which possesses no internal set. Feebly hydraulic lime, however, could be slaked and stored (even as a putty). After banking as a coarse stuff, it would still have much of the workability of a pure lime, and yet possess the important internal chemical set (a result of a silicate reaction of the clay impurities of up to 8%), which allowed work to progress with growing strength. This mortar could be 'banked' as coarse stuff for a

short period (few bricklayers' coarse stuffs were stored longer), getting 'fatter' and, despite the mortar beginning to stiffen, once 'knocked-up' again for use would go on to achieve a perfectly adequate set.⁷

In the particular procedure that was carried out on site at the Banqueting House, the mortar was “banked” in an airtight container for a period of 3 to 5 days. The masons believed that the “banked” mortar would give better performance and that the process should help to mitigate shrinkage-related failures, alongside other necessary field practices such as wetting the substrate, and tending after the applied stucco to avoid rapid drying. This “banking” process is also practiced with the belief that it improves the adhesion of lime and sand. No technical references were available with regard to shrinkage or to cohesive properties.



Figure 1-1. The author conducted a mini experiment under the guidance of the senior mason on site.

In order to gain an initial sense of the concept of “banking”, the author conducted a mini experiment under the guidance of the senior mason on site (Figure 1-1). A 2’x1’ brick wall was constructed with the idea that the “banked” mortar would be applied on an area of 1’x1’

⁷ Gerard Lynch, “Lime Mortar for Brickwork: Part One,” *Journal of Architectural Conservation*, 4.1(1998), p. 13

and the freshly-mixed mortar applied next it, on the same surface for easy visual comparison. The stucco was a 1:2½ (binder:aggregate) ratio, a mix design that was used for all of the lime-based materials employed on the project. The stucco was mixed using a handheld power mixer (also known as jiffler) and kept in a sealed plastic bag for a period of 5 days. After 5 days, a new batch of freshly mixed stucco was prepared using the same type of lime and sand, as well as the binder:aggregate ratio that was used in preparing the “banked” mortar.

The appropriate field practice such as wetting the brick wall with lime slurry (a mixture of lime stucco and excessive amount of water to produce a very wet consistency) was carried out to ensure that the bricks would not absorb moisture from the stucco, and to provide keying for the stucco to adhere to the wall. The stucco was applied in two coats, 3 hours apart. Within two hours of application, the author observed cracks forming on the surface of both of the coats, with the “banked” mortar actually having more cracks than the freshly-mixed mortar. The phenomenon was surprising to the masons.

The author repeated the experiment in Malaysia, in August 2015, with the same design and methodology that was used in London. The materials, however, were inherently different. The lime putty that was available in Malaysia was very runny, and after a period of five days, bleed water was observed, covering the top of the “banked” mortar despite the 1:2½ ratio. The bleed water seemed to have been caused by the sand of the “coarse stuff” sinking to the bottom of the bucket, displacing some water that was in the putty. The bleed water was then drained from the mortar before it was applied on the wall. The result was significantly different than that obtained in London. The freshly-mixed mortar demonstrated cracks within an hour of application while the “banked” showed much less cracking several hours later (Figure 1-2).

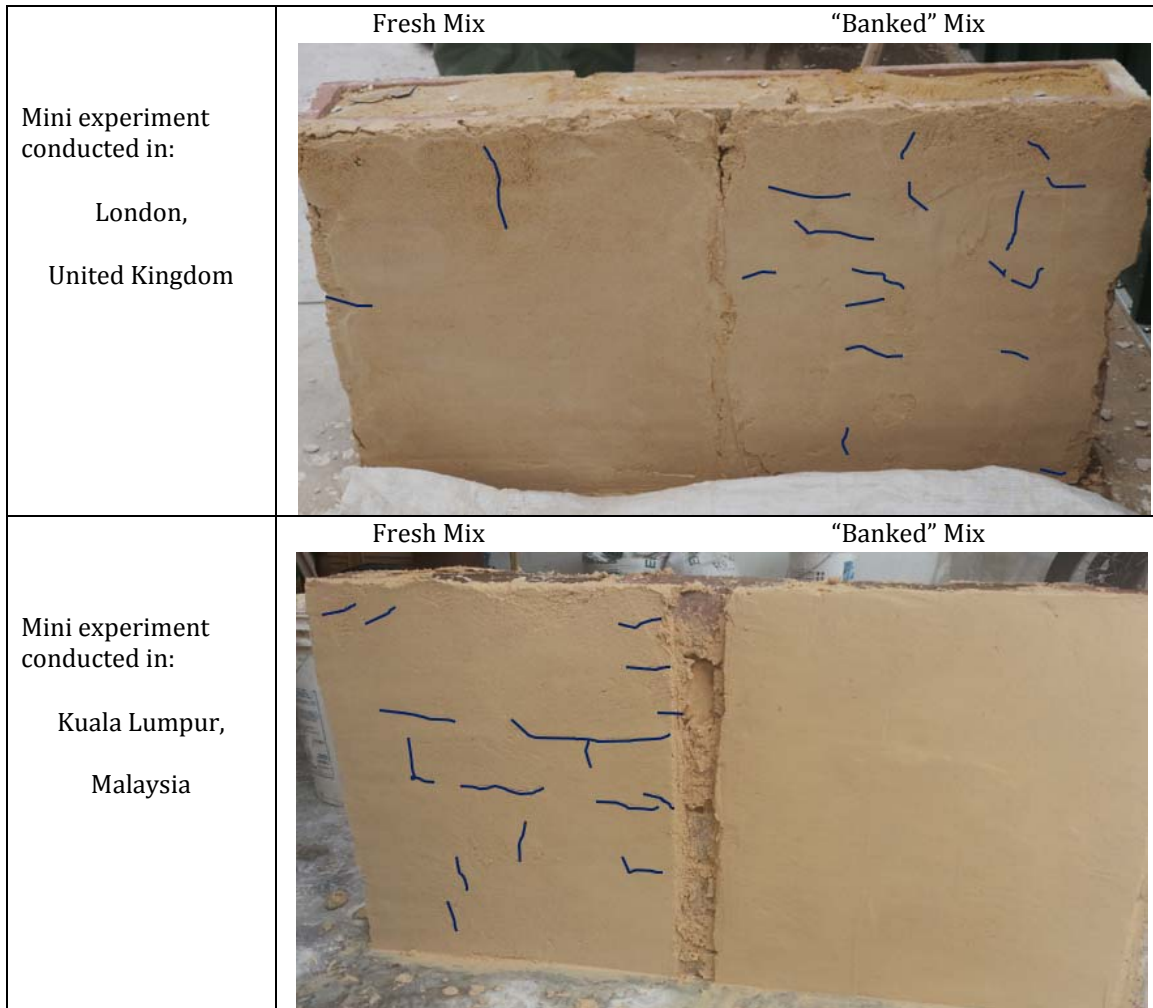


Figure 1-2. Contradiction in the experiments carried out in London and Kuala Lumpur. The blue lines mark the shrinkage cracks observed on the stucco a few hours after application.

In assessing these two experiments, it is important to acknowledge the existence of uncontrolled variables. Firstly, it was obvious that the climates were very different in these two localities whereby the temperature and relative humidity vary greatly between the two. Secondly, the wall itself was certainly different. The absorption characteristics of the bricks used in London and Kuala Lumpur were not studied, and were unlikely to be similar. Common to both in the London and Malaysia experiments was that the freshly-mixed mortars were more workable than those that were “banked”. This was more obvious in the Malaysian situation, perhaps owing to the fact that there was more water in the freshly-mixed mortar than in the “banked” mortar, from which some water had been drained.

The contradiction in the results was puzzling. It seemed to challenge the validity of the “banking” practice in the UK, at least with respect to shrinkage. This led the author to a very important question: what does “banking” do and how does the relatively short period of time in “banking” improve the performance of the stucco?

1.4 Thesis direction

This thesis will explore “banking” and the role it plays in mitigating shrinkage. Chapter 2 will look at shrinkage in lime stucco and mortar, and the parameters that affect it. One important point to raise here is that the discussion of lime stucco in most of the technical literature is quite small compared to that for lime mortar. At a very fundamental level, mortar and stucco are made of similar materials: lime, sand and water. Therefore, the terms mortar and stucco will be used somewhat interchangeably throughout the text, as the two materials often only differ in their final application.

Chapter 3 will look at field practice and recommendations in the historic literature pertinent to the practice of “banking”. The thesis used the information gathered in this section to inform the design of the experiments that are presented in Chapter 4. A comprehensive discussion of the design development and improvements in the experiment will be given. This chapter will also inform the reader of the total number of specimens produced to obtain the raw data that is interpreted in Chapter 5.

Chapter 5 is the heart of the thesis. The experimental data are analyzed and plotted in bar graphs to observe emerging patterns in relation to shrinkage. The data are then interpreted and discussed. Finally, Chapter 6 will provide a summary of what has been learned about “banking”. This final chapter will also provide some recommendations for future research.

2. Shrinkage

2.1 Stages of shrinkage

There are many factors that influence shrinkage in lime stucco but the most common are the amount of water and aggregate in the mix. Shrinkage occurs in two distinct stages: early shrinkage that is associated with the first 48 hours after application; and later shrinkage that refers to the mortar at 3 days and beyond.^{8,9,10} The early stage of shrinkage is commonly known as drying shrinkage, caused by evaporation of water from the mortar.^{11,12} It could also be caused by rapid loss of moisture by suction from the underlying substrate, causing shrinkage that could occur as early as the first few hours.¹³

Although drying shrinkage is commonly recorded in laboratory setting in the first few hours, it is important to note that the loss of water continues beyond this period of time. Hansen et al. explained the phenomena of drying shrinkage as follows:

Setting of mortar first occurs upon drying, with capillary forces causing the first strength increase through jellification, i.e., it gains limited cohesion resulting from the capillary forces between water and the material surfaces and not from a chemical conversion reaction. This process is accompanied by some shrinkage and the carbonation reaction of calcium hydroxide with

⁸ Javier A. Sanchez, Jesus Barrios, Angela Barrios, Antonio R. De Arellano Agudo, "The shrinkage in lime mortars," *Materiales de Construccion*, 47.245 (1997), p. 17

⁹ Anna Arizzi, Giuseppe Cultrone, "The water transfer properties and drying shrinkage of aerial lime- based mortars: an assessment of their quality as repair rendering materials." *Environ Earth Science*, 71 (2014) p. 1708

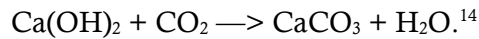
¹⁰ J. Lanas, J.I. Alvarez, "Masonry repair lime-based mortars: Factors affecting the mechanical behavior," *Cement and Concrete Research*, 33 (2003), p. 1872

¹¹ Arizzi et al. (2014), Water transfer..., p.1708

¹² Sanchez et al., Shrinkage in..., p.17

¹³ Maria Rosario Veiga, Ana L. Velosa, Ana C. Magalhaes, "Evaluation of mechanical compatibility of renders to apply on old walls based on a restrained shrinkage test," *Materials and Structures*, 40 (2007), p. 1115

carbon dioxide in the atmosphere to produce calcium carbonate starts:



The later stage of shrinkage is often associated with carbonation. Carbonation of lime-based mortar involves a prolonged process of portlandite transformation into calcite¹⁵ and much of the literature seems to agree that longer curing time allows for a more complete carbonation, which will then contribute to the improvement of the strength of the mortar.^{16,17} This carbonation process is associated with internal stresses that take place in small pores, during the portlandite transformation.¹⁸ In the long run, these cracks can move into the larger pores, causing loss of strength.¹⁹

Shrinkage in both early and later stage is an issue because it could lead to a number of problems such as cracks, loss of adhesion to the substrate and overall loss of strength. In the discussion of stucco, mechanical strength is not a crucial property that needs to be as controlled as other characteristics such as capillary absorption and vapor transmission.²⁰ This is because stucco is generally used non-structurally, for its aesthetic appearance. As mentioned earlier, stucco also acts as the protective external coating, and hence, a greater emphasis is placed on its role in moisture movement.

¹⁴ Eric F. Hansen, Carlos Rodríguez-Navarro and Koenraad Van Balen, "Lime putties and mortars: Insights into fundamental properties," *Studies in Conservation*, 53.1 (2008), p. 12

¹⁵ The carbonation process of lime-based material goes back to the mechanism known as *lime cycle*.

¹⁶ Lanas et al., *Masonry repair...*, p. 1870

¹⁷ Robert M. Lawrence, Timothy J. Mays, Sean P. Rigby, Peter Walker, Dina D' Ayala, "Effects of carbonation on the pore structure of non-hydraulic lime mortar," *Cement and Concrete Research*, 37 (2007), pp. 1059-1060

¹⁸ Othman Omikrine Metalssi, Abdelkarim Aït-Mokhtar, Philippe Turcry, Bertrand Ruot, "Consequences of carbonation on microstructure and drying shrinkage of a mortar with cellulose ether," *Construction and Building Materials*, 34 (2012) p. 224

¹⁹ Lanas et al., p.1874

²⁰ Anna Arizzi, G. Cultrone, "The difference in behaviour between calcitic and dolomitic lime mortars set under dry conditions: The relationship between textural and physical-mechanical properties," *Cement and Concrete Research*, 42.6 (2012a), p. 819

Shrinkage during the early stage is especially of concern because mortar in a plastic state is weak and susceptible to deterioration.^{21,22} Loss of water from the mortar will cause in a reduction of volume and this phenomenon could generate stress that will cause the stucco to deform.²³ When properly applied on a wall, the stucco is generally well adhered to the substrate and any deformation caused by restrained shrinkage can lead to cracking.²⁴ These initial cracks could develop into larger cracks and cause accelerated degradation via penetration of not only water (that might result in freezing damage), but also aggressive agents such as chlorides and sulfates.²⁵

The excessive suction of water into the wall could also weaken the bond between the stucco and the substrate. According to Gillmore (1896), adhesion of mortar takes place in the drying process whereby “small crystals of soluble lime are deposited onto adjacent surfaces and adhere with such force to them, as to increase very materially the strength of the aggregates, when the surfaces become closely approximated, as is the case with mortars.”²⁶ Because stuccos were typically applied on the substrate in layers, the adhesion of the first coat (often known as the ‘scratch coat’), to the substrate is imperative in ensuring that the weight of the subsequent coats will not cause the stucco to fall off. Therefore, any shrinkage during the early stage of application of a lime stucco can produce undesirable results in its long-term mechanical properties.

²¹ Veiga et al., Evaluation of..., p. 1115

²² Sanchez et al., pp. 17-18

²³ Ibid.

²⁴ Veiga et al., p. 1115

²⁵ A Kronlof., M. Leivo., P. Sipari, “Experimental study on the basic phenomena of shrinkage and cracking of fresh mortar”, *Cement and Concrete Research*, 25.8 (1995), pp. 1747

²⁶ Quincy Adams Gillmore, *Practical treatises on limes, hydraulic cements and mortars*, 11th ed. (New York: D. Van Nostrand, 1896) p.299

There is a limited amount of study dedicated to investigating the phenomenon of shrinkage in lime stucco and its mitigation. Hansen et al. have stated that heavy reliance on “often contradictory empirical observations” by the architect and architectural conservator, as opposed to systematic scientific knowledge, was the primary reason behind slow progress in the technical evaluation of high-calcium lime-based materials.²⁷ Repair works on historic building within the period of 1950 through the 1980s saw the wide use of portland cement without an understanding of its potential adverse impact in the long run. It was not until more recently, as studies of traditional lime-based materials were carried out, that there was an understanding of failures observed with the use of cement on historic buildings.²⁸

Some recent scientific studies have pointed out a number of factors that influence shrinkage in lime-based materials. The most common are associated with the fundamental components of the mortar; lime, sand and water.^{29,30} However, the majority of these studies (as well as the historic literature) do not specifically discuss shrinkage, but instead look at the mechanical properties of lime-based mortars and stuccos.

2.2 Lime and water

Often the limes used as plaster and stucco in historic buildings were non-hydraulic. The most common type used was high-calcium lime, slaked into putty and left to age for a considerable period of time. There were many views with regard to an appropriate aging time, including empirical observations dating back to the time of Vitruvius, through to the 18th and 19th centuries. More recent research has found that prolonged aging of lime putty

²⁷ Hansen et al., *Lime putties...*, p. 10

²⁸ John Ashurst, “Mortars for stone buildings,” *Conservation of Building and Decorative Arts*, Vol. 2. Edited by J. Ashurst and F. G. Dimes. (London: Butterworth Henemann, 1990), pp. 78–96

²⁹ Sanchez et al., p. 17

³⁰ Arizzi et al. (2014), p. 1708

will cause significant particle size reduction of the portlandite crystals, allowing them to retain larger quantity of water, resulting in an increase in plasticity and workability.^{31,32,33} These qualities were said to be fundamental to the “superior behavior of lime-based mortars and plaster.”³⁴ High plasticity also generally coincides with high sand-carrying capacity, which could potentially increase shrinkage in mortars with an insufficient amount of aggregate. This theory is supported by a 2000 study that found that higher water retention in aged lime putty could lead to greater shrinkage.³⁵

Although the use of aged lime putty had been considered to be very desirable, technological advancements led to the development of so-called dry hydrates. Lazell (1915) defined hydrated lime as “the dry flocculen powder resulting from the treatment of quick lime with sufficient water to satisfy the calcium oxide.”³⁶ The use of dry hydrate also had its own appeal over putties, including lower cost of transportation, and ease of storage and use on site. Numerous studies have been conducted to compare the properties of aged putties with those prepared from soaked dry hydrates. In most of these studies, the major difference is seen in the rheological properties offered by lime putty.³⁷ The lime putty was found to have higher water content and retentivity when compared to the soaked dry hydrate and this is linked to smaller crystal size. In theory, use of aged lime putty should result in greater

³¹ Carlos Rodriguez-Navarro, Eric Hansen, and William S. Ginell, “Calcium hydroxide crystal evolution upon aging of lime putty,” *Journal of the American Ceramic Society*, 81 (1998), p.3034

³² Hansen et al., p. 17

³³ C. Atzeni, A. Farci, D. Floris, and P. Meloni, “Effect of aging on rheological properties of lime putty,” *Journal Of The American Ceramic Society*, 87.9 (2004), p. 1764

³⁴ Rodrigues-Navarro et al., Calcium hydroxide..., p. 3034

³⁵ Olga Cazalla, Carlos Rodriguez-Navarro, Eduardo Sebastian, Giuseppe Cultrone, Maria Jose De la Torre, “Aging of lime putty: Effects on traditional lime mortar carbonation,” *Journal of the American Ceramic Society*, 83.5 (2000), p. 1075

³⁶ Ellis Warren Lazell, *Hydrated Lime: History, Manufacture and Uses in Plaster, Mortar, Concrete; A Manual for the Architect, Engineer, Contractor and Builder*. (Pittsburgh: Jackson-Remlinger Printing Co., 1915), p. 41

³⁷ Hansen et al., pp.16-17

drying shrinkage in stuccos. A microscopic investigation reported in 2012 found, in fact, that shrinkage cracks and micro-cracks were present in lime putty mortars (and hot-mixed mortars)³⁸ but not in mortars made from dry hydrates.³⁹

2.3 Sand

The other major ingredient in mortar is sand. Lime, if used by itself, will shrink excessively in drying and curing.^{40,41} Sand is important in making up the bulk of the mortar,⁴² while providing pores (in leaner mixes) to allow for carbonation.^{43,44} Most sand is understood as an inert substance, hence its role in mortar is generally to fill up the space within the paste, while the latter, of course, acts to bind the system together by the chemical reactions that take place in the presence of water.⁴⁵ The size (and size distribution), shape and amount of sand are major determining factors in the shrinkage of lime mortar. If the sand content is too low, a mortar will shrink and crack, but if it is too high, the mortar can be poorly adhered to masonry surfaces, and be extremely weak.⁴⁶

³⁸ Hot-mixed mortar is mortar prepared from slaking quicklime and wet sand. The quicklime undergo slaking process from the moisture that exist in the sand. Sometimes, water was added to the mix.

³⁹ Jan Valek, Tomas Matas, "Experimental study of hot mixed mortars in comparison with lime putty and hydrate mortars," *Historic Mortars: Characterization, Assessment and Repair*, RILEM Bookseries 7 (2012), pp. 269-270

⁴⁰ Gillmore, *Practical treatises...*, p. 70

⁴¹ Joseph Gwilt. *An Encyclopedia of Architecture: Historical, Theoretical, and Practical*. (London: Longman, Brown, Green and Longmans, 1842), p. 507

⁴² Lazell, *Hydrated lime...*, p. 52

⁴³ K. Elert, C. Rodriguez-Navarro, E.S. Pardo, E. Hansen, & O. Cazalla, "Lime mortars for the conservation of historic buildings," *Studies in Conservation*, 47.1 (2002), p. 62

⁴⁴ Cazalla et al., *Aging of...*, p. 1075

⁴⁵ Lauren B. Sickels-Taves & Michael S. Sheehan, "Specifying historic material: the use of lime," *Masonry: Opportunities for the 21st Century, ASTM STP 1432*, D. Throop and R.E. Klingner, Eds., ASTM International, West Conshohocken, PA, 2002. p. 5

⁴⁶ H. Ries, *Lime and Cement Industries of New York*, (Albany: University of the state of New York, 1901), p. 675

Gwilt, writing in 1842, stated that most public works executed in Great Britain in the second quarter of the 19th century employed a mix of 1 part lime to 3 parts sand.⁴⁷ Publications of the early 20th century also discussed ratios of 1:3 or 4 parts of sand.^{48,49,50} Ries (1901) commented that such ratios “will give a plastic mortar which does not crack.”⁵¹ A more recent publication recommended a wider range of ratios, from 1:1 to 1:4, for stuccos.⁵²

Common specifications call for sand to be clean, sharp and well-graded, while the proportion of sand depends “partly upon the degree of fineness of the sand.”^{53,54,55} With a graded sand, made up of a range of coarse to fine particles, is important for the binder to fill the spaces between the particles (or to at least fully coat the sand particles) to create a cohesive mass upon curing. Modern standards such as ASTM C270 further clarify the importance of having a “well-graded aggregate” in that it

...reduces separation of materials in plastic mortar, which reduces bleeding and improves workability. Sands deficient in fines produces harsh mortars, while sands with excessive fines produce weak mortars and increase shrinkage....⁵⁶

⁴⁷ Gwilt, *An Encyclopedia...*, p. 507

⁴⁸ Frank W Macey, *Specifications In Detail*, 2nd ed., rev. & enl. (London: C. Lockwood, 1904), p. 63

⁴⁹ G.T. Powell, *Foundations and Foundation Walls, For All Classes of Building, Pile Driving, Building Stones & Bricks, Pier and Wall Construction, Mortars, Lime, Cements, Concrete, Stuccos, Etc.* 4th ed. (New York: William T. Comstock, 1889), p. 99

⁵⁰ Frederick Thomas Hodgson, *Plaster And Plastering: Mortars And Cements, How to Make, And How to Use ... To Which Is Appended an Illustrated Glossary of Terms Used In Plastering, Etc.* (New York: The Industrial Publication Company, 1906), p. 36

⁵¹ Ries, *Lime and...*, p. 676

⁵² John Ashurst, *Mortar, Plasters and Renders in Conservation*, (London: Ecclesiastical Architects' and Surveyors' Association, 1984), p. 10

⁵³ Chas. H. Haswell, “Limes, cements, mortars and concretes: Collected from the observations and experiments of General Gillmore and Totten, U.S.A., and Vicat, Chatoney, Rivot and Dupont,” *Journal of the Franklin Institute*, 79.6 (1865), p. 366

⁵⁴ L.J. Vicat, *A Practical And Scientific Treatise On Calcareous Mortars And Cements: Artificial And Natural*. London: J. Weale, 1837. p. 87

⁵⁵ Ashurst, (1984), *Mortar plasters...*, p. 43

⁵⁶ ASTM C270-14a, “Standard specification for mortar for unit masonry,” (Philadelphia: ASTM International, 2014), p. 9

ASTM C144 suggests a near-ideal gradation of masonry sand, requiring that all particles pass a no. 4 sieve, and with no more than 5% passing the no. 200.⁵⁷ (For the experimental work of this thesis, a single sand was used, from a local supplier, and this will be further discussed in Chapter 4.)

Some studies have suggested that specific types of aggregates could also influence the mechanical properties of a mortar. Lanas et al. wrote a lengthy explanation with regard to this matter:

...siliceous aggregates provide small radius pores which obstruct an adequate CO₂ flow through the mortar.... Nevertheless, limestone aggregates, increasing the amount of medium and large radius pores, allow mortar carbonation and improve mortar strength. Moreover, during the drying and crystallization process, stress is higher in smaller pores due to their low radius. This stress could produce cracks during shrinkage and subsequent calcite crystallization....⁵⁸

Historically, shrinkage in lime-based materials was well recognized as an undesirable situation, and some specialized additives were introduced. Fibrous materials, such as horsehair, were commonly used to prevent cracking, as noted in construction-related documents that date back to the early 1700's.^{59,60} Two centuries later, Lazell recommended animal hair for a scratch coat made of 1 part dry hydrate and 4 parts sand.⁶¹ (Other admixtures, such as pozzolans, are also mentioned in these publications, and were said to

⁵⁷ ASTM C144-11, "Standard Specification for Aggregate for Masonry Mortar." p. 1

⁵⁸ Lanas et al., p. 1874

⁵⁹ J. Moxon, *Mechanik Exercises or the Doctrine of Handy Works Applied to the Art of the Bricklayer's Work*. 2nd ed, (London: 1700), p. 244

⁶⁰ Richard Neve, *The City and Countery Purchaser, and Builder's Dictionary: or, The Complete Builder's Guide*. (London: 1703), p. 234

⁶¹ Lazell, p. 54

improve setting; in East Asia, organic materials, including sticky rice soup was employed to improve the mechanical properties of lime-based mortars.⁶²⁾

Another important factor in controlling stucco shrinkage, and one that is not material related, is field practice. The craftsmanship of the mason throughout the process of applying lime stucco involves both skill and careful thought, from the preparation of the substrate and the mixing of the stucco to the covering and re-wetting of it to avoid shrinkage.

⁶² Fuwei Yang, Binjian Zhang, Qinglin Ma, "Study of sticky rice – lime mortar technology for the restoration of historical masonry construction", *Accounts of Chemical Research*, 43.6 (2010), p. 942

3. “Banking” and Pre-soaking

In mitigating shrinkage, to improve the performances of lime-based materials, a number of working methods were employed in the field, over a long period of time. These practices will be discussed in this chapter. Both historical and contemporary notes on some aspects of mortar preparation will be examined. (Portions of some of the texts are emphasized in bold.)

3.1 “Banking”

Just as there were differing opinions on binder:aggregate ratio, there was also a variety of methods (such as “beating”) for the preparation and storage of mortar mixes.⁶³ Lynch (1998) compiled many of these, and named the practice of storing the “coarse stuff” as the “banking” of lime mortars.⁶⁴

The earliest document referenced by Lynch that records this short-term storage practice was Moxon’s *Mechanik Exercises...*, written in 1700:

...And Lime mixt with Sand, and made into Morter, **if it lye in an heap two or three Years before ‘tis used, it will be the stronger and better**, and the reason of so many insufficient Buildings, is the using of the Morter, as soon as ‘tis made, as *Agricola* faith.⁶⁵

...That you beat all your Morter with a Beater three or four times over before you use it, for thereby you break all the Knots of Lime that go through the Sieve, and incorporate the Sand and Lime well together, and the Air which the Beater forces into the Morter at every stroak, conduces very much to the strength thereof... If I might advise any one that is minded to build well, or use strong Morter for Repairs, I

⁶³ Mortar is often referred to as “coarse stuff”—a mixture of sand and lime. In this chapter, the two terms will be used somewhat interchangeably.

⁶⁴ Lynch, *Lime mortar...*, p. 18

⁶⁵ Moxon, *Mechanik Excercises...*, p. 243

would have them beat the Morter wel, **and let it lie 2 or 3 days**, and then beat it well again when 'tis to be used.⁶⁶

In 1703, Richard Neve commented on the subject, based on his interactions with craftsmen:

Some Workmen tell me, that 'tis the best way **not to use Mortar as soon as 'tis made; nor (in making it)** to make the Lime run before it is mixt with the Sand, (as some will do,) but rather to take the Sand and throw it on the Lime whilst it is in Stones, before it is run, and so to mix it together, and then wet it; by which Means, (say they) it will be the stronger, and when it has lain a while made before it is us'd, will not be so subject to blow and blister. Others advise to **let Mortar (when made) lie in a heap two or three years** before 'tis us'd; for so (say they) 'twill be the stronger and better; for the Reason of so many insufficient Buildings, (say they,) is the using of the Mortar as soon as 'tis made.⁶⁷

At the start of the 20th century, Hodgson said that:

Mortar for the plasterer's use should be well made, and the following rules should be strictly complied with: 1st. The lime should be thoroughly slaked, and brought to a paste or putty state. 2d. It should remain in the mortar bed until it is perfectly cool before mixing in the sand and hair. 3d. **Good mortar can be used with safety eight or ten days after it is made, but in no case should it be used before it is six days old.**^{*68}

***Some authorities say it is best to use mortar for plastering within three or four days after it is first made.** They claim that in mortar which stands ten or more days before using, the lime loses a portion of its strength, and the mortar becomes deteriorated thereby. This, to a certain extent, is true: but, notwithstanding the loss of strength by the lime, and the consequent deterioration of the mortar, **every observant plasterer knows that walls coated with mortar made two or three weeks previous to using, stand better than those coated with "green" or freshly-made mortar.** Newly-made mortar, immediately applied, frequently causes the walls to

⁶⁶ Moxon, pp. 258-259

⁶⁷ Neve, *The City...*, p. 205

⁶⁸ Hodgson, *Plaster and...*, p. 29

chip, crack, and become mottled. **Mortar well-tempered, and as well seasoned, works better and cooler than the hastily made new mortar, and invariably gives better satisfaction.** Col. Gillmore, quoting from Vicat, and apparently endorsing the statement, says: It was supposed, for many years, that the longer the lime was slacked before it was used, the better mortar it would make. Recent experiments prove, however, that this is not the case with mixtures of fat lime and sand only. **Better results are obtained with such mortars if the paste be mixed with the sand as soon as the slaked lime has become cold, and care should be taken to use no more water, in the process of extinction,** than may be required to produce a thick pulp.”⁶⁹

These traditional practices lived on in a fairly recent document published by Ashurst (1986):

A recommended compromise between slaking the lime and sand mixture and turning over dry constituents later, **is to mix the slaked putty with the sand and other aggregates and to store the constituents together, protected from the air as wet “coarse stuff” for as long as possible to mature.** This coarse stuff is the best possible base for mortar and lime plaster, whether or not it is to be gauged later with any pozzolanic additives. Storage is best arranged in plastic bins with air-tight lids, with an additional covering inside the bin of wet underlay felt, or wet sack. Another advantage of storing wet coarse stuff is that all the mixing for a large job can be carried out in one or two operations and a consistent mortar or plaster will be available for use as required.⁷⁰

It seems to have been Lynch who, in discussing the storage of “coarse stuff”, named it “banking”:

For limited storage of mortar as a coarse stuff, one could readily use a hydraulic lime, especially the feebly hydraulic class of lime that is today so often ignored for this capability. For increased storage times, one can only be talking about pure or non-hydraulic lime, which possesses no internal set. Feebly hydraulic lime, however, could be slaked and stored (even as a putty). After banking as a coarse

⁶⁹ Hodgson, p. 29

⁷⁰ Ashurst(1984), p.10

stuff, it would still have much of the workability of a pure lime, and yet possess the important internal chemical set (a result of a silicate reaction of the clay impurities of up to 8%), which allowed work to progress with growing strength. **This mortar could be “banked” as coarse stuff for a short period** (few bricklayers' coarse stuffs were stored longer), getting 'fatter' and, despite the mortar beginning to stiffen, once 'knocked-up' again for use would go on to achieve a perfectly adequate set.⁷¹

The most recent publication known to the author was published in 2012 by Historic England. It mentions “banking” as follows:

Non-hydraulic lime mortar can be stored as coarse stuff for very long periods of time, provided it is protected from the exposure to the air and protected from frost. **Long storage improves the bond between the lime and aggregate, and allows excess water to collect on top of the mortar; this water should be poured off before use.** Coarse stuff stiffens during storage, particularly if it contains crushed limestone as part of the aggregate. After a few months it can be knocked up by hand or by a plaster mixing drill, but after prolonged storage it can be extremely hard to re-work by any means other than a mortar mill.⁷²

There are, of course, some significant contradictions in the literature. Higgins, writing in the latter part of the 18th century, described a 1777 field test of two small test walls of brick, both constructed with chalk lime mortar. One wall used a freshly-mixed mortar, and the other a mortar of the same composition that had been stored for 24 days. The walls were examined by him every two weeks over a period of one year. Higgins' conclusion was that the best mortar was that which had been used soon after mixing.⁷³

⁷¹ Lynch, p. 13

⁷² Historic England. *Practical Building Conservation: Mortars, plasters and render*, eds. A. Henry and J. Stewart (Surrey: Ashgate Publishing, 2011), p. 287

⁷³ Bry Higgins, *Experiments and Observations made with the view of improving the art of composing and applying Calcareous Cements...* (London: 1780), pp. 37-40

3.2 Timing

In terms of an optimum period of time for “banking”, there is no general agreement. Some texts, such as Moxon, are particularly confusing, as he says: “..And Lime mixt with Sand, and made into Morter, if it lye in an heap two or three Years before ‘tis used, it will be the stronger and better....”⁷⁴ Does the “it” here refer to the lime itself or to the mortar? In the wording related to repair mortar, he seems to make it clear that it is the mortar, after beating, that is allowed to sit for 2 to 3 days, and then beaten again before use.⁷⁵ If this is “banking”, then the two or three year period perhaps refers to the aging of the putty.

That interpretation seems to be undermined by Neve, as he offers suggestions (more clearly worded as specifically for mortar) that range from “a while” to “two or three years”.⁷⁶

Hodgson discusses relatively short periods of time between mixing and use, but recognizes differing opinions. He speaks of mortars for plastering (that is, plaster and stucco) as requiring at least 6 days of storage, while adding that “some authorities” suggested that plastering mortar should be used within three to four days, despite the fact that plasterers themselves were using lime-sand mixes that were prepared two to three weeks earlier.⁷⁷

Recent discussions by Ashurst, Lynch and Historic England are even more vague. Ashurst and Historic England both recommended “banking” the mortar for “as long as possible to mature” without a clear minimum number of days.^{78,79} Lynch suggested “banking” for “a short period” while making a side note that “few bricklayers' coarse stuffs were stored longer.”⁸⁰

⁷⁴ Moxon, p. 243

⁷⁵ Moxon, p. 258

⁷⁶ Neve, p. 205

⁷⁷ Hodgson, p. 29

⁷⁸ Ashurst(1984), p. 10

⁷⁹ Historic England, *Practical Building...*, p. 287

⁸⁰ Lynch, p. 13

An important observation about a possible result of “banking” that is only mentioned in the recent publication by Historic England is that “long storage” will allow bleed water to be observed on the surface, and this this water should not be re-incorporated into the mix.⁸¹

This concept was incorporated into the experimental design, described in Chapter 4.

3.3 Soaking of dry hydrates

Lazell (1915) pointed out that an improvement in the workability of mortars derived from dry hydrates can be achieved by soaking.

A mortar made with hydrated lime often does not trowel quite so easily as a mortar made from lime putty. **The smooth working qualities of the hydrate can be greatly improved by proper method of manufacturing and by allowing the mortar or paste to soak over night** so that the gauging water becomes thoroughly incorporated. The great ease of handling hydrate and the thoroughness with which it has been slaked make up to a great extent for any lack of plasticity.⁸²

As to the preparation of the mortar, he went on to describe the methods of mixing, either by machine or by hand. For the latter, he commented:

If hand mixing is to be used, two methods may be employed in preparing the mortar. **FIRST--Soak the hydrate with water so as to produce a thick paste, and allow to stand over night**, then add the desired amount of sand and sufficient water to give the required consistency to the mortar. It is generally conceded that this method produces the more plastic mortar.

SECOND—Mix the hydrate and sand dry, the same as with cement mortar, then add the water to produce the required consistency.⁸³

Even for machine mixing, he seems to suggest that mortar, with water already incorporated into the mix, be allowed to sit before use. Describing mortar prepared for a particular brick

⁸¹ Historic, p. 287

⁸² Lazell, p. 49

⁸³ Lazell, p. 55

project, he says:

The mixing machine was operated only during the last few hours in the afternoon, enough mortar being prepared for next day's requirements. **The mortar mixed in the machine was dumped into the basement in a pile and was allowed to age overnight.** When used the mortar was entirely satisfactory and worked free and smooth.⁸⁴

Today, ASTM C206, Standard specification for finishing hydrated lime, states in Section 7 that the plasticity of Type N shall be no less than 200 Emley units when soaked for a period of not less than 16 hours nor more than 24 hours. Type S, on the other hand, should have the same plasticity after only 30 minutes of soaking. Section 11, on package marking, requires the supplier to identify that Type N “shall be soaked for a minimum of 16 hours prior to use.”⁸⁵ These wordings had been in place since the committee responsible for C206 was established in 1979. Similar discussions of pre-soaking are also to be found in C207, Standard specification for hydrated lime for masonry purposes, in Section 8 (Plasticity) and 9 (Water Retention).⁸⁶

The question of pre-soaking has also been discussed by Cazalla et al. (2000)⁸⁷, Rodriguez-Navarro (2005)⁸⁸ and Hansen et al. (2008)⁸⁹, in studies of the microstructure of the soaked dry hydrates in comparison with lime putties. In actual construction practice, it is unclear to what extent this is done, as the introduction of dry hydrates was well received in the building industry decades ago, based on its convenience of use and ease of on-site storage.

⁸⁴ Lazell, p. 53

⁸⁵ ASTM C206–14. “Standard specification for finishing hydrated lime,” (Philadelphia: ASTM International, 2014), p. 1

⁸⁶ ASTM C207–06 (Reapproved 2011), “Standard specification for hydrated lime for masonry purposes,” (Philadelphia: ASTM International, 2011), p. 2

⁸⁷ Cazalla et al., p. 1075

⁸⁸ C. Rodriguez-Navarro, E. Ruiz-Agudo, M. Ortega-Huertas, and E. Hansen, “Nanostructure and irreversible colloidal behavior of Ca(OH)₂: Implications in cultural heritage conservation.”

Langmuir, 21.24 (2005), p. 10949

⁸⁹ Hansen et al., pp. 18-21

4. Experimental Design

4.1 Basic concepts

The primary aim of the experiment was to find out if the practice of “banking” mixed mortar has any effect on early shrinkage, that is, shrinkage that occurs within the first 48 hours after placement. The author took on a neutral stance on this question following the evaluation of the London and Kuala Lumpur test walls. The overall design of the experiments undertaken at Columbia University was driven by an attempt to address the question by limiting the number of variables, and performing as many individual tests as possible to look at the relationship between lime types, mix ratios, methods of specimen preparation, and the practices of “banking” and hydrate pre-soaking.

Those processes have been presented in detail in the previous chapter. For the laboratory experimentation, the specifics of those two terms are further defined as follows. The “banking” period used throughout is 4 days, within the range suggested by the conservation masons working on the facade conservation of the Banqueting House, in the summer of 2015. Pre-soaking was comparatively evaluated with both of the dry hydrates for a period of 24 hours. The quantities of pre-soak water used for the sanded specimens were the amounts required to produce workable mixes once the sand was added. (In the paste experiments, however, the same amount of water was used for all hydrate specimens.)

4.2 Materials

4.2.1 Lime

Two types of lime--both of them are non-hydraulic--were used in all aspects of the research: lime putty and dry hydrates. The lime putty been aged for 2 years.⁹⁰ It is a high-calcium putty, sourced from US Heritage.⁹¹

The dry hydrates used in the research are high-calcium Type N and dolomitic hydrate Type S, sourced from Mississippi Lime and Graymont, respectively⁹². Although high-calcium hydrates have the same chemistry as most putty worldwide (including the US Heritage product), dolomitic dry hydrates are used more widely in North America. This has been the case for more than half a century.⁹³

Dry hydrates are commonly used in the repair of historic buildings. It is important to understand that direct comparison of the results of the putty and hydrate portions of the testing program may be limited by the fact that one part (volumetrically) of putty is not equal to one part of dry hydrate.^{94,95,96} (This difference seems to be disregarded in the ASTM C270 standard, which treats putty and hydrate as equivalent.)⁹⁷

⁹⁰ The lime putty was aged for a period of 2 years by the supplier. Aging of putty is different from the “banking” of “coarse stuff”. This thesis is not looking at the aging of lime putty.

⁹¹ Product specification of the lime putty from US Heritage is available in the Appendix A.

⁹² Product specification of the dry hydrates from Mississippi Lime and Graymont are available in the Appendix A.

⁹³ Jennifer Schork, “Dolomitic Lime in the US,” *Journal of Architectural Conservation*, 18.3(2012), p. 10

⁹⁴ Morgan Phillips, “A source of confusion about mortar formulas,” *APT Bulletin*, Vol. 25, No. 3/4 (1993), p. 50

⁹⁵ ASTM C206–14, pp. 1-2

⁹⁶ ASTM C1713-15, “Standard specification for mortars for the repair of historic masonry,” (Philadelphia: ASTM International, 2014), p. 3

⁹⁷ ASTM C270-14a, pp. 3-4

4.2.2 Sand

A well-graded masonry sand was purchased for the work from a local hardware and building supply store. Particle size distribution (as acquired) is presented in section 4.3.2, below. For use in the experiment it was subsequently screened to eliminate particles passing a no. 200 sieve, that is, less than 75 microns in diameter. (As more substantial amounts of sand were needed, a few particles larger than 4.8 mm were observed on the no. 4 sieve, and were also removed.)

Two volumetric binder:aggregate ratios were chosen for most of the research. The first ratio is 1:1, representing the richest mix described in the literature as for lime stucco.⁹⁸ The second ratio, 1:2¼, is the low limit referenced in ASTM C270, as yields a mix with good workability.⁹⁹ An additional set of experiments was carried out with putty only to look at higher sand content, based on comments in the literature, noted earlier, in Chapter 2, that aged putty can have a high sand-carrying capacity.¹⁰⁰ This experiment (called experiment 3) was executed with 1:3 and 1:4 binder:aggregate ratios.^{101,102,103}

4.2.3 Water

With the lime putty, no additional water is required for sample preparation. For the dry hydrates, two volumetric water:binder ratios were used to achieve acceptable and similar workability for the two binder:aggregate ratios. (De-ionized water was used in all experiments.) These ratios are 1:0.5 and 1:0.6 for 1:1 and 1:2¼ mixes, respectively. They

⁹⁸ Ashurst (1984), p. 40

⁹⁹ It was also based on the mix used in a comparative laboratory evaluation of conservation mortars carried out by Schork et al. in 2012.

¹⁰⁰ Elert et al., Lime mortars..., p.70

¹⁰¹ Ibid.

¹⁰² Arizzi et al. (2014), p. 1709

¹⁰³ Cazalla et al., p. 1075

were determined through an initial experiment (see 4.3.3) that attempted to match the workability of the mixes by “feel” as would typically be done in the field.

Some further experimentation was done to examine the effect of having more water in the 1:2¼ pre-soaked high calcium mix. Increasing amounts of water were introduced into the mixes. This small set of tests is referred to as experiment 4. The details of this experiment, along with experiment 3, are discussed in 4.4.4, below.

4.3 Initial evaluation of materials

4.3.1 Lime paste (binder only) shrinkage

All of the binders used were subjected to a simple test to assess the pattern and amount of drying shrinkage as paste only, without any addition of sand. One challenge with lime putty is the fact that it is shipped and stored covered with a layer of water (herein referred to as capping water) to prevent it from drying and carbonating at/near the surface. Scooping the putty from the bucket can thus cause it to be mixed with a small amount of the capping water, diluting the lime. To lessen this, the bucket can be tilted to one side, directing the capping water away before scooping from the exposed putty surface. This method still yielded putty of a “runny” consistency. The author was able to scoop deeper into the bucket where the putty is denser and does not have direct contact with the capping water. These samples are referred to as of “dry” consistency.

In the case of the dry hydrates, both high calcium and dolomitic, the powders were mixed with a known amount of water (1:0.5) that had already been determined for the 1:1 mix. Two sets of samples were produced for each of the dry hydrates, one set that was not pre-soaked and another that was pre-soaked for the standard period of 24 hours.

Five specimens were produced for each set of samples, as summarized in Table 4-1. All of the samples were cast in Petri dishes and left to dry in the laboratory, at normal indoor conditions of temperature and RH (see 4.4.1). The weight of each specimen was initially recorded (less the dish weight), and then again at 24 and 48 hours.

Sample type	Number of specimen
High calcium putty - runny consistency	5
High calcium putty - dry consistency	5
High calcium dry hydrate - Not pre-soaked	5
High calcium dry hydrate - Pre-soaked	5
Dolomitic dry hydrate - Not pre-soaked	5
Dolomitic dry hydrate - Pre-soaked	5
TOTAL	30

Table 4-1. Specimens cast for the lime paste shrinkage experiment.

4.3.2 Sand sieve analysis

A sieve analysis was carried out as per ASTM C144, Standard specification for aggregate for masonry mortar.¹⁰⁴ The sand was graded within the limits of 4.75 mm (no. 4) and 0.074 mm (no. 200). The weight data revealed that the screened mason's sand falls essentially within the acceptable range of particle size as specified.

Sieve No	Particle Size (mm)	Cumulative Sand Passed (%)	ASTM Standard (% passing)
4	4.76	100.00	100.00
8	2.38	99.77	95 to 100
16	1.19	92.88	70 to 100
30	0.595	65.15	40 to 75
50	0.297	14.85	10 to 35
100	0.149	1.73	2 to 15
200	0.074	0.73	0 to 5

Table 4-2. Summary of data for the sieve analysis.

¹⁰⁴ ASTM C144-11, "Standard specification for aggregate for masonry mortar," (Philadelphia: ASTM International, 2013), p. 1



Figure 4-1. Elimination of particles retained on the no. 4 and passing the no. 200 sieve.

4.3.3 Water ratio

An initial experiment was carried out in October 2015 to determine reasonable amounts of water mortar mixes prepared with dry hydrate. This early experiment was carried out using available materials on hand in the laboratory at that time: sand from Arizona, and a high calcium dry hydrate from Mississippi Lime.

All dry materials were first measured volumetrically for the selected binder:aggregate ratios of 1:1 and 1: 2 ¼, and their weights recorded. They were pre-mixed in a bucket, and de-ionized water was gradually added into the mix until an acceptable workability was achieved. A small-scale trowel test—picking up the wet mix and inverting the spatula to test the adhesion of the mix on the spatula--was carried out to determine a proper consistency for both of the mixes. The weight of the added water (versus the dry hydrates) was then recorded.

	Mix 1	Mix 2
Dry Hydrates	1	1
Sand	1	2 ¼
Water	0.5	0.6

Table 4-3. Amount of water used as a volumetric ratio for the experiments.

4.4 Sample preparation

4.4.1 General procedures

Weight measurements recorded in the initial volumetric experiment allowed all subsequent sample preparation to be done gravimetrically, for reproducibility. A series of experiments was carried out, with some design changes as the work progressed. (For example, in the first two experiments, the stucco was mixed manually using a large spatula, without noting a specific period of time.) Mixes in the subsequent experiments, discussed here, were prepared using by power mixing for a period of 3 to 5 minutes. This was carried out with a jiffler and a DeWalt DCD940 Cordless Driver, at 500 RPM. The shift in the mixing procedure will be discussed later.

Samples were cast in circular plastic Petri dishes, 54mm inner diameter and 13mm in depth. All experiments were carried out Columbia University's conservation laboratory, at temperatures ranging from 69-73 deg F and a relative humidity of 20-25%. The weight of each specimen was recorded at 12 hour intervals, for a period of 48 hours.

Shrinkage observed was measured after 48 hours using an electronic digital caliper (0-150mm with 0.01mm sensitivity). The specific method of measurement will be discussed in Chapter 5.



Figure 4-2. Sample preparation included weighing, power-mixing and casting.

4.4.2 Lime putty specimens

Material was scooped from deep within the tilted putty bucket. No additional water was added. The putty was combined with the sand and power mixed. A portion of each mix was cast in Petri dishes. The remaining material, divided into two halves, was “banked” for a period of 4 days in sealed glass beakers, stored within a zip-lock bag.

After the 4-day period, the beakers were observed, to note if the “banked” mixes produced bleed water. Where this was the case, two different procedures followed, to test the hypothesis that draining bleed water might reduce shrinkage. In one mix, the bleed water was carefully drained; in another, the bleed water was re-incorporated into the mix (Figure 4-3 and 4-4). All of the putty mixes were then re-mixed by hand and cast in Petri dishes.

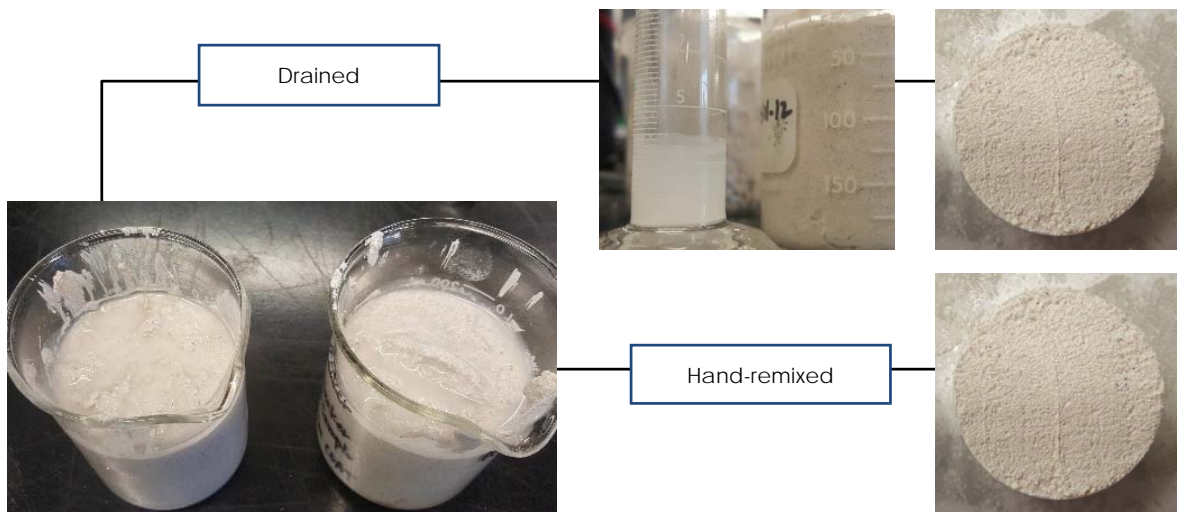


Figure 4-3. Bleed water observed in the “banked” rich mixes. In one, the bleed water was drained, and in another it was re-incorporated into the mix.

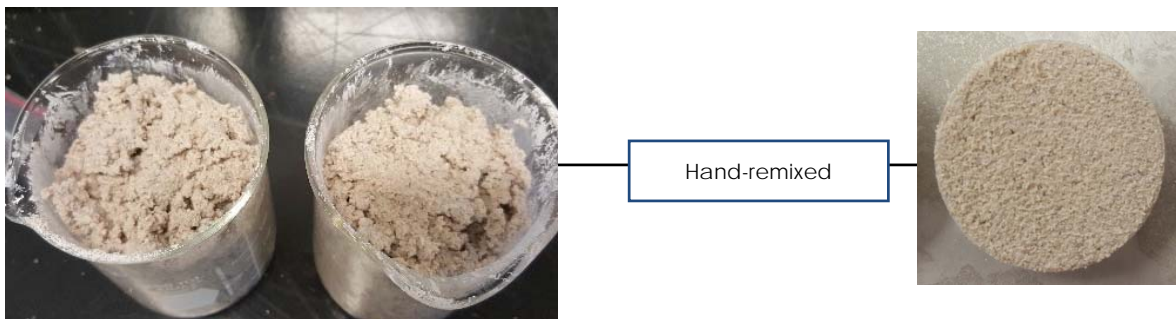


Figure 4-4. No bleed water observed in the “banked” lean mix. It is re-mixed by hand and cast in Petri dishes.

4.4.3 Dry hydrate specimens

Two procedures were used in the preparation of the mixes, pre-soaking some of the dry hydrates and not pre-soaking the remainder. For pre-soaking, the powders were placed in the amount of water required for each of the mixes, in a sealed beaker within in zip-lock bag. After 24 hours, any bleed water was re-mixed into the paste, to ensure uniform water ratio throughout the experiment (Figure 4-5). The pre-soaked hydrates were added into the sand and mixed thoroughly. For the no pre-soaking procedure, dry hydrates were mixed with sand, then combined with the water and mixed thoroughly (Figure 4-6).



Figure 4-5. Pre-soaking procedure: Bleed water formed on top of the pre-soaked dry hydrate is remixed into the paste before added into the sand



Figure 4-6. No pre-soaking procedure: sand and dry hydrate are mixed and added into the water.

Some samples were then cast in Petri dishes. The remaining material was “banked” for a period of 4 days, then re-mixed by hand and cast in Petri dishes.

4.4.4 Other mixes

Experiment 3 was executed with lime putty. The amount of sand is varied in this experiment to look at higher sand contents, 1:3 and 1:4. The mixes are casted and the remaining was “banked”. After the “banking” period, the mixes are hand-remixed and casted in Petri dish. Table 4-4 summarized the number of specimens produced for Experiment 3.

Experiment	Experiment 3 Start date – 4/9/2016	
Mixes	Fresh	Banked
Lime putty – High calcium 1:3	5	5
Lime putty – High calcium 1:4	5	5
TOTAL	20	

Table 4-4. Specimens produced for experiment 3, increasing sand content in the putty mixes.

In experiment 4, the amount of water in 1:2¼ pre-soaked high-calcium hydrate mix was increased. The additional water produced samples with binder:water ratios of 1:0.66 and 1:0.82 by volume. No “banking” was done for these mixes.

Procedure for the third set of this experiment was executed differently. The high calcium dry hydrate was pre-soaked for one week using 1:1 water ratio. At the end of the week, bleed water collecting on the surface was extracted using a syringe and measured in a graduated cylinder (Figure 4-7). The subtraction of the water content was then translated into volumetric ratio which is 1:0.85 water ratio. The pre-soaked hydrates was then added into the sand and power-mixed before casted in the Petri dish. No “banking” was done for this mix. Table 4-5 summarized the number of specimens produced for Experiment 4.

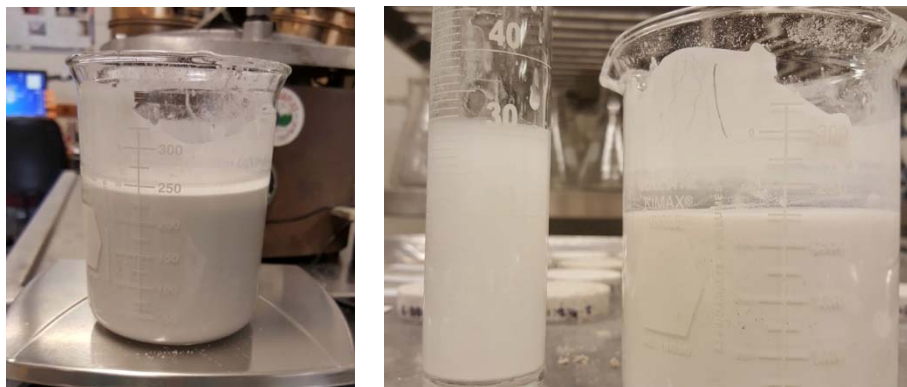


Figure 4-7. The dry hydrate was pre-soaked at 1:1 water ratio and after a week, the bleed water was extracted into a graduated cylinder.

Mixes – water ratio	Experiment 4 Start date – 3/18/2016
Dry hydrate – High calcium 1:2 ¼:0.66	5
Dry hydrate – High calcium 1:2 ¼:0.82	5
Dry hydrate – High calcium 1:2 ¼:0.85	5
TOTAL	15

Table 4-5. Specimens produced for experiment 3, increasing water content in the putty mixes.

4.5 Design improvements

Figure 4-7 illustrates the full experiment, as it ultimately evolved. It illustrates the role of pre-soaking for the dry hydrate mixes, and the drainage of bleed water (at the lower left) for the putty mixes. (The letters F and B refer to fresh and “banked” mixes.)

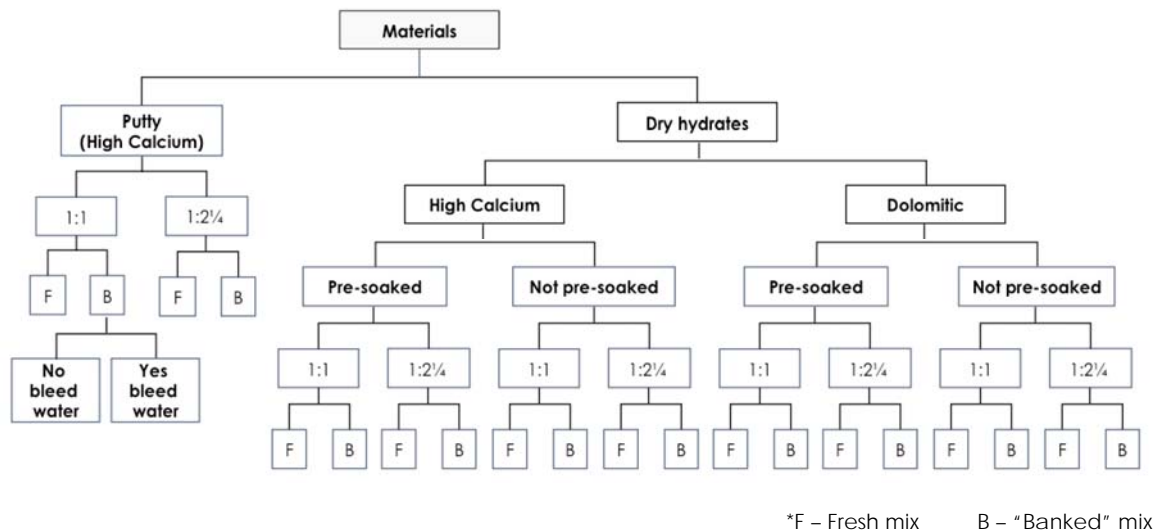


Figure 4-7. Chart showing the structure of the primary experiment.

A series of preliminary experiments was carried out in developing the mixing procedures used in the final version. The experiment to determine the water:binder ratios was done with manually mixing. This procedure, which seemed acceptable at first, was then found to

be difficult for preparing a large number of specimens. Residues of unmixed sand were sometimes found at the bottom of the mixing container, and the time required for mixing each sample set varied greatly. The decision was made to shift to power mixing.

After the assessment of one of the early experiments, the number of specimens for each sample set was increased. Experiment 1A was carried out with 3 specimens per set; this number was too small for data interpretation. Subsequent experiments are then executed with 5 specimens in each sample set. A shortage of material for the “banked” mixes in experiment 2A required a second version, called experiment 2B. It is the data for 2B that are used for the discussion in Chapter 5.

Another design improvement was in the method of “banking”. In experiment 1A, the mixes were “banked” in plastic bags, as had been done on a larger scale on the job site in London. It proved to be difficult to drain the bleed water with this method. Use of glass beakers proved to be a more reasonable technique in the laboratory.

Experiment 1A, done with hand mixing, was also repeated (called 1B) with the improvement of increasing the number of specimens and “banking” in beakers. Experiment 1B will be briefly discussed in Chapter 5 as it relates to the shrinkage behaviour seen in experiments 2A and 2B.

The last improvement made to the experiments was in the recording of weight of the individual specimens. In experiments 1A and 2A, the weight of individual specimens was recorded at 24 and 48 hours. However, in calculating the weight loss percentage and assessing the weight loss pattern in the samples, smaller time intervals seemed necessary for interpretation. Consequently, the weight of the specimens was recorded at 12 hour intervals in experiments 1B and 2B.

Table 4-6 summarizes the improvements in experimental design. Table 4-7 identifies the sample sets in the experiments.

Improvement	Experiment 1A (Hand mixing)	Experiment 2A (Power mixing)	Experiment 1B (Hand mixing)	Experiment 2B (Power mixing)
Number of samples	3	5	5	5
Mixing method	Hand mix	Power mix	Hand mix	Power mix
“Banking” method	Plastic bag	Sealed beaker that is stored in zip-lock plastic bag	Sealed beaker that is stored in zip-lock plastic bag	Sealed beaker that is stored in zip-lock plastic bag
Time interval for recording weight of specimens	24 hours interval	24 hours interval	12 hours interval	12 hours interval

Table 4-6. Summary of improvements made in the design of the experiment.

Experiment	Experiment 1A Start date – 1/31/2016		Experiment 2A Start date – 3/3/2016		Experiment 1B Start date – 4/19/2016		Experiment 2B Start date – 4/19/2016	
	Fresh	Banked	Fresh	Banked	Fresh	Banked	Fresh	Banked
Mixes								
Lime putty – High calcium 1:1 mix	3	6	5	10	5	10	5	10
Lime putty – High calcium 1:2 ¼ mix	3	3	5	5	5	5	5	5
Dry hydrate – High calcium 1:1 Pre-soaked	3	3	5	1	5	5	5	5
Dry hydrate – High calcium 1:2 ¼ Pre-soaked	3	3	5	5	5	5	5	5
Dry hydrate – High calcium 1:1 Not pre-soaked	3	3	5	5	5	5	5	5
Dry hydrate – High calcium 1:2 ¼ Not pre-soaked	3	3	5	5	5	5	5	5
Dry hydrate – High calcium 1:1 Pre-soaked	3	3	5	1	5	5	5	5

Dry hydrate – High calcium 1:2 ¼ Pre-soaked	3	3	5	5	5	5	5	5
Dry hydrate – High calcium 1:1 Not pre-soaked	3	3	5	5	5	5	5	5
Dry hydrate – High calcium 1:2 ¼ Not pre-soaked	3	3	5	5	5	5	5	5
Total	30	33	50	47	50	55	50	55
TOTAL	63		101		105		105	

Table 4-7. Summary of the specimens produced for 4 rounds of experiments.

5. Findings

5.1 Paste (binder only)

All specimens were photographed, and a grid superimposed onto the images using Adobe Photoshop software. The shrinkage cracks were shaded and the area (in mm²) summed.

This value for each specimen was divided by the area of the dish, to compute shrinkage as an area percent.







Type	Shrinkage crack pattern (after 48 hours)
High-Calcium Putty - Runny consistency	
High-Calcium Putty - Dry consistency	
High-Calcium Dry Hydrate - Not pre-soaked	
High-Calcium Dry Hydrate - Pre-soaked	
Dolomitic Dry Hydrate - Not pre-soaked	
Dolomitic Dry Hydrate - Pre-soaked	

Figure 5-1. Pattern of shrinkage cracks for paste (binder only) samples.

Based on visual observations made immediately after casting, paste from the putty of dry consistency was the first to develop cracks, in the first 2 hours. This was followed by the runny putty, the high-calcium hydrate, and the dolomitic. Most of the pastes exhibited a network of “eggshell” cracks through the samples, with the exception of 3 specimens of the non pre-soaked high-calcium hydrate that developed the “ring” cracks that are typical of all of the sanded samples in other experiments.

Crack measurement revealed that the dolomitic dry hydrate pastes exhibited considerably more shrinkage than the other sample sets. The patterns seen in Figure 5-1, however, seem to require further interpretation. There are wide “eggshell” cracks with the dolomitic dry hydrate specimens. The putty shows more cracks, but they are narrower. The fewest and narrowest cracks were observed on the high-calcium hydrate pastes.

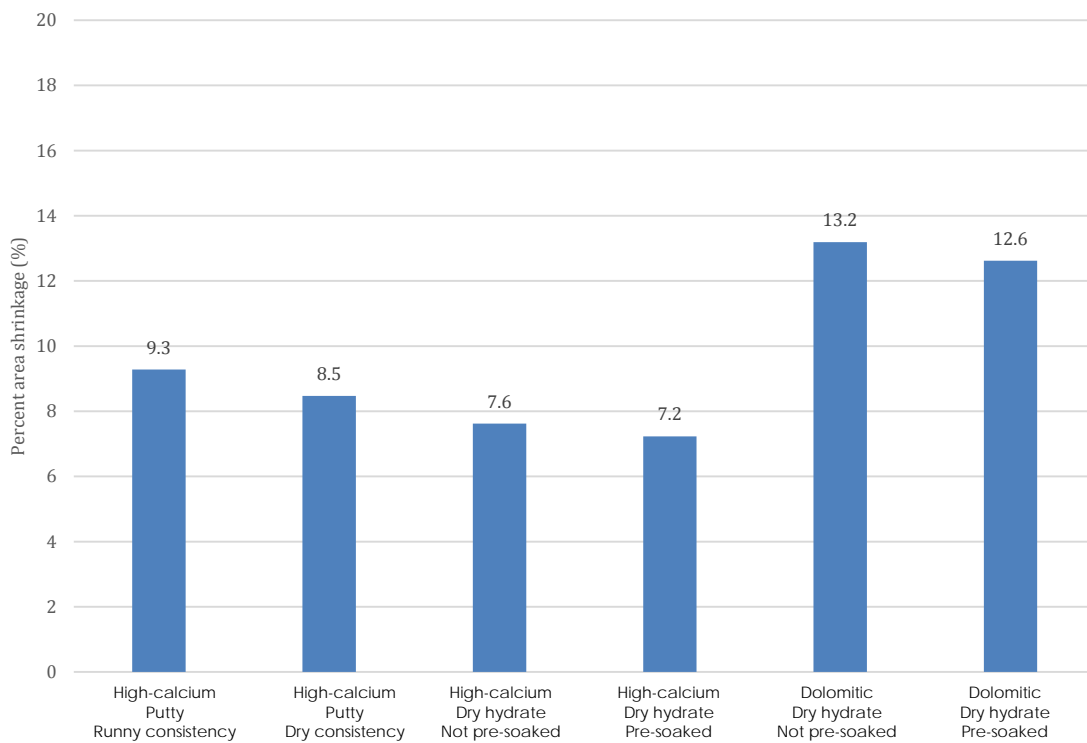


Figure 5-2. Bar chart summarizing percent area shrinkage in the pastes.

There is a slight improvement (that is, reduction) in shrinkage associated with the pre-soaking of both the high-calcium and dolomitic hydrates. Although pastes from the putty of dry consistency were first to form cracks, the putty of runny consistency exhibited slightly more shrinkage, as would be expected.

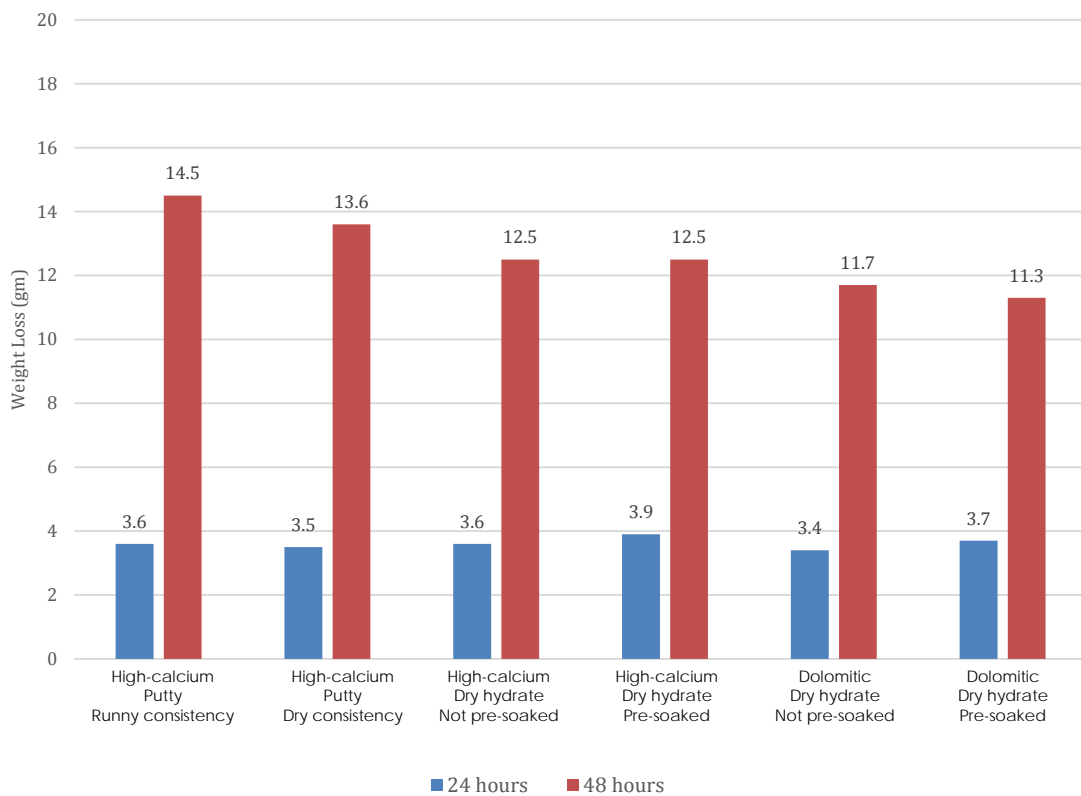


Figure 5-3. Bar chart summarizing weight loss from paste samples.

Data for weight loss in Figure 5-3 revealed that the majority of early evaporation happened in the period between 24 and 48 hours. All of the 12-hour values are quite similar. The putty of runny consistency exhibited the highest 48 hour loss; the dolomitic hydrate showed the least. For both dry hydrates, there was no significant change with pre-soaking. With respect to the high-calcium hydrate, designated as Type N, this is a bit puzzling because the

ASTM standard seems to suggest that pre-soaking would improve the water retentivity of the paste¹⁰⁵ which should mean a slower release of water.¹⁰⁶ The lower 48-hour loss exhibited by the dolomitic hydrate, 6 to 10% less than for the high-calcium hydrate, is at least consistent with the water retentivity of dolomitic hydrate discussed in the C207 standard, and reported in a recent scientific study.¹⁰⁷ The fact that it showed the most severe cracking in paste samples cannot easily be explained.

5.2 Stucco, power-mixed

Measurements were carried out using the electronic caliper. Minimum and maximum shrinkage was measured along the edges of the Petri dishes. The total of these values was divided by the diameter of the dish and expressed as percent diametral shrinkage for each specimen.

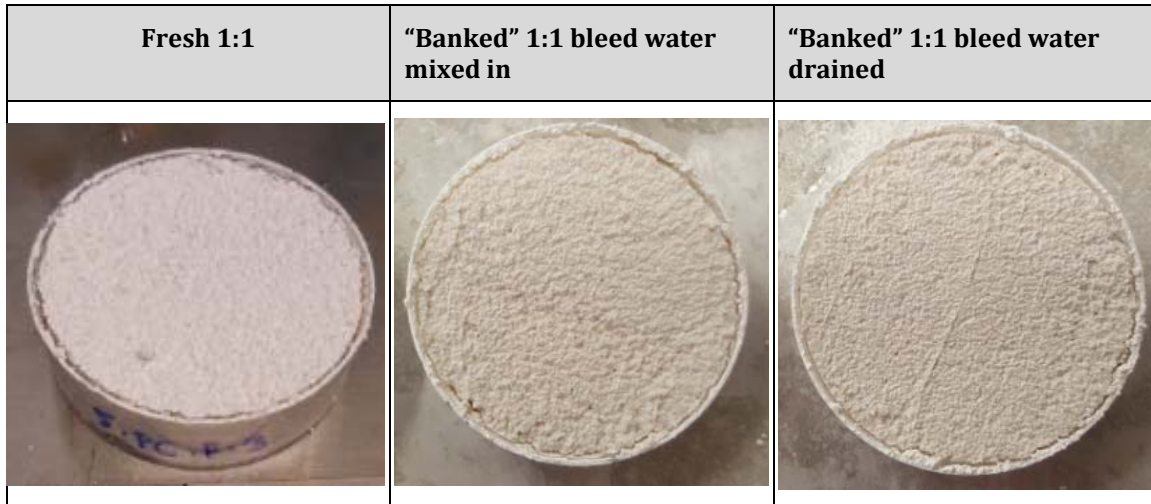


Figure 5-4. Shrinkage observed, 1:1 putty, fresh, "banked"& mixed in, and "banked" & drained specimens.

¹⁰⁵ ASTM C207, p. 2

¹⁰⁶ E.M. Levin, W.F. Clarke, and L.S. Wells, "Plasticity and Water Retentivity of Hydrated Limes for Structural Purposes," *Building Materials and Structures Report*, 146, US Department of Commerce, National Bureau of Standards, Washington DC, 1956. p. 6

¹⁰⁷ Arizzi et al. (2012), p. 824



Figure 5-5. Measuring shrinkage at the edges of a Petri dish.

5.2.1 Putty

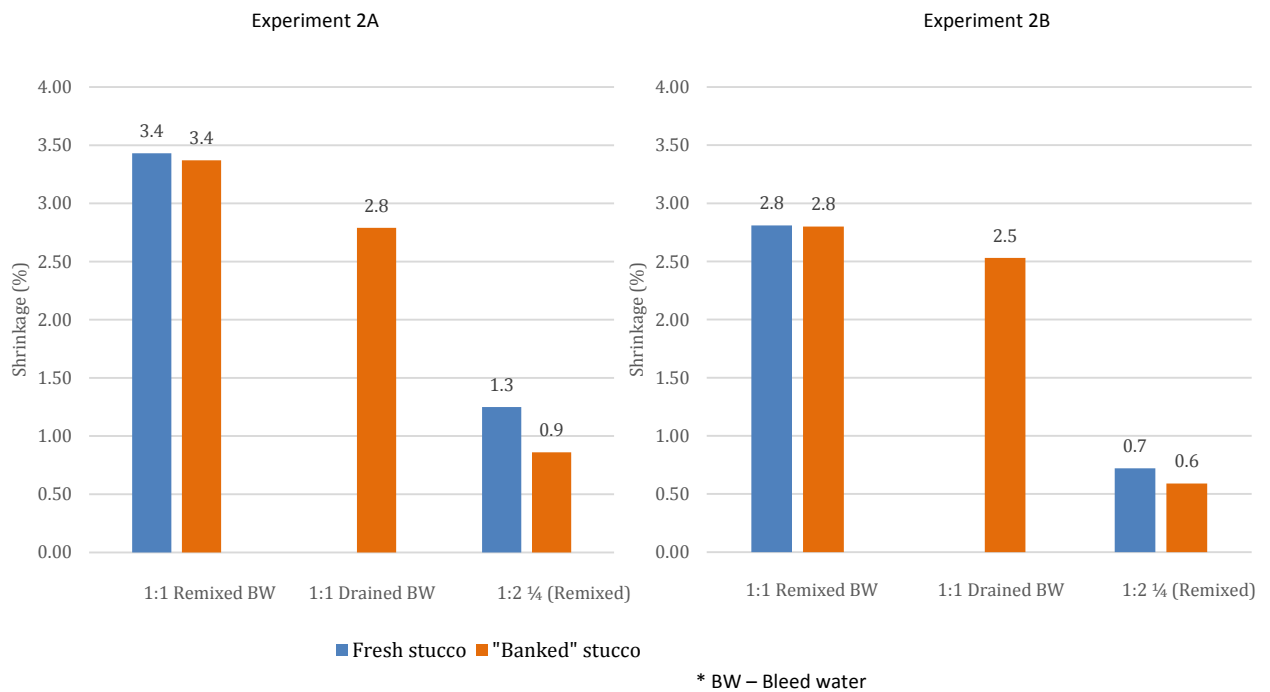


Figure 5-6. Bar charts summarizing shrinkage results with lime putty as the binder.

As expected, there is greater shrinkage observed in the 1:1 mix as compared to 1:2¼ mix.

The additional sand in the mix has reduced shrinkage by about 63 to 74%. Data patterns are the same for the two versions of the experiment.

For 1:1 putty mix, there was observable bleed water. When the water is re-incorporated into the mix, there is no significant change in shrinkage. When the bleed water is drained, however, shrinkage reduction is between 10 and 20%. For the 1:2¼ mix, there is no bleed water, yet there is shrinkage reduction of approximately 20 and 30%.

5.2.2 High-calcium hydrate

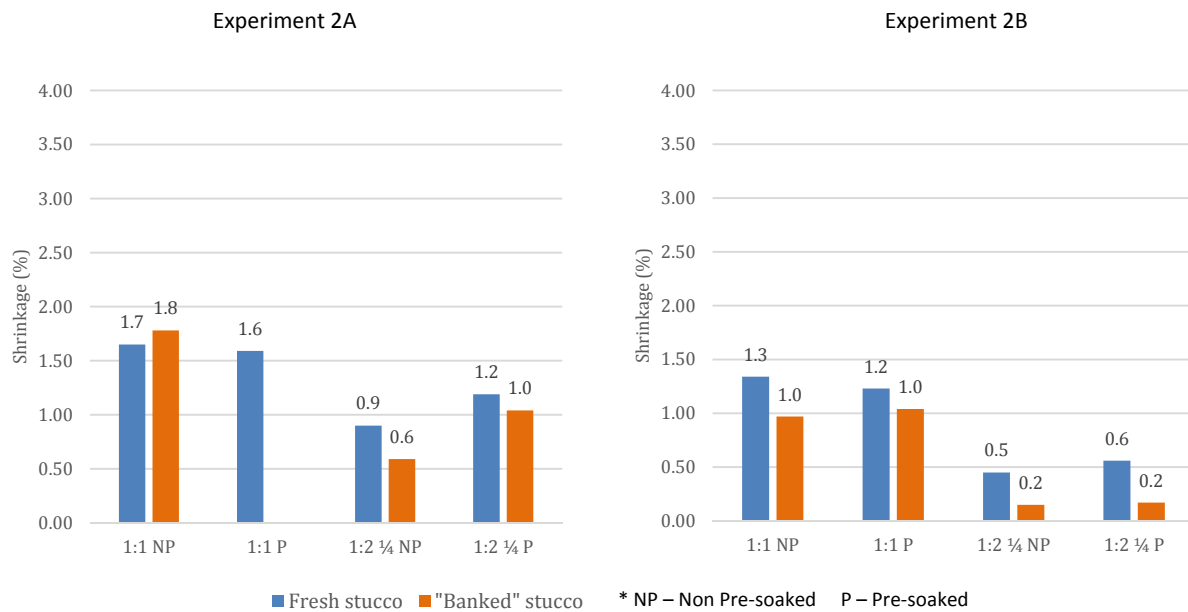


Figure 5-7. Bar charts summarizing shrinkage, high-calcium hydrate.

Figure 5-7 shows the results with the high-calcium hydrate. Overall, shrinkage is approximately 50 to 75% less than for the specimens prepared with lime putty. All of the 1:1 mixes display greater shrinkage than the 1:2¼ mixes. Shrinkage reduction with added sand is between 25 to 65%. For the 1:1 samples, pre-soaking only marginally reduced shrinkage in both experiments 2A and 2B (4 to 8%). Oddly, pre-soaking for the 1:2¼ ratio resulted in more shrinkage.

When the 1:1 mixes were “banked”, the results from experiments 2A and 2B contradicted each other. This is unusual in the context of the entire program of research. If only the data from 2B is examined, “banking” does seem to be effective, and so the experiment is worth repeating at some point in the future. For the 1:2¼ mixes, all of the “banked” samples exhibited less shrinkage, with particularly significant reductions observed in experiment 2B for both non pre-soaked and pre-soaked mixes.

5.2.3 Dolomitic hydrate

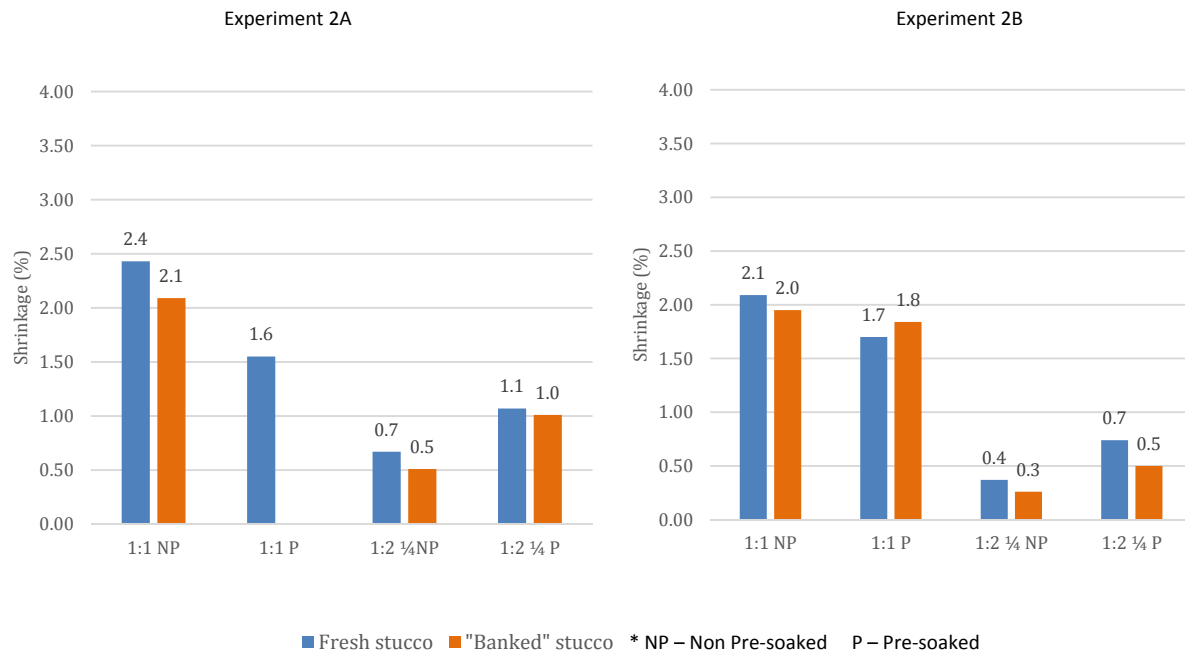


Figure 5-8. Bar charts summarizing shrinkage results, dolomitic hydrate

Figure 5-8 shows the results for experiments 2A and 2B using dolomitic hydrate. Shrinkage is about 30 to 50% less than for lime putty, although 30 to 60% higher than with the high-calcium hydrate. Higher sand content produced less shrinkage, the leaner mix shrinking between 30 and 75% less than the 1:1.

In both experiment 2A and 2B, the 1:1 pre-soaked mixes produce significant reductions in shrinkage while pre-soaking of the 1:2¼ mixes induced increased shrinkage, as noted for the high-calcium hydrate. “Banking” reduced shrinkage in the 1:1 non pre-soaked mixes in both experiment 2A and 2B, but increased shrinkage in the 1:1 pre-soaked mix in experiment 2B. “Banking” reduced shrinkage in all of the 1:2¼ mixes, as it had done with the high-calcium hydrate.

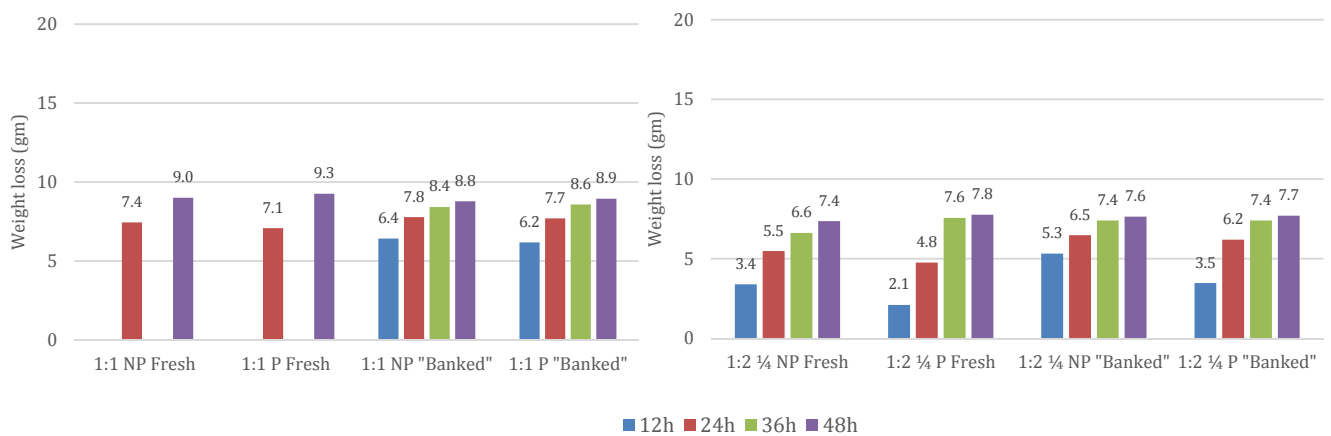


Figure 5-9. Bar charts summarizing weight loss for experiment 2B, dolomitic hydrate.

Figure 5-9 shows evaporative water loss at 12 hour intervals. 48-hour values for 1:2¼ are lower than for 1:1, as there is simply less paste. 12-hour and 24-hour values for the lean pre-soaked mixes indicate a more gradual initial evaporation, yet their shrinkage is actually greater than for the samples that were not pre-soaked.

5.3 Stucco, hand-mixed

The results of experiment 1B, with hand mixing, are presented in comparison to those of experiment 2B. A summary discussion is given after the third chart.

5.3.1 Putty

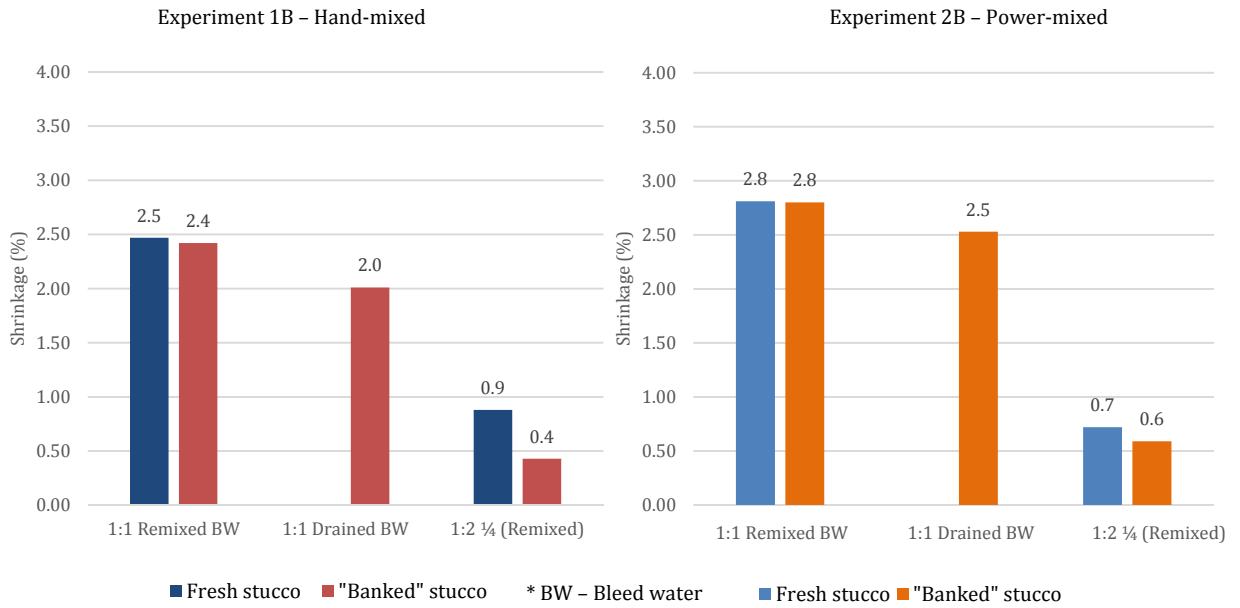


Figure 5-10. Bar charts comparing hand mixing and power mixing, shrinkage of lime putty samples

5.3.2 High-calcium hydrate

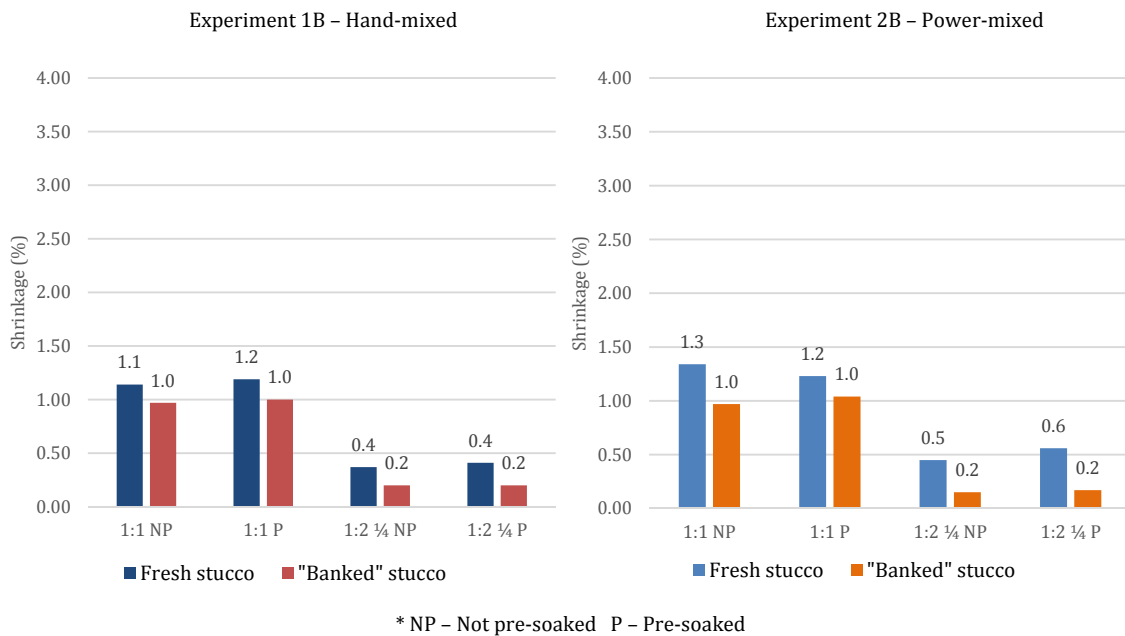


Figure 5-11. Bar charts, comparative shrinkage, high-calcium hydrate, hand-mixed and power-mixed

5.3.3 Dolomitic hydrate

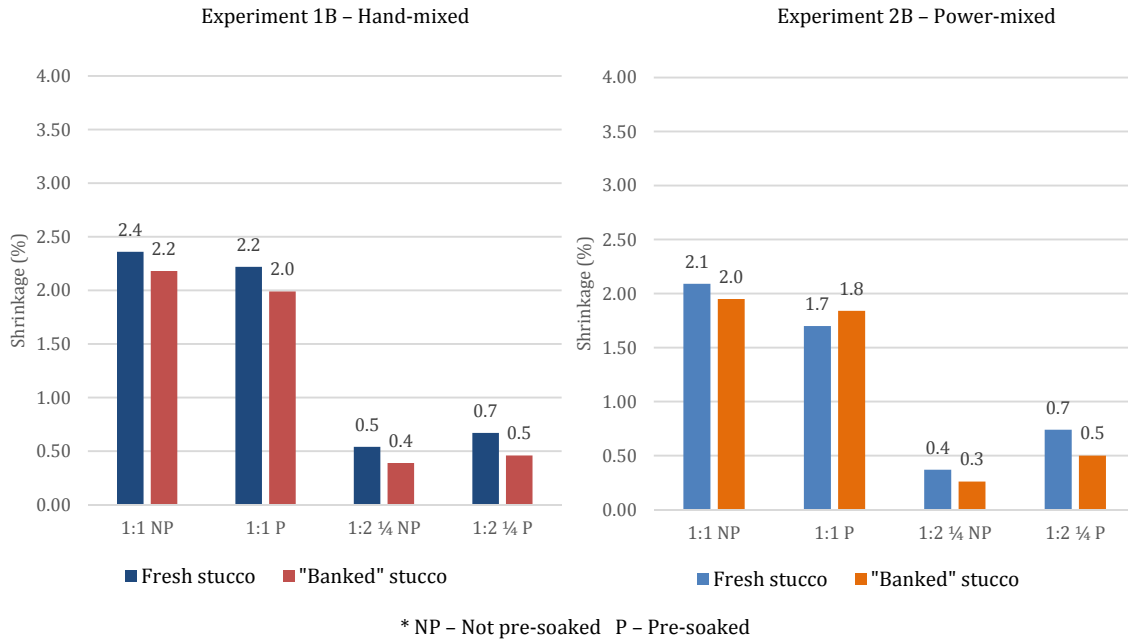


Figure 5-12. Bar charts, comparative shrinkage, dolomitic hydrate, hand-mixed and power-mixed. The two experiments gave generally similar results in terms of shrinkage, with only a few exceptions. Hand mixing seemed to decrease shrinkage slightly in the 1:1 samples prepared with putty, and enhance the “banking” effect with the 1:2 ¼. It also gave somewhat more shrinkage with the 1:1 dolomitic hydrate (as compared with power mixing).

5.4 Stucco, other mixes

The other mixes look at the variance of sand content for the putty mix and water content in the 1:2¼ high calcium hydrate mixes.

5.4.1 Putty, lean mixes (experiment 3)

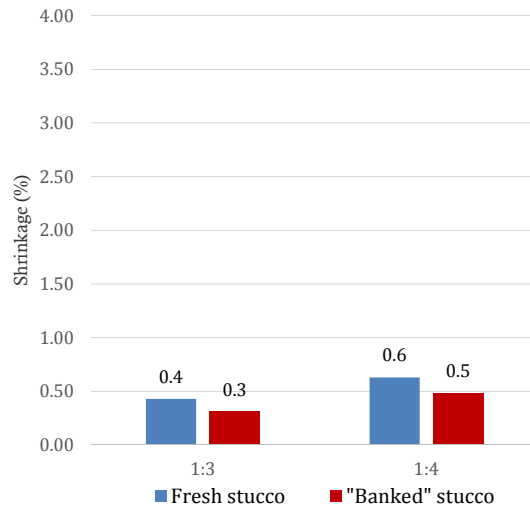


Figure 5-13. Bar charts summarizing shrinkage for lean mixes using lime putty (experiment 3). A further reduction in shrinkage was observed in experiment 3 as compared to the 1:2 ¼ results in experiments 2A and 2B. There was, however, slightly more shrinkage in the 1:4 samples than for the 1:3 group. As the actual numbers are quite small, this could simply be an experimental error. Of course, no bleed water was observed in the “banked” mixes, and “banking” marginally improved shrinkage in both instances.

5.4.2 High-calcium hydrate, higher water content (experiment 4)

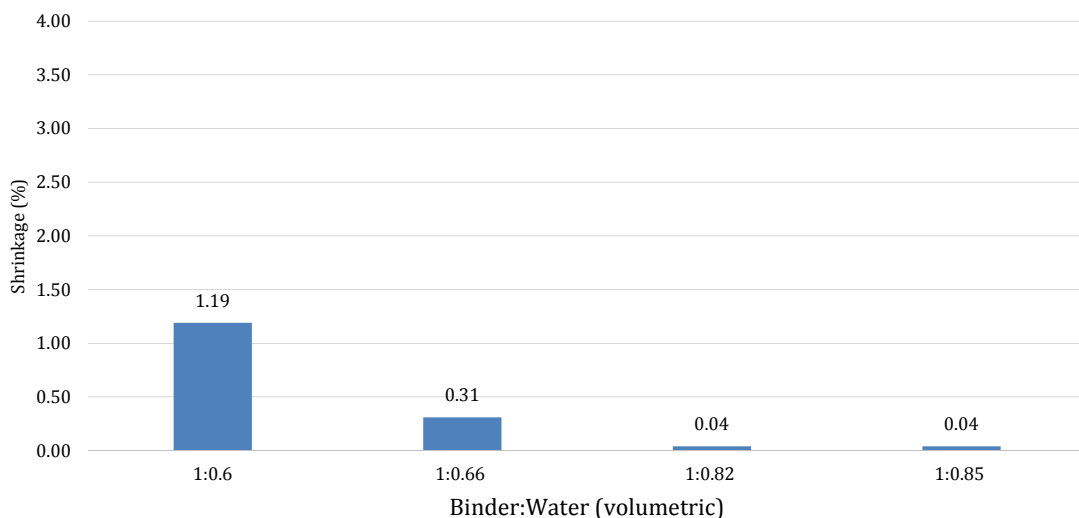


Figure 5-14. Bar charts summarizing shrinkage, more water, high-calcium hydrate, 1:2¼ pre-soaked

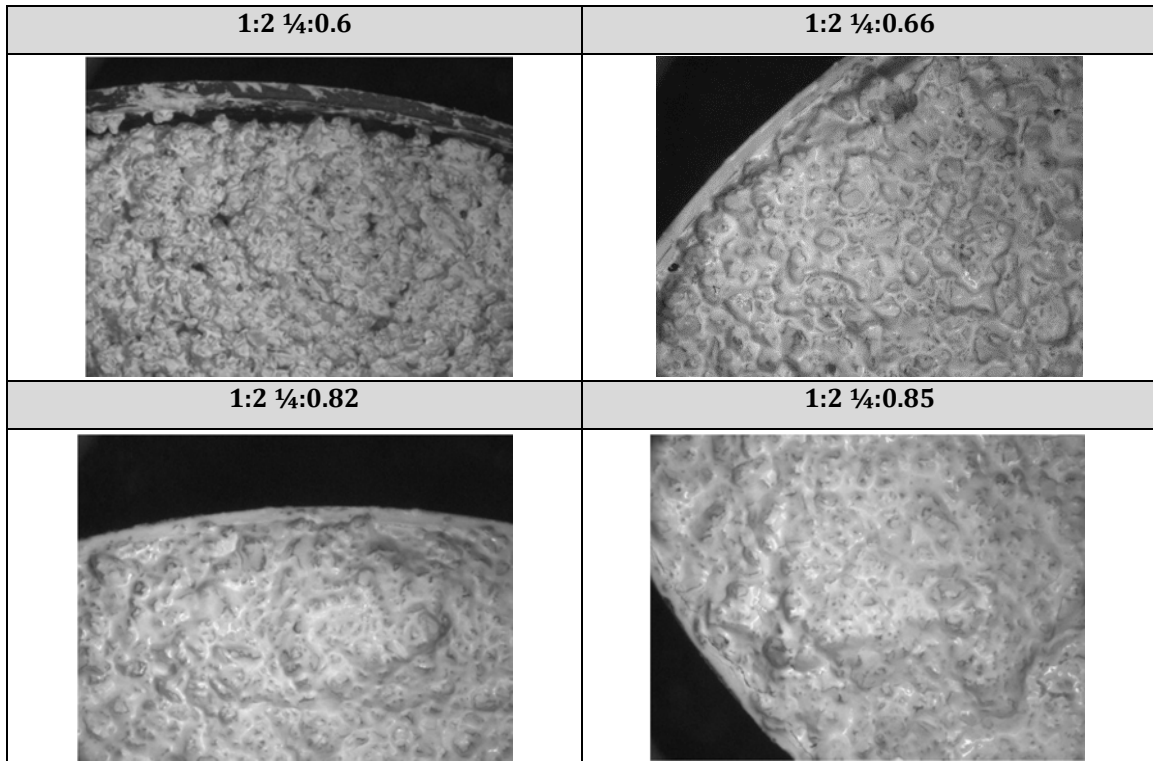


Figure 5-15. Images of the dish edges, 20x magnification, varying water content.

When compared to the 1:0.6 water:binder samples, higher water content resulted in a surprising reduction of measured shrinkage in all specimens. There was only very slight separation along the dish edges samples, in some instances difficult to observe with the naked eye. Images taken under the 20x magnification showed interesting differences in the surface of these specimens, all of which were prepared with 2 ¼ parts of sand. The 1:0.6 displayed a typically coarse texture, with some visible pores between the sand particles. At higher water content, the surfaces were slick, with the sand fully coated; no pores could be observed.

5.5 Discussion

5.5.1 Sand content

Sand content played an important role in the reduction of shrinkage in all mixes. The addition of sand into the pastes produced significant reduction in shrinkage, and limited cracks to the dish edges. For the putty, the 1:1 showed about 60% less shrinkage; for the high-calcium and dolomitic hydrate, the reduction was 75 to 80% and 80 to 86%, respectively. Further reduction in shrinkage was observed with the addition of more sand to create the 1:2¼ mixes, confirming both empirical knowledge and published results of technical studies.^{108,109}

5.5.2 Pre-soaking

Pre-soaking of the 1:1 binder:aggregate samples before mixing in the sand reduced shrinkage with both of the dry hydrates. A marginal improvement is observed for the high calcium mixes (4-8%) while a significant improvement is observed in the dolomitic mixes (18-40%).

Pre-soaking for the 1:2¼ mixes seemed to induce more shrinkage with both hydrates and in both experiment 2A and 2B. This finding is puzzling but may be related to the contradiction between shrinkage and measured evaporative loss (presumably associated with water retentivity¹¹⁰) that was seen in the paste experiments.

One important observation that the author made during the pre-soaking procedure was with respect to the amounts of water (0.5 and 0.6) required for the 1:1 and 1:2¼ mixes. These were the amounts used for the pre-soaking procedure. After a period of 24 hours, bleed

¹⁰⁸ Gwilt, p. 507

¹⁰⁹ Elert et al., p. 62

¹¹⁰ Levin et al., Plasticity and..., p. 6

water was observed with the 0.6 pre-soaks and not with the 0.5. For the uniformity within the experiment, the bleed water was re-mixed into the pre-soaked hydrates before mixing with sand. It is possible that this water, although required for workability of the leaner mixes, contributed to the increase in shrinkage attributable to pre-soaking.

5.5.3 “Banking”

Formation of bleed water after “banking” was observed with the 1:1 high calcium putty mix. When the water was re-incorporated into the mix, there was no significant reduction in shrinkage, but when it was drained, a shrinkage reduction of 10 to 20% was achieved. This experimental observation is certainly consistent with the literature on water content^{111,112} and with the recent Historic England publication.¹¹³

Yet many other “banked” mixes (such as the 1:2 ¼ high-calcium hydrate stuccos) exhibited shrinkage reduction in shrinkage despite not producing any bleed water. The phenomenon is consistent with the belief of the conservation masons at the Banqueting House. The “banking” period is simply too short to have a significant effect on the microstructure of the lime putty, but it is not impossible that there could be a minor hydraulic reaction with the finest sand particles to cause a minor internal set¹¹⁴ which in turn could modify shrinkage.

Another possibility is that reduced shrinkage may be connected with an improvement in workability after “banking”. There seemed to be a noticeable difference in terms of the feel of the freshly prepared mixes and the re-mixed “banked” mixes. The fresh mixes are slightly

¹¹¹ Elert et al., p. 71

¹¹² Ashurst, p. 85

¹¹³ Historic England, p. 287

¹¹⁴ Lynch, p. 18

crumbly while the “banked” mixes seem smoother. This observation is consistent with Lynch’s suggestion that a mortar will become “fatter” after storage.¹¹⁵

5.5.4 Water content

The role of water content in the performance of the “banked” and drained samples is clear. In experiment 4, the results were counter-intuitive, in that increasing water content seemed to contribute to a reduction in shrinkage. The 20x images showed a liquidified surface, suggesting that flow of the paste in the first few hours might somehow have filled the dish more fully, and created a different spatial relationship between the sand and the paste. Perhaps this situation was only possible because the dish was in a horizontal position during curing. A very different result might have been observed if the stucco had been applied to a wall (that is, placed in a vertical orientation), assuming that this was possible despite the higher fluidity of the wetter mixes.

5.5.5 Putty versus dry hydrates

Shrinkage of lime putty mixes is considerably greater than that observed for either of the dry hydrates at 1:1. The high-calcium 1:1 mixes exhibit less shrinkage than the dolomitic. The difference between putty and the dry hydrates is not substantial, however, in the 1:2 ¼ mixes.

In experiment 2B, the “banking” effect with putty is small for the 1:2 ¼ mixes. It is proportionally greater for both high-calcium and dolomitic hydrate, pre-soaked or not. Shrinkage of the “banked” mixes with high-calcium hydrate is 0.2%, the lowest values recorded in the study.

¹¹⁵ Lynch, p. 18

5.5.6 Hand mixing versus power mixing

The method of mixing did not seem to affect shrinkage significantly. “Banking” was useful with both techniques with the exception of a single data set, 1:1 pre-soaked and “banked”, for the dolomitic hydrate. For the freshly prepared stuccos, power mixing shrinkage data are higher for 1:1 putty, but lower for the 1:1 dolomitic hydrate. With the dolomitic hydrate, the results for hand versus power mixing are about the same for the 1:2 ¼ mixes.

Data for the high-calcium hydrate are particularly interesting. “Banked” samples are identical when compared by technique. Power mixing increased shrinkage for three out of the four data sets that were prepared without “banking”.

In terms of workability, observations of “feel” by the author indicate that the power-mixed materials are of a smoother consistency than those prepared by hand mixing. This is consistent with Gwilt’s suggestion that mortar should be well tempered in a pug-mill, to produce a more workable mix that will allow for a higher sand content.¹¹⁶

¹¹⁶ Gwilt, p. 507

6. Summary and Future Recommendations

6.1 Summary

This research did not attempt to look at all of the factors that affect shrinkage, but rather to study a few selected parameters. A series of laboratory experiments was developed to study these, including the type of lime, and the amount of sand. The process of “banking” was (at least initially) the central issue in the research. It is important to note that “banking” is quite different than the aging of a lime putty, in that “banking” is carried out in a short period of time.

The findings confirmed the practical knowledge and the many scientific studies that have reported that the amount of sand in the mix plays an important role in shrinkage. All of the rich mixes showed much more shrinkage than the lean mixes, depending on the type of binder; the greatest reductions were observed with the putty and the dolomitic hydrate.

“Banking” only produced bleed water in the rich putty mix (1:1). A significant reduction in shrinkage was achieved when the bleed water was drained. No improvement was observed when the bleed water was incorporated back into the mix. This observation confirmed that the amount of water in the mix also plays an important role in shrinkage.

It must be noted that draining bleed water alone cannot be the sole reason for shrinkage reduction in “banked” mortars. The leaner putty mix (1:2 ¼) did not exhibit any bleed water, but shrinkage reduction was observed with “banking”.

Although the original thesis question concerned only the “banking” of mixes that employ lime putty, the scope of the experiment was expanded to examine the effect on both high-calcium and dolomitic dry hydrates. The majority of the dry hydrate mixes showed shrinkage reduction upon “banking”. (The consideration of pre-soaking of the dry hydrates

was another expansion of the research program, and the data showed a surprising increase in shrinkage.)

When “banked” mixes were re-mixed prior to casting, the “feel” of them was noticeably different--smoother and more workable as compared to the freshly prepared mixes. In summary, the observations made during the thesis research support the belief of some conservation masons that “banking” does mitigate shrinkage.

6.2 Future recommendations

It is clear that an increase in the number of specimens would provide for more reliable data sets and more meaningful analysis. It would probably also be useful to increase the size of the Petri dishes. Larger batches of the mixes would improve the ability to judge consistency; instrumental methods to do so should be considered.

It would be very useful to see the effect of draining “bleed water” from the 1:2¼ pre-soaked dry hydrates. It might be possible to do all pre-soaking with the same amount of water, then determining if the 1:2 ¼ dry hydrate mixes do require more water after the pre-soak or not. Another approach would be pre-soaking in a larger volume of water, then draining the excess as was done with the “banked” 1:1 putty.

It would be particularly interesting to examine cured “banked” mixes using advanced analytical tools such as SEM, as has been done in the study of putty aging. The obvious question is whether or not microstructural changes have taken place during the “banking” procedure.

Finally, this research has raised many questions concerning the relationship between water retention, readily measurable evaporation rates, and early shrinkage. Pre-soaking of the dry hydrates resulted in increased shrinkage for the lean mixes, which are characteristic of

mortars and some stuccos that are used in conservation. A better understanding of this phenomenon would certainly help the many individuals who care for historic buildings worldwide.

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**Appendix A –
Product Data Sheet**

Appendix A. Lime binders' product data sheet

A.1 US Heritage Lime Putty

Chemical Analysis

Table 1: Chemical Analysis Results

Sample ID	US Heritage Lime Putty
Component (wt. %)	
SiO ₂	0.92
CaO	92.85
MgO	2.41
Al ₂ O ₃	0.42
Fe ₂ O ₃	0.22
Trace elements	0.65
Measured Totals	97.47

Notes:

1. The lime putty sample was dried to 950°C prior to sampling. A lithium metaborate fusion was performed on a subsample of the dried material in a platinum crucible. This was followed by an acid digestion of the fused glass bead.

Table 2: Normalized Chemical Composition

Sample ID	US Heritage Lime Putty
Component (wt. %)	
SiO ₂	1.0
CaO	95.9
MgO	2.5
Al ₂ O ₃	0.4
Fe ₂ O ₃	0.2
Other	0.0
CaO/MgO ratio	38.5
Hydraulicity index	0.01
Cementation index	0.03

Notes:

- The chemical composition is normalized assuming the five measured oxides represent approximately 100% of the total. Hydraulicity index is calculated by dividing the sum of silica and alumina by the measured calcium oxide. Cementation index is calculated by dividing the "hydraulic elements" by the "lime elements" after multiplying each by coefficients normalizing them to their molecular rather than weight contribution.

HERITAGE PURE LIME PUTTY

Product Data Sheet

Product Highlights

Slaked lime putty is a traditional material used up until the introduction of portland cement. It is lime paste produced from fresh quicklime and water. The slaking process, which requires the addition of 2 or 3 molecules of water for each molecule of lime, yields calcium paste or lime putty, an aqueous gel of thin crystals of calcium hydroxide. Before cement was invented, slaked lime putty was commonly used binder in mortar and plaster formulations. It was also a main ingredient of historic lime paints. Today it is used in historic masonry restoration work.

Portland cement wasn't widely available in the United States until the early 1870s. More rigid and less permeable than lime, portland cement can cause extensive damage to historic masonry buildings that were originally constructed with lime mortars. Slaked lime putty is recommended for masonry buildings constructed before 1872, and it is often specified when a historic building (pre-1930) is being repointed in the absence of a mortar analysis.

Recommended Uses

This product is recommended as a binder for lime mortars and plasters.

Mixing Instructions

Typical lime mortar should be mixed using 1 part slaked lime and two and a half or three parts damp sand (by volume). Plasters and frescos may contain more lime in the mix especially when use as a finish coats. No addition of water is recommended for pointing mortars. Stucco or mortar for laying bricks may require addition of water.

Application Procedures

The mortar should resemble the consistency of brown sugar for repointing work. (More water can be added for bricklaying.) This drier consistency enables the material to be tightly packed into the joint, allows for cleaner work, and prevents shrinkage cracks as the mortar cures. Joints should be pointed in layers or "lifts" where the joints are deeper than one and one quarter inch (1 ¼"). Apply in layers not greater than one half (1/2) the depth until a uniform depth is formed. Compact each layer thoroughly and allow it to become thumbprint hard before applying the next layer.

The joints should be finished to match the original historic point profile. Remove all excess mortar from face of brick before it dries.

Curing Procedures

Lime mortar sets by carbonation rather than by hydration, and it requires more time to set than portland cement-based mortar. During carbonation, the mortar hardens as the lime putty slowly converts back to limestone by absorbing carbon dioxide from the atmosphere. It is necessary to initiate the carbonation process by misting the material with water after the tooling of the joint profile has been completed. Nine (9) complete wet-and-dry cycles are required, usually within the first three days after application.

The speed at which the carbonation process initially starts depends on the conditions. Carbon dioxide is sequestered in the mortar as the moisture evaporates from the surface of the joint. Air temperature, wall surface temperature, direct sunlight, air circulation, application width and depth, and the tooling style will dictate the frequency of misting and the length of time required to complete the nine wet and dry cycles.

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HERITAGE PURE LIME PUTTY

Product Data Sheet

Water misting is still necessary in wetter climates, but the amount of water used will vary as will the timing between water misting applications.

The mortar must make contact with the atmosphere in order to cure properly. Acceptable curing methods include sheltering the repointed wall with plastic sheeting, periodic hand misting, and regular mist spraying using a system of pipes, mist heads, and timers. Adjust curing methods to ensure that the pointing mortar is damp without eroding the surface of the mortar. Curing methods will vary in different parts of the country and at different times of the year, calling for different amounts of water to be used in the wet-and-dry cycles. Adjustments also have to take into account how much time is remaining before freezing weather arrives. This mortar should not be exposed to temperatures above 85 degrees F or below 40 degrees during the curing cycle. The full carbonation cycle can take up to 28 days, and longer depending on the weather conditions. This mortar should not be installed when there is a danger of freezing temperatures unless it is enclosed and protected from temperatures below 40 degrees F.

It is important to note that keeping the wall in a damp condition for 72 hours, which is a common instruction in specifications for cement-based mortar, provides no benefit at all and will slow the carbonation process.

Clean-Up

After the replacement mortar has fully hardened, thoroughly clean the exposed masonry surfaces of excess mortar and foreign matter. Use wood scrapers, stiff-nylon or fiber brushes and clean water that is spray-applied at garden-hose pressure. When repointing work precedes the cleaning of

existing masonry, allow the mortar to harden to the point that cleaning can be accomplished without eroding the surface of the mortar. This can be carried out as early as three days after repointing is finished and as long as one month later depending on the curing conditions. When possible, it is better to clean existing masonry before repointing. Do not use metal scrapers or brushes. Do not use acidic or alkaline cleaners.

Safety Requirements

CAUTION! Avoid contact with eyes and skin. Prolonged contact with skin may cause irritation. Wash skin thoroughly with water after handling. In case of eye contact, flush with plenty of water for at least 15 minutes. If irritation persists, consult a physician immediately. Gloves and eye protection is recommended when handling or opening this package. **KEEP OUT OF REACH OF CHILDREN.**

Limitations

Not suitable for mortars used within: -Marine environment or other damp conditions where a fast set-time is required; -Fireboxes in fireplaces; -Landscaping retaining walls; -Architectural curbing; -Swimming pools -Paving;

Storage

Keep away from extreme heat and direct sunlight in buckets for long periods of time. Keep from freezing.

Shelf Life

Save any unused material and return it to the original shipping bucket. Pour one inch of water on the top of the material and cover with plastic sheet or burlap and reseal the bucket. This material can be kept indefinitely if every three



HERITAGE PURE LIME PUTTY

Product Data Sheet

months the material is inspected and remixed adding water as needed.

Limited Warranty

U.S. Heritage Group, Inc. warrants this product to be of merchantable quality when used or applied in accordance with the manufacturer's instructions. This product is not warranted as suitable for any purpose or use other than the general purpose for which it is intended. Liability under this warranty is LIMITED to the replacement of the product (as purchased) found to be defective, or at the shipping companies' option, to refund the purchase price. In the event of a claim under this warranty, notice must be given in writing to U.S. Heritage Group, Inc., 3516 North Kostner Ave., Chicago, IL 60641. THIS LIMITED WARRANTY IS ISSUED AND ACCEPTED IN LIEU OF ALL OTHER EXPRESSED WARRANTIES AND EXPRESSLY EXCLUDES LIABILITY FOR CONSEQUENTIAL DAMAGES.



Standard Hydrated Lime

Discovering what's possible with calcium

TECHNICAL DATA SHEET

PRODUCT DESCRIPTION

Standard Hydrated Lime is a refined hydrate that has a small median particle size, good flow properties, high surface area, and high total & available Ca(OH)_2 . Standard Hydrated Lime is used in flue gas treatment (for the control of SO_2 and SO_3 emissions), water and waste water treatment, acid neutralization, construction and other environmental applications.

TYPICAL CHEMICAL PROPERTIES	
Ca(OH)_2 - Total	98.0%
Ca(OH)_2 - Available	96.8%
CO_2	0.5%
Free Moisture	0.7%
CaSO_4	0.1%
Sulfur - Equivalent	240 ppm
Crystalline Silica	<0.1%
SiO_2	0.5%
Al_2O_3	0.2%
Fe_2O_3	0.06%
MgO	0.4%
P_2O_5	100 ppm
MnO	25 ppm

TYPICAL PHYSICAL PROPERTIES	
Specific Gravity	2.34
Dry Brightness, G.E.	92.0
Median Particle Size - Sedigraph	2 micron
pH	12.4
-100 Mesh (150 μm)	100.0%
-200 Mesh (75 μm)	99.0%
-325 Mesh (45 μm)	94.0%
Apparent Dry Bulk Density - Loose	22 lbs./ft ³
Apparent Dry Bulk Density - Packed	35 lbs/ft ³

- ✓ Meets the AWWA standard B202-02
- ✓ Meets AASHTO standard M303-89
- ✓ Certified to NSF standard 60
- ✓ Certified to ASTM standards:
 - C977-03
 - C1097-06a
 - C207-06 (type N only)
 - C911-06



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 Contact: sales@mississippilime.com
 Web site: www.mississippilime.com

All information provided and recommendations made herein are intended to assist customers in determining whether our products are suitable for their applications. We request that customers inspect and test our products before use in order to make their own final decision regarding suitability. We do not guarantee results, freedom from patent infringement, or suitability of resultant products for any suggested application with respect to the use of any formula or material described herein.

SUPER LIMOID® S

Mason's Lime

Description

SUPER LIMOID® S Mason's Lime is a fine-grind, white, high-purity dolomitic lime, fully hydrated for immediate use. When properly combined with portland cement and sand, it creates a lime mortar having superior performance and ageless durability.

SUPER LIMOID® S Mason's Lime complies with ASTM C207, Type S. Available in durable 3-ply, weather-resistant and poly-lined 50-lb. bags.

Uses

Recommended for all Type M, S, N and O cement-lime mortar (ASTM C270) applications in interior and exterior masonry walls.

Advantages

High Plasticity

SUPER LIMOID® S Lime develops exceptional plasticity and workability immediately upon mixing with water by machine or hand. Carries more sand than most masonry cements or mortar cements for better yield without sacrificing workability.

Excellent Water Retentivity

Increases workability and bonding characteristics, reduces segregation of materials, requires less retempering of mortar during use. SUPER LIMOID® S Mason's Lime mortar resists suction, even from dry masonry, leaves ample time to strike joints.

Balanced Strength

Permits optimum balance between workability and bond strength; provides adequate compressive and tensile strength to accommodate structural movement, plus flexibility to absorb normal stresses from winds and vibration.

Weather Resistance

Offers tight, uniform bond to resist water penetration, helps prevent efflorescence, leaky walls and frost damage. Self-healing properties of SUPER LIMOID® S Mason's Lime repair fine cracks for many years after construction.

Lower Costs

Easily mixed, makes a richer mortar that carries more sand, works easier, and can save on cementitious material cost. Masonry units lay up faster with less waste and "shake-up" time for greater on-site production.

Technical Data

ASTM C270 Specifications

Mortar Type	Physical Properties		Proportions by Volume		
	Min. Ave. Comp. Strength —PSI 28 Days	Water Retention % Min.	Cement ^(1,2)	Lime ⁽³⁾	Sand ⁽⁴⁾
M	2500	75	1	1/4	2.8 to 3 3/4
S	1800	75	1	1/4 to 1/2	2.8 to 4 1/2
N	750	75	1	1/2 to 1 1/4	3.4 to 6 3/4
O	350	75	1	1 1/4 to 2 1/2	5.1 to 10 1/2

NOTES: (1) Portland Cement-To comply with ASTM C150, Type I,II,III.
(2) Blended Hydraulic Cements - to comply with ASTM C595, Types IS, IP or I(PM).
(3) Lime-To comply with ASTM C207 (Hydrated) Type S.
(4) Sand Aggregate-To comply with ASTM C144.

Average Test Results

Mortar Type	Volume Proportions ⁽¹⁾	Comp. Strength-PSI		Water Retention -% ⁽²⁾
		7 Days	28 Days	
S ⁽³⁾	1:1/2: 4 1/2	4370	4984	87
N	1:1:6	2026	2532	89
O	1:2:9	648	904	90

NOTES: (1) Cement: Mason's Lime; sand.
(2) Based on materials having an initial flow of 110± 5%.
(3) Test results exceed requirements for Type M mortar.

Letters of certification of compliance of SUPER LIMOID® S to ASTM C207 specifications are available.



GRAYMONT

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SUPER LIMOID® S

Mason's Lime

Good Design Practices

- Specifications below are offered as desirable inclusions in any masonry specifications, but are not intended to be complete.
- Generally, masons consider a 94-lb. bag of Portland Cement and a 50-lb. bag of hydrated lime to each equal one cu. ft. and would add 6 cu. ft. sand to make a 1: 1: 6 mix. Actually, a bag of hydrated lime equals about 1 1/4 cu. ft.
- Environmental Conditions -- Refer to the Masonry Industry Council Publication "Hot & Cold Weather Masonry Construction" (1999).

Architectural Specification

Part 1: General

1.1 Scope

Specify to meet project requirements.

1.2 Delivery and Storage of Materials

All materials shall be delivered in their original unopened packages, containers or bundles, and stored in a place providing protection from damage, deterioration and contamination. Damaged, deteriorated or contaminated materials shall be removed from the premises.

1.3 Environmental Conditions

In cold weather, temperature of masonry materials shall be above freezing when placed. Masonry shall be protected from freezing for 48 hrs. after placing. Unless precautions against freezing are taken, masonry shall not be erected when temperature is below 32° F on a rising temperature, or below 40° F on a falling temperature. Masonry shall not be laid on walls or footings that are frozen or contain frost. (See good design practices note 3 above.)

Part 2: Products

2.1 Materials

- Portland Cement—Conforming to ASTM C150, Type I.
- Hydrated Lime—SUPER LIMOID® S Mason's Lime, conforming to ASTM C207, Type S
- Aggregate—Sand conforming to ASTM C144.
- Water-Clean and free of deleterious amounts of acids, alkalis and organic materials.

2.2 Mixes

- Type M Mortar, shall be mixed in proportion of one bag Portland Cement, one-quarter bag SUPER LIMOID® S Mason's Lime, to not more than 3 3/4 cu. ft. sand (1: 1/4 : 3 3/4).
- Type S Mortar shall be mixed in proportion of one bag Portland Cement, one-half bag SUPER LIMOID® S Mason's Lime, to not more than 4 1/2 cu. ft. sand (1: 1/2 : 4 1/2).
- Type N Mortar shall be mixed in proportion of one bag Portland Cement, one bag SUPER LIMOID® S Mason's Lime, to not more than 6 cu. ft. sand (1: 1: 6).
- Type O Mortar shall be mixed in proportion of one bag Portland Cement, 2 bags SUPER LIMOID® S Mason's Lime, to not more than 9 cu. ft. sand (1: 2 : 9).

Part 3: Execution

3.1 Mixing Mortar

Proportion ingredients accurately and mix for at least 5 minutes in mechanical batch mixer with enough water to produce a workable consistency.

3.2 Mortar Application

Lay mortar in a uniform bed and completely fill joints between masonry units.

WARNING:

MAY CAUSE EYE OR SKIN BURNS. HARMFUL IF SWALLOWED.

CONTAINS: Hydrated Lime (calcium magnesium hydroxide)
Avoid contact with eyes or skin.
Do not take internally.
Avoid breathing lime dust.

Always wear NIOSH approved eye goggles when handling lime. In case of eye contact flush eyes thoroughly, including under eyelids, with water for 15 minutes. CALL PHYSICIAN IMMEDIATELY.

Wear protective clothing to prevent skin contact. If skin contact occurs, wash with water. Should skin irritation continue, SEE PHYSICIAN.

If swallowed CALL PHYSICIAN IMMEDIATELY.

Ventilate or use dust collector to prevent airborne lime dust. If there is airborne lime dust use a NIOSH approved dust respirator.

Do not use this material on playing fields or children's play areas.

KEEP OUT OF REACH OF CHILDREN.

Hazardous ingredient info—(419) 855-8336

NOTICE: There are no warranties which extend beyond the description contained herein. We shall not be liable for incidental and consequential damages, directly or indirectly sustained, nor for any loss caused by application of these goods not in accordance with current printed instructions or for other than the intended use. Our liability is expressly limited to replacement of defective goods. Any claim shall be deemed waived unless made in writing to us within 30 days from the earlier of the date it was or reasonably should have been discovered.

**Appendix B –
Raw Data**

LIME PASTE SHRINKAGE EXPERIMENT - SHRINKAGE MEASUREMENT

LIME PASTE	FRESH	1	2	3	4	5	TOTAL	MEAN (mm)
No contact with excess water	Approximate	88.50	78.00	88.00	101.75	116.00		
		22.13	19.50	22.00	25.44	29.00		
	Shrinkage percentage	8.64	7.62	8.59	9.94	11.33	46.12	9.22
Contact with excess water	Approximate	79.5	80.5	82.25	72.5	116.25		
		19.875	20.125	20.5625	18.125	29.0625		
	Shrinkage percentage	7.76	7.86	8.03	7.08	11.35	42.09	8.42
Not pre-soaked high-calcium	Approximate	73.5	84	76.5	87	66.75		
		18.375	21	19.125	21.75	16.6875		
	Shrinkage percentage	7.18	8.20	7.47	8.50	6.52	37.87	7.57
Pre-soaked high-calcium	Approximate	65.25	75.5	74	69	84		
		16.3125	18.875	18.5	17.25	21		
	Shrinkage percentage	6.37	7.37	7.23	6.74	8.20	35.91	7.18
Not pre-soaked dolomitic	Approximate	118	121.5	151.5	128	152		
		29.5	30.375	37.875	32	38		
	Shrinkage percentage	11.52	11.87	14.79	12.50	14.84	65.53	13.11
Pre-soaked dolomitic	Approximate	161.5	127.5	120	116	117		
		40.375	31.875	30	29	29.25		
	Shrinkage percentage	15.77	12.45	11.72	11.33	11.43	62.70	12.54

LIME PASTE SHRINKAGE EXPERIMENT - WEIGHT LOSS (gm)

		sum	mean	percent
No contact with excess water	0 hr	134.27	26.854	
	24 h	18.07	3.614	13.45796
	48 h	72.71	14.542	54.15208
Contact with excess water	0 hr	136.21	27.242	
	24 h	17.56	3.512	12.89186
	48 h	67.81	13.562	49.78342
Not pre-soaked high-calcium	0 hr	136.05	27.21	
	24 h	18.24	3.648	13.40684
	48 h	62.66	12.532	46.0566
Pre-soaked high-calcium	0 hr	134.72	26.944	
	24 h	19.66	3.932	14.59323
	48 h	65.26	13.052	48.44121
Not pre-soaked dolomitic	0 hr	143.5	28.7	
	24 h	16.84	3.368	11.73519
	48 h	58.29	11.658	40.62021
Pre-soaked dolomitic	0 hr	152.01	30.402	
	24 h	18.63	3.726	12.25577
	48 h	56.57	11.314	37.21466

SHRINKAGE MEASUREMENT

EXPERIMENT 1A Start date 1-31-2016 PETRI DISH : 54.00mm

Mixing procedure Hand-mixed

PUTTY	FRESH	Measurement (mm)	1	2	3	TOTAL	MEAN (mm)
1:1		Range (min - max)	0.51-1.12	0.22-1.36	0.45-1.32		
		Total (mm)	1.63	1.58	1.77	4.98	1.66
		Shrinkage percentage	3.02	2.93	3.28	9.22	3.07
1:2 1/4		Range (min - max)	0.19-0.35	0.10-0.34	0.15-0.40		
		Total (mm)	0.54	0.44	0.55	1.53	0.51
		Shrinkage percentage	1.00	0.81	1.02	2.83	0.94
PUTTY	BANKED	Measurement (mm)	1	2	3		MEAN (mm)
1:1	BW DRAINED	Range (min - max)	0.41-1.16	0.32-1.23	0.29-1.20		
		Total (mm)	1.57	1.55	1.49	4.61	1.54
		Shrinkage percentage	2.91	2.87	2.76	8.54	2.85
1:1	BW REMIXED	Range (min - max)	0.25-1.31	0.35 - 1.35	0.42 - 1.25		
		Total (mm)	1.56	1.70	1.67	4.93	1.64
		Shrinkage percentage	2.89	3.15	3.09	9.13	3.04
1:2 1/4	REMIXED	Range (min - max)	0.11-0.33	0.08-0.36	0.05-0.34		
		Total (mm)	0.43	0.44	0.39	1.26	0.42
		Shrinkage percentage	0.80	0.81	0.72	2.33	0.78

EXPERIMENT 1A

DC	FRESH	Measurement (mm)	1	2	3	TOTAL	MEAN (mm)
1:1	NOT PRE-SOAKED	Range (min - max)	0.22-0.52	0.23-0.55	0.26 - 0.50		
		Total (mm)	0.74	0.78	0.76	2.28	0.76
		Shrinkage percentage	1.37	1.44	1.41	4.22	1.41
1:1	PRE-SOAKED	Range (min - max)	0.22-0.66	0.08-0.64	0.15-0.51		
		Total (mm)	0.88	0.72	0.66	2.26	0.75
		Shrinkage percentage	1.63	1.33	1.22	4.19	1.40
DC	FRESH	Measurement (mm)	1	2	3	TOTAL	MEAN (mm)

1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0-0.14	0-0.25	0-0.15		
		Total (mm)	0.14	0.25	0.15	0.54	0.18
		Shrinkage percentage	0.26	0.46	0.28	1.00	0.33
1:2 1/4	PRE-SOAKED	Range (min - max)	0-0.22	0.11-0.18	0-0.14		
		Total (mm)	0.22	0.29	0.14	0.65	0.22
		Shrinkage percentage	0.41	0.54	0.26	1.20	0.40
DC	BANKED	Measurement (mm)	1	2	3	TOTAL	MEAN (mm)
1:1	NOT PRE-SOAKED	Range (min - max)	0.19-0.53	0.18-0.52	0.12-0.43		
		Total (mm)	0.72	0.70	0.55	1.97	0.66
		Shrinkage percentage	1.33	1.30	1.02	3.65	1.22
1:1	PRE-SOAKED	Range (min - max)	0.14-0.47	0.10-0.25	0.12-0.31		
		Total (mm)	0.61	0.35	0.43	1.39	0.46
		Shrinkage percentage	1.13	0.65	0.80	2.57	0.86
DC	BANKED	Measurement (mm)	1	2	3	TOTAL	MEAN (mm)
1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0 - 0.10	0.00-0.25	0.05-0.14		
		Total (mm)	0.10	0.25	0.19	0.54	0.18
		Shrinkage percentage	0.19	0.46	0.35	1.00	0.33
1:2 1/4	PRE-SOAKED	Range (min - max)	0.11-0.24	0.05-0.35	0.05-0.38		
		Total (mm)	0.35	0.40	0.43	1.18	0.39
		Shrinkage percentage	0.65	0.74	0.80	2.19	0.73

EXPERIMENT 1A

DD	FRESH	Measurement (mm)	1	2	3	TOTAL	MEAN (mm)
1:1	NOT PRE-SOAKED	Range (min - max)	0.18-0.92	0.38-0.80	0.23-0.95		
		Total (mm)	1.10	1.18	1.18	3.46	1.15
		Shrinkage percentage	2.04	2.19	2.19	6.41	2.14
1:1	PRE-SOAKED	Range (min - max)	0.27-0.77	0.21-0.65	0.29-0.46		
		Total (mm)	1.04	0.86	0.75	2.65	0.88
		Shrinkage percentage	1.93	1.59	1.39	4.91	1.64
DD	FRESH	Measurement (mm)	1	2	3	TOTAL	MEAN (mm)
1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0.05-0.20	0.05-0.21	0.10-0.23		
		Total (mm)	0.25	0.26	0.33	0.84	0.28
		Shrinkage percentage	0.46	0.48	0.61	1.56	0.52

1:2 1/4	PRE-SOAKED	Range (min - max)	0.12-0.23	0.05-0.39	0.10-0.22		
		Total (mm)	0.35	0.44	0.32	1.11	0.37
		Shrinkage percentage	0.65	0.81	0.59	2.06	0.69
DD	BANKED	Measurement (mm)	1	2	3	TOTAL	MEAN (mm)
1:1	NOT PRE-SOAKED	Range (min - max)	0.32 - 0.43	0.29 - 0.89	0.27 - 0.58		
		Total (mm)	0.75	1.18	0.85	2.78	0.93
		Shrinkage percentage	1.39	2.19	1.57	5.15	1.72
1:1	PRE-SOAKED	Range (min - max)	0.18-0.45	0.25-0.46	0.15-0.59		
		Total (mm)	0.63	0.71	0.74	2.08	0.69
		Shrinkage percentage	1.17	1.31	1.37	3.85	1.28
DD	BANKED	Measurement (mm)	1	2	3	TOTAL	MEAN (mm)
1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0.10-0.35	0.10-0.20	0.05-0.27		
		Total (mm)	0.45	0.30	0.32	1.07	0.36
		Shrinkage percentage	0.83	0.56	0.59	1.98	0.66
1:2 1/4	PRE-SOAKED	Range (min - max)	0.08-0.60	0.10-0.20	0.10-0.23		
		Total (mm)	0.68	0.30	0.33	1.31	0.44
		Shrinkage percentage	1.26	0.56	0.61	2.43	0.81

SHRINKAGE MEASUREMENT

EXPERIMENT 1B Start date 4-19-2016 Petri dish : 54.00mm

Mixing procedure Hand mixed

PUTTY	FRESH	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:1		Range (min - max)	0.25-1.29	0.30-1.13	0.40-0.80	0.27-0.80	0.24-1.19		
		Total (mm)	1.54	1.43	1.20	1.07	1.43		
		Shrinkage percentage	2.85	2.65	2.22	1.98	2.65	12.35	2.47
1:2 1/4		Range (min - max)	0.16-0.21	0.10-0.42	0.15-0.46	0.10-0.38	0.10-0.30		
		Total (mm)	0.37	0.52	0.61	0.48	0.40		
		Shrinkage percentage	0.69	0.96	1.13	0.89	0.74	4.41	0.88
PUTTY	BANKED	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:1	BW DRAINED	Range (min - max)	0.20-0.97	0.25-0.73	0.10-1.03	0.20-1.07	0.30-0.58		
		Total (mm)	1.17	0.98	1.13	1.27	0.88		
		Shrinkage percentage	2.17	1.81	2.09	2.35	1.63	10.06	2.01
1:1	BW REMIXED	Range (min - max)	0.30-0.98	0.20-1.02	0.20-0.95	0.20-1.39	0.40-0.90		
		Total (mm)	1.28	1.22	1.15	1.59	1.30		
		Shrinkage percentage	2.37	2.26	2.13	2.94	2.41	12.11	2.42
1:2 1/4	REMIXED	Range (min - max)	0-0.20	0-0.25	0-0.22	0-0.20	0.05-0.25		
		Total (mm)	0.20	0.25	0.22	0.20	0.30		
		Shrinkage percentage	0.37	0.46	0.41	0.37	0.56	2.17	0.43

EXPERIMENT 1B

DC	FRESH	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:1	NOT PRE-SOAKED	Range (min - max)	0.15-0.38	0.15-0.43	0.15-0.55	0.10-0.50	0.10-0.58		
		Total (mm)	0.53	0.58	0.70	0.60	0.68	3.09	
		Shrinkage percentage	0.98	1.07	1.30	1.11	1.26	5.72	1.14
1:1	PRE-SOAKED	Range (min - max)	0.20-0.52	0.15-0.28	0.20-0.48	0.22-0.50	0.20-0.45		
		Total (mm)	0.72	0.43	0.68	0.72	0.65		
		Shrinkage percentage	1.33	0.80	1.26	1.33	1.20	5.93	1.19
DC	FRESH	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0.05-0.15	0.05-0.20	0.05-0.20	0-0.15	0-0.15		
		Total (mm)	0.20	0.25	0.25	0.15	0.15		
		Shrinkage percentage	0.37	0.46	0.46	0.28	0.28	1.85	0.37
1:2 1/4	PRE-SOAKED	Range (min - max)	0.05-0.15	0.05-0.20	0.05-0.20	0.05-0.15	0.05-0.15		
		Total (mm)	0.20	0.25	0.25	0.20	0.20		
		Shrinkage percentage	0.37	0.46	0.46	0.37	0.37	2.04	0.41
DC	BANKED	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:1	NOT PRE-SOAKED	Range (min - max)	0.15-0.35	0.17-0.35	0.15-0.25	0.15-0.40	0.20-0.45		
		Total (mm)	0.50	0.52	0.40	0.55	0.65		

		Shrinkage percentage	0.93	0.96	0.74	1.02	1.20	4.85	0.97
1:1	PRE-SOAKED	Range (min - max)	0.10-0.38	0.15-0.38	0.20-0.30	0.15-0.40	0.20-0.45		
		Total (mm)	0.48	0.53	0.50	0.55	0.65		
		Shrinkage percentage	0.89	0.98	0.93	1.02	1.20	5.02	1.00
DC	BANKED	Measurement (mm)	1	2	3	4	5 TOTAL		MEAN (mm)
1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0-0.10	0-0.10	0-0.15	0-0.10	0-0.10		
		Total (mm)	0.10	0.10	0.15	0.10	0.10		
		Shrinkage percentage	0.19	0.19	0.28	0.19	0.19	1.02	0.20
1:2 1/4	PRE-SOAKED	Range (min - max)	0-0.10	0-0.15	0-0.05	0-0.15	0-0.10		
		Total (mm)	0.10	0.15	0.05	0.15	0.10		
		Shrinkage percentage	0.19	0.28	0.09	0.28	0.19	1.02	0.20

EXPERIMENT 1B

DD	FRESH	Measurement (mm)	1	2	3	4	5 TOTAL		MEAN (mm)
1:1	NOT PRE-SOAKED	Range (min - max)	0.30-1.11	0.29-0.97	0.30-0.98	0.35-0.83	0.25-0.98		
		Total (mm)	1.41	1.26	1.28	1.18	1.23		
		Shrinkage percentage	2.61	2.33	2.37	2.19	2.28	11.78	2.36
1:1	PRE-SOAKED	Range (min - max)	0.25-1.10	0.25-0.87	0.25-1.01	0.25-0.93	0.23 - 0.86		
		Total (mm)	1.35	1.12	1.26	1.18	1.09		
		Shrinkage percentage	2.50	2.07	2.33	2.19	2.02	11.11	2.22
DD	FRESH	Measurement (mm)	1	2	3	4	5 TOTAL		MEAN (mm)
1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0.05-0.25	0.05-0.25	0.05-0.30	0.05-0.20	0-0.15		
		Total (mm)	0.30	0.30	0.35	0.35	0.15		
		Shrinkage percentage	0.56	0.56	0.65	0.65	0.28	2.69	0.54
1:2 1/4	PRE-SOAKED	Range (min - max)	0.05-0.35	0.07-0.35	0.10-0.20	0.05-0.20	0.05-0.40		
		Total (mm)	0.40	0.42	0.30	0.25	0.45		
		Shrinkage percentage	0.74	0.78	0.56	0.46	0.83	3.37	0.67
DD	BANKED	Measurement (mm)	1	2	3	4	5 TOTAL		MEAN (mm)
1:1	NOT PRE-SOAKED	Range (min - max)	0.30-0.75	0.22-0.97	0.20-1.00	0.25-1.05	0.20 - 0.95		
		Total (mm)	1.05	1.19	1.20	1.30	1.15		
		Shrinkage percentage	1.94	2.20	2.22	2.41	2.13	10.91	2.18
1:1	PRE-SOAKED	Range (min - max)	0.25-0.77	0.31-0.66	0.20-0.95	0.30-0.80	0.20-0.94		
		Total (mm)	1.02	0.97	1.15	1.10	1.14		
		Shrinkage percentage	1.89	1.80	2.13	2.04	2.11	9.96	1.99
DD	BANKED	Measurement (mm)	1	2	3	4	5 TOTAL		MEAN (mm)
1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0-0.15	0-0.20	0-0.20	0-0.25	0-0.25		
		Total (mm)	0.15	0.20	0.20	0.25	0.25		
		Shrinkage percentage	0.28	0.37	0.37	0.46	0.46	1.94	0.39
1:2 1/4	PRE-SOAKED	Range (min - max)	0-0.30	0-0.20	0-0.30	0-0.25	0-0.20		
		Total (mm)	0.30	0.20	0.30	0.25	0.20		
		Shrinkage percentage	0.56	0.37	0.56	0.46	0.37	2.31	0.46

SHRINKAGE MEASUREMENT		
EXPERIMENT 2A	Start date 3-3-2016	PETRI DISH : 54.00mm
Mixing procedure	Initial power-mixed	

PUTTY	FRESH	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:1		Range (min - max)	0.60 - 1.20	0.38 - 1.29	0.54 - 1.55	0.50 - 1.27	0.78 - 1.14		
		Total (mm)	1.80	1.67	2.09	1.77	1.92	9.25	1.85
		Shrinkage percentage	3.33	3.09	3.87	3.28	3.56	17.13	3.43
1:2 1/4		Range (min - max)	0.10 - 0.50	0.10 - 0.62	0.20 - 0.73	0.20 - 0.30	0.15 - 0.47		
		Total (mm)	0.60	0.72	0.93	0.50	0.62	3.37	0.67
		Shrinkage percentage	1.11	1.33	1.72	0.93	1.15	6.24	1.25
PUTTY	BANKED	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:1	BW DRAINED	Range (min - max)	0.57 - 1.05	0.35 - 1.08	0.59 - 1.38	0.40 - 0.71	0.50 - 0.90		
		Total (mm)	1.62	1.43	1.97	1.11	1.40	7.53	1.51
		Shrinkage percentage	3.00	2.65	3.65	2.06	2.59	13.94	2.79
1:1	BW REMIXED	Range (min - max)	0.55 - 1.32	0.40 - 1.60	0.45 - 1.15	0.56 - 1.19	0.50 - 1.30		
		Total (mm)	1.87	2.00	1.68	1.75	1.80	9.10	1.82
		Shrinkage percentage	3.46	3.70	3.11	3.24	3.33	16.85	3.37
1:2 1/4	REMIXED	Range (min - max)	0.10 - 0.32	0.10 - 0.35	0.15 - 0.43	0.10 - 0.30	0.10 - 0.30		
		Total (mm)	0.42	0.45	0.58	0.40	0.48	2.33	0.47
		Shrinkage percentage	0.78	0.83	1.07	0.74	0.89	4.31	0.86

EXPERIMENT 2A

DC	FRESH	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:1	NOT PRE-SOAKED	Range (min - max)	0.24 - 0.46	0.28 - 0.87	0.23 - 0.50	0.2 - 0.57	0.3 - 0.81		
		Total (mm)	0.70	1.15	0.73	0.77	1.11	4.46	0.89
		Shrinkage percentage	1.30	2.13	1.35	1.43	2.06	8.26	1.65
1:1	PRE-SOAKED	Range (min - max)	0.40 - 0.98	0.22 - 0.49	0.15 - 0.38	0.35 - 0.50	0.10 - 0.72		
		Total (mm)	1.38	0.71	0.53	0.85	0.82	4.29	0.86
		Shrinkage percentage	2.56	1.31	0.98	1.57	1.52	7.94	1.59
DC	FRESH	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0 - 0.20	0 - 0.13	0.20 - 0.30	0.11 - 0.69	0.15 - 0.66		
		Total (mm)	0.20	0.13	0.50	0.80	0.81	2.44	0.49
		Shrinkage percentage	0.37	0.24	0.93	1.48	1.50	4.52	0.90
1:2 1/4	PRE-SOAKED	Range (min - max)	0.10 - 0.18	0.22 - 0.40	0.15 - 0.36	0.22 - 0.58	0.20 - 0.80		
		Total (mm)	0.28	0.62	0.51	0.80	1.00	3.21	0.64
		Shrinkage percentage	0.52	1.15	0.94	1.48	1.85	5.94	1.19
DC	BANKED	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:1	NOT PRE-SOAKED	Range (min - max)	0.10 - 0.72	0.28 - 0.69	0.30 - 0.58	0.28 - 0.89	0.30 - 0.66		
		Total (mm)	0.82	0.97	0.88	1.17	0.96	4.80	0.96
		Shrinkage percentage	1.52	1.80	1.63	2.17	1.78	8.89	1.78

DD	BANKED	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0-0.10	0-0.05	0-0.15	0-0.20	0-0.20		
		Total (mm)	0.10	0.05	0.15	0.20	0.20		
		Shrinkage percentage	0.19	0.09	0.28	0.37	0.37	1.30	0.26
1:2 1/4	PRE-SOAKED	Range (min - max)	0-0.30	0-0.25	0-0.25	0-0.30	0-0.25		
		Total (mm)	0.30	0.25	0.25	0.30	0.25		
		Shrinkage percentage	0.56	0.46	0.46	0.56	0.46	2.50	0.50

1:1	PRE-SOAKED	Range (min - max)	0.79	x	x	x	x												0.79	
		Total (mm)	0.79	x	x	x	x													
		Shrinkage percentage	1.46	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
DC	BANKED	Measurement (mm)	1	2	3	4	5	TOTAL											MEAN (mm)	
1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0 - 0.14	0.05 - 0.25	0.10 - 0.50	0.05 - 0.19	0.10 - 0.20													
		Total (mm)	0.14	0.30	0.60	0.24	0.30						1.58						0.32	
		Shrinkage percentage	0.26	0.56	1.11	0.44	0.56						2.93						0.59	
1:2 1/4	PRE-SOAKED	Range (min - max)	0.10 - 0.59	0.15 - 0.45	0.15 - 0.43	0.15 - 0.33	0.10 - 0.35													
		Total (mm)	0.69	0.60	0.58	0.48	0.45						2.80						0.56	
		Shrinkage percentage	1.28	1.11	1.07	0.89	0.83						5.19						1.04	

EXPERIMENT 2A

DD	FRESH	Measurement (mm)	1	2	3	4	5	TOTAL											MEAN (mm)	
1:1	NOT PRE-SOAKED	Range (min - max)	0.45 - 0.90	0.45 - 0.80	0.45 - 0.80	0.30 - 0.90	0.60 - 0.90													
		Total (mm)	1.35	1.25	1.25	1.20	1.50						6.55							
		Shrinkage percentage	2.50	2.31	2.31	2.22	2.78						12.13						2.43	
1:1	PRE-SOAKED	Range (min - max)	0.35 - 0.65	0.29 - 0.59	0.23 - 0.58	0.12 - 0.59	0.23 - 0.56													
		Total (mm)	1.00	0.88	0.81	0.71	0.79						4.19							
		Shrinkage percentage	1.85	1.63	1.50	1.31	1.46						7.76						1.55	
DD	FRESH	Measurement (mm)	1	2	3	4	5	TOTAL											MEAN (mm)	
1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0.15 - 0.35	0.20 - 0.30	0.10 - 0.20	0.10 - 0.20	0 - 0.20													
		Total (mm)	0.50	0.50	0.30	0.30	0.20						1.80							
		Shrinkage percentage	0.93	0.93	0.56	0.56	0.37						3.33						0.67	
1:2 1/4	PRE-SOAKED	Range (min - max)	0.25 - 0.5	0.2 - 0.48	0.11 - 0.39	0.26 - 0.34	0.28 - 0.07													
		Total (mm)	0.75	0.68	0.50	0.60	0.35						2.88							
		Shrinkage percentage	1.39	1.26	0.93	1.11	0.65						5.33						1.07	
DD	BANKED	Measurement (mm)	1	2	3	4	5	TOTAL											MEAN (mm)	
1:1	NOT PRE-SOAKED	Range (min - max)	0.25 - 0.77	0.25 - 0.91	0.25 - 0.76	0.25 - 1.04	0.20 - 0.95													
		Total (mm)	1.02	1.16	1.01	1.29	1.15						5.63							
		Shrinkage percentage	1.89	2.15	1.87	2.39	2.13						10.43						2.09	
1:1	PRE-SOAKED	Range (min - max)	0.30 - 1.12	x	x	x	x													
		Total (mm)	1.42	x	x	x	x						1.42							
		Shrinkage percentage	2.63	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	
DD	BANKED	Measurement (mm)	1	2	3	4	5	TOTAL											MEAN (mm)	
1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0.05 - 0.15	0.10 - 0.20	0.15 - 0.29	0.05 - 0.14	0.10 - 0.15													
		Total (mm)	0.20	0.30	0.44	0.19	0.25						1.38							
		Shrinkage percentage	0.37	0.56	0.81	0.35	0.46						2.56						0.51	
1:2 1/4	PRE-SOAKED	Range (min - max)	0.10 - 0.49	0.20 - 0.40	0.20 - 0.40	0.10 - 0.40	0.10 - 0.35													
		Total (mm)	0.59	0.60	0.60	0.50	0.45						2.74							
		Shrinkage percentage	1.09	1.11	1.11	0.93	0.83						5.07						1.01	

SHRINKAGE MEASUREMENT

EXPERIMENT 2B

Start date 4-19-2016

Petri dish : 54.00mm

Mixing procedure

Machine mixed

PUTTY	FRESH	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:1		Range (min - max)	0.35-1.50	0.30-1.35	0.30-1.03	0.27-1.15	0.20-1.23		
		Total (mm)	1.85	1.65	1.33	1.32	1.43		
		Shrinkage percentage	3.43	3.06	2.46	2.44	2.65	14.04	2.81
1:2 1/4		Range (min - max)	0.05-0.20	0.10-0.30	0.05-0.20	0.10-0.40	0.05-0.50		
		Total (mm)	0.25	0.40	0.25	0.50	0.55		0.51
		Shrinkage percentage	0.46	0.74	0.46	0.93	1.02	3.61	0.72
PUTTY	BANKED	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:1	BW DRAINED	Range (min - max)	0.25-1.14	0.20-0.96	0.30-0.78	0.25-1.38	0.28-1.29		
		Total (mm)	1.39	1.16	1.08	1.63	1.57		
		Shrinkage percentage	2.57	2.15	2.00	3.02	2.91	12.65	2.53
1:1	BW REMIXED	Range (min - max)	0.30-1.15	0.25-1.40	0.45-1.05	0.25-1.16	0.25-1.29		
		Total (mm)	1.45	1.65	1.50	1.41	1.54		
		Shrinkage percentage	2.69	3.06	2.78	2.61	2.85	13.98	2.80
1:2 1/4	REMIXED	Range (min - max)	0.05-0.20	0-0.30	0-0.50	0-0.18	0.05-0.31		
		Total (mm)	0.25	0.30	0.50	0.18	0.36		
		Shrinkage percentage	0.46	0.56	0.93	0.33	0.67	2.94	0.59

EXPERIMENT 2B

DC	FRESH	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:1	NOT PRE-SOAKED	Range (min - max)	0.20-0.48	0.20-0.60	0.13-0.45	0.20-0.65	0.3 -0.41		
		Total (mm)	0.68	0.80	0.58	0.85	0.71		
		Shrinkage percentage	1.26	1.48	1.07	1.57	1.31	6.70	1.34
1:1	PRE-SOAKED	Range (min - max)	0.25-0.58	0.21-0.43	0.15 - 0.40	0.22-0.42	0.22-0.45		
		Total (mm)	0.83	0.64	0.55	0.64	0.67		
		Shrinkage percentage	1.54	1.19	1.02	1.19	1.24	6.17	1.23
DC	FRESH	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0-0.15	0 - 0.13	0.10-0.25	0.05-0.15	0.10-0.28		
		Total (mm)	0.15	0.13	0.35	0.20	0.38		
		Shrinkage percentage	0.28	0.24	0.65	0.37	0.70	2.24	0.45
1:2 1/4	PRE-SOAKED	Range (min - max)	0.11-0.20	0-0.10	0.05-0.35	0.05-0.20	0.05-0.39		
		Total (mm)	0.31	0.10	0.40	0.25	0.44		
		Shrinkage percentage	0.57	0.19	0.74	0.46	0.81	2.78	0.56

DC	BANKED	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:1	NOT PRE-SOAKED	Range (min - max)	0.15-0.31	0.20-0.30	0.25-0.31	0.20-0.35	0.20-0.40		
		Total (mm)	0.46	0.50	0.51	0.55	0.60		
		Shrinkage percentage	0.85	0.93	0.94	1.02	1.11	4.85	0.97
1:1	PRE-SOAKED	Range (min - max)	0.10-0.67	0.10-0.45	0.10-0.40	0.10-0.35	0.10-0.45		
		Total (mm)	0.77	0.55	0.50	0.45	0.55		
		Shrinkage percentage	1.43	1.02	0.93	0.83	1.02	5.22	1.04
DC	BANKED	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0-0.10	0-0.05	0-0.10	0-0.10	0-0.05		
		Total (mm)	0.10	0.05	0.10	0.10	0.05		
		Shrinkage percentage	0.19	0.09	0.19	0.19	0.09	0.74	0.15
1:2 1/4	PRE-SOAKED	Range (min - max)	0-0.05	0-0.05	0-0.20	0-0.10	0-0.05		
		Total (mm)	0.05	0.05	0.20	0.10	0.05		
		Shrinkage percentage	0.09	0.09	0.37	0.19	0.09	0.83	0.17

EXPERIMENT 2B

DD	FRESH	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:1	NOT PRE-SOAKED	Range (min - max)	0.25-0.89	0.30-0.72	0.23-0.93	0.20-1.01	0.20 - 0.90		
		Total (mm)	1.14	1.02	1.16	1.21	1.10		
		Shrinkage percentage	2.11	1.89	2.15	2.24	2.04	10.43	2.09
1:1	PRE-SOAKED	Range (min - max)	0.20-0.75	0.30-0.60	0.20-0.75	0.31-0.70	0.23 - 0.56		
		Total (mm)	0.95	0.90	0.95	1.01	0.79		
		Shrinkage percentage	1.76	1.67	1.76	1.87	1.46	8.52	1.70
DD	FRESH	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0-0.15	0-0.20	0-0.15	0-0.25	0 - 0.25		
		Total (mm)	0.15	0.20	0.15	0.25	0.25		
		Shrinkage percentage	0.28	0.37	0.28	0.46	0.46	1.85	0.37
1:2 1/4	PRE-SOAKED	Range (min - max)	0.15-0.25	0.15-0.61	0-0.25	0.10-0.25	0.05-0.20		
		Total (mm)	0.40	0.76	0.25	0.35	0.25		
		Shrinkage percentage	0.74	1.41	0.46	0.65	0.46	3.72	0.74
DD	BANKED	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:1	NOT PRE-SOAKED	Range (min - max)	0.45-0.69	0.31-0.71	0.20-0.69	0.30-0.71	0.25-0.95		
		Total (mm)	1.14	1.02	0.89	1.01	1.20		
		Shrinkage percentage	2.11	1.89	1.65	1.87	2.22	9.74	1.95
1:1	PRE-SOAKED	Range (min - max)	0.20 - 0.58	0.25-0.71	0.20-0.89	0.31-0.75	0.30-0.77		
		Total (mm)	0.78	0.96	1.09	1.06	1.07		
		Shrinkage percentage	1.44	1.78	2.02	1.96	1.98	9.19	1.84

DD	BANKED	Measurement (mm)	1	2	3	4	5	TOTAL	MEAN (mm)
1:2 1/4	NOT PRE-SOAKED	Range (min - max)	0-0.10	0-0.05	0-0.15	0-0.20	0-0.20		
		Total (mm)	0.10	0.05	0.15	0.20	0.20		
		Shrinkage percentage	0.19	0.09	0.28	0.37	0.37	1.30	0.26
1:2 1/4	PRE-SOAKED	Range (min - max)	0-0.30	0-0.25	0-0.25	0-0.30	0-0.25		
		Total (mm)	0.30	0.25	0.25	0.30	0.25		
		Shrinkage percentage	0.56	0.46	0.46	0.56	0.46	2.50	0.50

SHRINKAGE MEASUREMENT

EXPERIMENT 3 Start date 4-19-2016 PETRI DISH : 54.00mm

Mixing procedure Power-mixing

PUTTY	FRESH	Measurement (mm)	1	2	3	TOTAL	MEAN (mm)
1:3	4/19	Range (min - max)	0-0.30	0-0.20	0-0.20	0-0.20	0-0.25
		Total (mm)	0.30	0.20	0.20	0.20	0.25
		Shrinkage percentage	0.56	0.37	0.37	0.37	0.46
						1.15	0.23
						2.13	0.43
1:4	4/19	Range (min - max)	0-0.30	0.10-0.35	0.05-0.30	0.05-0.20	0.10-0.25
		Total (mm)	0.30	0.45	0.35	0.25	0.35
		Shrinkage percentage	0.56	0.83	0.65	0.46	0.65
						1.70	0.34
						3.15	0.63
PUTTY	BANKED	Measurement (mm)	1	2	3	TOTAL	MEAN (mm)
1:3	4/23	Range (min - max)	0-0.30	0-0.10	0-0.05	0-0.15	0-0.25
		Total (mm)	0.30	0.10	0.05	0.15	0.25
		Shrinkage percentage	0.56	0.19	0.09	0.28	0.46
						0.85	0.17
						1.57	0.31
1:4	4/23	Range (min - max)	0-0.20	0-0.30	0-0.25	0-0.25	0-0.30
		Total (mm)	0.20	0.30	0.25	0.25	0.30
		Shrinkage percentage	0.37	0.56	0.46	0.46	0.56
						1.30	0.26
						2.41	0.48

SHRINKAGE MEASUREMENT

EXPERIMENT 4 Start date 3-18-2016 PETRI DISH : 54.00mm

Pre-soaked with 1:0.66 ratio, then have extra 30ml water added to the second set

DC	FRESH pre-soaked (WATER RATIO)	Measurement (mm)	1	2	3	4	5 TOTAL	MEAN (mm)
1:2 1/4	0.66	Range (min - max)	0.10 - 0.35	0.05 - 0.15	0 - 0.05	0 - 0.10	0 - 0.05	
		Total measurement	0.45	0.20	0.05	0.10	0.05	0.85
		Shrinkage percentage	0.83	0.37	0.09	0.19	0.09	1.57
1:2 1/4	0.82	Range (min - max)	0 - 0.06	0.00	0 - 0.05	0.00	0.00	
		Total measurement	0.06	0.00	0.05	0.00	0.00	0.11
		Shrinkage percentage	0.11	0.00	0.09	0.00	0.00	0.20
		Start date 3-26-2016						
		Pre-soaked for a week, initial water was 1:1.						
		pre-soaking with too much water						
DC	PRE-SOAKED FRESH (WATER RATIO)	Measurement (mm)	1	2	3	4	5 TOTAL	MEAN (mm)
1:2 1/4	0.85	Range (min - max)	0 - 0.05	0.00	0.00	0.00	0 - 0.05	
		Total measurement	0.05	0.00	0.00	0.00	0.05	0.10
		Shrinkage percentage	0.09	0.00	0.00	0.00	0.09	0.19

**Appendix C –
ASTM Standards**



Standard Specification for Mortar for Unit Masonry¹

This standard is issued under the fixed designation C270; 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.

This standard has been approved for use by agencies of the U.S. Department of Defense.

1. Scope

1.1 This specification covers mortars for use in the construction of non-reinforced and reinforced unit masonry structures. Four types of mortar are covered in each of two alternative specifications: (1) proportion specifications and (2) property specifications.

NOTE 1—When the property specification is used to qualify masonry mortars, the testing agency performing the test methods should be evaluated in accordance with Practice C1093.

1.2 The proportion or property specifications shall govern as specified.

1.3 When neither proportion or property specifications are specified, the proportion specifications shall govern, unless data are presented to and accepted by the specifier to show that mortar meets the requirements of the property specifications.

1.4 This standard is **not** a specification to determine mortar strengths through field testing (see Section 3).

1.5 The text of this specification 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.

1.6 The terms used in this specification are identified in Terminologies C1180 and C1232.

1.7 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.8 The following safety hazards caveat pertains only to the test methods section of this specification: *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

¹ This specification is under the jurisdiction of ASTM Committee C12 on Mortars and Grouts for Unit Masonry and is the direct responsibility of Subcommittee C12.03 on Specifications for Mortars.

Current edition approved Dec. 15, 2014. Published December 2014. Originally approved in 1951. Last previous edition approved in 2014 as C270 – 14. DOI: 10.1520/C0270-14A.

2. Referenced Documents

2.1 ASTM Standards:²

- C5 Specification for Quicklime for Structural Purposes
- C91 Specification for Masonry Cement
- C109/C109M Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)
- C110 Test Methods for Physical Testing of Quicklime, Hydrated Lime, and Limestone
- C128 Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate
- C144 Specification for Aggregate for Masonry Mortar
- C150 Specification for Portland Cement
- C188 Test Method for Density of Hydraulic Cement
- C207 Specification for Hydrated Lime for Masonry Purposes
- C305 Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency
- C511 Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes
- C595 Specification for Blended Hydraulic Cements
- C780 Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry
- C952 Test Method for Bond Strength of Mortar to Masonry Units
- C979 Specification for Pigments for Integrally Colored Concrete
- C1072 Test Methods for Measurement of Masonry Flexural Bond Strength
- C1093 Practice for Accreditation of Testing Agencies for Masonry
- C1157 Performance Specification for Hydraulic Cement
- C1180 Terminology of Mortar and Grout for Unit Masonry
- C1232 Terminology of Masonry
- C1324 Test Method for Examination and Analysis of Hardened Masonry Mortar

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.

*A Summary of Changes section appears at the end of this standard

- C1329 Specification for Mortar Cement
- C1384 Specification for Admixtures for Masonry Mortars
- C1489 Specification for Lime Putty for Structural Purposes
- C1506 Test Method for Water Retention of Hydraulic Cement-Based Mortars and Plasters
- C1586 Guide for Quality Assurance of Mortars
- E72 Test Methods of Conducting Strength Tests of Panels for Building Construction
- E514 Test Method for Water Penetration and Leakage Through Masonry
- E518 Test Methods for Flexural Bond Strength of Masonry
- 2.2 Masonry Industry Council.³
- Hot and Cold Weather Masonry Construction Manual, January 1999

3. Specification Limitations

3.1 Laboratory testing of mortar to ensure compliance with the property specification requirements of this specification shall be performed in accordance with 5.3. The property specification of this standard applies to mortar mixed to a specific flow in the laboratory.

3.2 Property specifications requirements in Table 1 shall not be used to evaluate construction site-produced mortars.

NOTE 2—Refer to X1.5.3.1 for further explanation.

3.3 Since the compressive strength values resulting from field tested mortars do not represent the compressive strength of mortar as tested in the laboratory nor that of the mortar in the wall, physical properties of field sampled mortar shall not be used to determine compliance to this specification and are not intended as criteria to determine the acceptance or rejection of the mortar (see Section 8 and Guide C1586).

4. Materials

4.1 Materials used as ingredients in the mortar shall conform to the requirements specified in 4.1.1 to 4.1.4.

³ Available from the Mason Contractors Association of America, 1910 South Highland Avenue, Suite 101, Lombard, IL 60148.

4.1.1 *Cementitious Materials*—Cementitious materials shall conform to the following ASTM specifications:

4.1.1.1 *Portland Cement*—Types I, IA, II, IIA, III, IIIA, or V of Specification C150.

4.1.1.2 *Blended Hydraulic Cements*—Types IS(<70), IS(<70)-A, IP, IP-A of Specification C595.

4.1.1.3 *Hydraulic Cements*—Types GU, HE, MS, and HS of Specification C1157 (Types MH and LH are limited to use in the property specifications only).

4.1.1.4 *Portland Blast-Furnace Slag Cement (for Use in Property Specifications Only)*—Types IS(≥70) or IS(≥70)-A of Specification C595.

4.1.1.5 *Masonry Cement*—See Specification C91.

4.1.1.6 *Mortar Cement*—See Specification C1329.

4.1.1.7 *Quicklime*—See Specification C5.

4.1.1.8 *Hydrated Lime*—Specification C207, Types S or SA. Types N or NA limes are permitted if shown by test or performance record to be not detrimental to the soundness of the mortar.

4.1.1.9 *Lime Putty*—See Specification C1489.

4.1.2 *Aggregates*—See Specification C144.

4.1.3 *Water*—Water shall be clean and free of amounts of oils, acids, alkalis, salts, organic materials, or other substances that are deleterious to mortar or any metal in the wall.

4.1.4 *Admixtures*—Admixtures shall not be added to mortar unless specified. Admixtures shall not add more than 65 ppm (0.0065 %) water soluble chloride or 90 ppm (0.0090 %) acid soluble chloride to the mortar’s overall chloride content, unless explicitly provided for in the contract documents.

4.1.4.1 *Classified Admixtures*—Admixtures which are classified as bond enhancers, workability enhancers, set accelerators, set retarders, and water repellents shall be in accordance with Specification C1384.

4.1.4.2 *Color Pigments*—Coloring pigments shall be in accordance with Specification C979.

4.1.4.3 *Unclassified Admixtures*—Mortars containing admixtures outside the scopes of Specifications C1384 and C979 shall be in accordance with the property requirements of this

TABLE 1 Property Specification Requirements^A

Mortar	Type	Average Compressive Strength at 28 days, min, psi (MPa)	Water Retention, min, %	Air Content, max, % ^B	Aggregate Ratio (Measured in Damp, Loose Conditions)
Cement-Lime	M	2500 (17.2)	75	12	Not less than 2 ¼ and not more than 3 ½ times the sum of the separate volumes of cementitious materials
	S	1800 (12.4)	75	12	
	N	750 (5.2)	75	14 ^C	
	O	350 (2.4)	75	14 ^C	
Mortar Cement	M	2500 (17.2)	75	12	
	S	1800 (12.4)	75	12	
	N	750 (5.2)	75	14 ^C	
	O	350 (2.4)	75	14 ^C	
Masonry Cement	M	2500 (17.2)	75	18	
	S	1800 (12.4)	75	18	
	N	750 (5.2)	75	20 ^D	
	O	350 (2.4)	75	20 ^D	

^ALaboratory prepared mortar only (see Note 5).

^BSee Note 6.

^CWhen structural reinforcement is incorporated in cement-lime or mortar cement mortar, the maximum air content shall be 12 %.

^DWhen structural reinforcement is incorporated in masonry cement mortar, the maximum air content shall be 18 %.

specification and the admixture shall be shown to be non-deleterious to the mortar, embedded metals, and the masonry units.

4.1.4.4 *Calcium Chloride*—When explicitly provided for in the contract documents, calcium chloride is permitted to be used as an accelerator in amounts not to exceed 2 % by weight of the portland cement content or 1 % of the masonry cement content, or both, of the mortar.

NOTE 3—If calcium chloride is allowed, it should be used with caution as it may have a detrimental effect on metals and on some wall finishes.

5. Requirements

5.1 Unless otherwise stated, a cement/lime mortar, a mortar cement mortar, or a masonry cement mortar is permitted. A mortar type of known higher strength shall not be indiscriminately substituted where a mortar type of anticipated lower strength is specified.

5.2 *Proportion Specifications*—Mortar conforming to the proportion specifications shall consist of a mixture of cementitious material, aggregate, and water, all conforming to the requirements of Section 4 and the proportion specifications' requirements of Table 2. See Appendix X1 or Appendix X3 for a guide for selecting masonry mortars.

5.3 *Property Specifications*—Mortar conformance to the property specifications shall be established by tests of laboratory prepared mortar in accordance with Section 6 and 7.2. The laboratory prepared mortar shall consist of a mixture of cementitious material, aggregate, and water, all conforming to the requirements of Section 4 and the properties of the laboratory prepared mortar shall conform to the requirements of Table 1. See Appendix X1 for a guide for selecting masonry mortars.

5.3.1 No change shall be made in the laboratory established proportions for mortar accepted under the property specifications, except for the quantity of mixing water. Materials with different physical characteristics shall not be utilized in the mortar used in the work unless compliance with the requirements of the property specifications is reestablished.

NOTE 4—The physical properties of plastic and hardened mortar complying with the proportion specification (5.1) may differ from the physical properties of mortar of the same type complying with the property specification (5.3). For example, laboratory prepared mortars batched to the proportions listed in Table 2 will, in many cases, considerably exceed the compressive strength requirements of Table 1.

NOTE 5—The required properties of the mortar in Table 1 are for laboratory prepared mortar mixed with a quantity of water to produce a flow of 110 ± 5 %. This quantity of water is not sufficient to produce a mortar with a workable consistency suitable for laying masonry units in the field. Mortar for use in the field must be mixed with the maximum amount of water, consistent with workability, in order to provide sufficient water to satisfy the initial rate of absorption (suction) of the masonry units. The properties of laboratory prepared mortar at a flow of 110 ± 5, as required by this specification, are intended to approximate the flow and properties of field prepared mortar after it has been placed in use and the suction of the masonry units has been satisfied. The properties of field prepared mortar mixed with the greater quantity of water, prior to being placed in contact with the masonry units, will differ from the property requirements in Table 1. Therefore, the property requirements in Table 1 cannot be used as requirements for quality control of field prepared mortar. Test Method C780 may be used for this purpose.

NOTE 6—Air content of non-air-entrained portland cement-lime mortar is generally less than 8 %.

6. Test Methods

6.1 *Proportions of Materials for Test Specimens*—Laboratory mixed mortar used for determining conformance to this property specification shall contain construction materials in proportions indicated in project specifications. Measure

TABLE 2 Proportion Specification Requirements

NOTE 1—Two air-entraining materials shall not be combined in mortar.

Mortar	Type	Proportions by Volume (Cementitious Materials)							Aggregate Ratio (Measured in Damp, Loose Con- ditions)	
		Cement ⁴	Mortar Cement			Masonry Cement				Hydrated Lime or Lime Putty
			M	S	N	M	S	N		
Cement-Lime	M	1	1/4	Not less than 2 1/4 and not more than 3 times the sum of the separate vol- umes of cementi- tious materials
	S	1	...	...	...	...	...	...	over 1/4 to 1/2
	N	1	...	...	...	...	...	...	over 1/2 to 1 1/4
	O	1	...	...	...	...	...	...	over 1 1/4 to 2 1/2
Mortar Cement	M	1	1	Not less than 2 1/4 and not more than 3 times the sum of the separate vol- umes of cementi- tious materials
	M	...	1	...	...	...	...	...	...
	S	1/2	...	...	1	...	...	...	...
	S	...	...	1	...	...	...	...	...
	N	...	...	...	1	...	...	...	...
	O	...	...	...	1	...	...	...	...
Masonry Cement	M	1	1	...	Not less than 2 1/4 and not more than 3 times the sum of the separate vol- umes of cementi- tious materials
	M	...	...	...	...	1	...	...	...
	S	1/2	...	...	...	...	...	...	1
	S	...	...	...	...	...	1	...	...
	N	...	...	...	...	...	...	1	...
	O	...	...	...	...	...	...	1	...

⁴Includes Specification C150, C595, and C1157 cements as described in 4.1.1.

materials by weight for laboratory mixed batches. Convert proportions, by volume, to proportions, by weight, using a batch factor calculated as follows:

Batch factor = 1440/(80 times total sand volume proportion) (1)
 Determine weight of material as follows:

$$\text{Mat. Weight} = \text{Mat. Volume Proportion} \times \text{Bulk Density} \times \text{Batch Factor} \quad (2)$$

NOTE 7—See Appendix X4 for examples of material proportioning.

6.1.1 When converting volume proportions to batch weights, use the following material bulk densities:

Material	Bulk Density
Portland Cement	Obtain from bag or supplier
Blended Cement	Obtain from bag or supplier
Hydraulic Cement	Obtain from bag or supplier
Slag Cement	Obtain from bag or supplier
Masonry Cement	Obtain from bag or supplier
Mortar Cement	Obtain from bag or supplier
Lime Putty	80 pcf (1280 kg/m ³)
Hydrated Lime	40 pcf (640 kg/m ³)
Sand	80 pcf (1280 kg/m ³)

NOTE 8—All quicklime should be slaked in accordance with the manufacturer's directions. All quicklime putty, except pulverized quicklime putty, should be sieved through a No. 20 (850 μm) sieve and allowed to cool until it has reached a temperature of 80°F (26.7°C). Quicklime putty should weigh at least 80 pcf (1280 kg/m³). Putty that weighs less than this may be used in the proportion specifications, if the required quantity of extra putty is added to meet the minimum weight requirement.

NOTE 9—The sand is oven-dried for laboratory testing to reduce the potential of variability due to sand moisture content and to permit better accounting of the materials used for purposes of air content calculations. It is not necessary for the purposes of this specification to measure the unit weight of the dry sand. Although the unit weight of dry sand will typically be 85–100 pcf (1360–1760 kg/m³), experience has shown that the use of an assumed unit weight of 80 pcf (1280 kg/m³) for dry sand will result in a laboratory mortar ratio of aggregate to cementitious material that is similar to that of the corresponding field mortar made using damp loose sand. A weight of 80 lb (36 kg) of dry sand is, in most cases, equivalent to the sand weight in 1 ft³ (0.03 m³) of loose, damp sand.

6.1.2 Oven dry and cool to room temperature all sand for laboratory mixed mortars. Sand weight shall be 1440 g for each individual batch of mortar prepared. Add water to obtain flow of 110 ± 5 %. A test batch provides sufficient mortar for completing the water retention test and fabricating three 2-in. cubes for the compressive strength test.

6.2 *Mixing of Mortars*—Mix the mortar in accordance with Practice C305.

6.3 *Water Retention*—Determine water retention in accordance with Specification C1506, except that the laboratory-mixed mortar shall be of the materials and proportions to be used in the construction.

6.4 *Air Content*—Determine air content in accordance with Specification C91 except that the laboratory mixed mortar is to be of the materials and proportions to be used in the construction. Calculate the air content to the nearest 0.1 % as follows:

$$D = \frac{(W_1 + W_2 + W_3 + W_4 + V_w)}{\frac{W_1}{P_1} + \frac{W_2}{P_2} + \frac{W_3}{P_3} + \frac{W_4}{P_4} + V_w}$$

$$A = 100 - \frac{W_m}{4D} \quad (3)$$

where:

- D = density of air-free mortar, g/cm³,
- W_1 = weight of portland cement, g,
- W_2 = weight of hydrated lime, g,
- W_3 = weight of mortar cement or masonry cement, g,
- W_4 = weight of oven-dry sand, g,
- V_w = millilitres of water used,
- P_1 = density of portland cement, g/cm³,
- P_2 = density of hydrated lime, g/cm³,
- P_3 = density of mortar cement or masonry cement, g/cm³,
- P_4 = density of oven-dry sand, g/cm³,
- A = volume of air, %, and
- W_m = weight of 400 mL of mortar, g.

6.4.1 Determine the density of oven-dry sand, P_4 , in accordance with Test Method C128, except that an oven-dry specimen shall be evaluated rather than a saturated surface-dry specimen. If a pycnometer is used, calculate the oven-dry density of sand as follows:

$$P_4 = X_1 / (Y + X_1 - Z) \quad (4)$$

where:

- X_1 = weight of oven-dry specimen (used in pycnometer) in air, g,
- Y = weight of pycnometer filled with water, g, and
- Z = weight of pycnometer with specimen and water to calibration mark, g.

6.4.1.1 If the Le Chantelier flask method is used, calculate the oven-dry density of sand as follows:

$$P_4 = X_2 / [0.9975 (R_2 - R_1)] \quad (5)$$

where:

- X_2 = weight of oven-dry specimen (used in Le Chantelier flask) in air, g,
- R_1 = initial reading of water level in Le Chantelier flask, and
- R_2 = final reading of water in Le Chantelier flask.

6.4.2 Determine the density of portland cement, mortar cement, and masonry cement in accordance with Test Method C188. Determine the density of hydrated lime in accordance with Test Methods C110.

6.5 Compressive Strength:

6.5.1 Determine compressive strength in accordance with Test Method C109/C109M. The mortar shall be composed of materials and proportions that are to be used in the construction with mixing water to produce a flow of 110 ± 5.

6.5.2 *Alternative Molding Procedure*—Immediately after determining the flow and mass of 400 mL of mortar, return all of the mortar to the mixing bowl and remix for 15 s at the medium speed. Then mold the test specimen in accordance with Test Method C109/C109M, except that the elapsed time for mixing mortar, determining flow, determining air entrainment, and starting the molding of cubes shall be within 8 min.

6.5.3 *Specimen Storage*—Keep mortar cubes for compressive strength tests in the molds on plane plates in a moist room or a cabinet meeting the requirements of Specification C511, from 48 to 52 h in such a manner that the upper surfaces shall

be exposed to the moist air. Remove mortar specimens from the molds and place in a moist cabinet or moist room until tested.

6.5.4 *Testing*—Test specimens in accordance with Test Method **C109/C109M**.

7. Construction Practices

7.1 *Storage of Materials*—Cementitious materials and aggregates shall be stored in such a manner as to prevent deterioration or intrusion of foreign material.

7.2 *Measurement of Materials*—The method of measuring materials for the mortar used in construction shall be such that the specified proportions of the mortar materials are controlled and accurately maintained.

7.3 *Mixing Mortars*—All cementitious materials and aggregate shall be mixed between 3 and 5 min in a mechanical batch mixer with the maximum amount of water to produce a workable consistency. Hand mixing of the mortar is permitted with the written approval of the specifier outlining hand mixing procedures.

NOTE 10—These mixing water requirements differ from those in test methods in Section 6.

7.4 *Tempering Mortars*—Mortars that have stiffened shall be retempered by adding water as frequently as needed to restore the required consistency. No mortars shall be used beyond 2½ h after mixing.

7.5 *Climatic Conditions*—Unless superseded by other contractual relationships or the requirements of local building codes, hot and cold weather masonry construction relating to mortar shall comply with the Masonry Industry Council’s “Hot and Cold Weather Masonry Construction Manual.”

NOTE 11—*Limitations*—Mortar type should be correlated with the particular masonry unit to be used because certain mortars are more compatible with certain masonry units.

The specifier should evaluate the interaction of the mortar type and masonry unit specified, that is, masonry units having a high initial rate of absorption will have greater compatibility with mortar of high-water retentivity.

8. Quality Assurance

8.1 Compliance to this specification is verified by confirming that the materials used are as specified, meet the requirements as given in 2.1, and added to the mixer in the proper proportions. Proportions of materials are verified by one of the following:

8.1.1 Implementation and observation of appropriate procedures for proportioning and mixing approved materials, as described in Section 7.

8.1.2 Test Method **C780** Annex 4, Mortar Aggregate Ratio to determine the aggregate to cementitious material ratio of mortars while they are still in a plastic state.

8.2 Guide **C1586** is suitable for developing quality assurance procedures to determine compliance of mortars to this standard.

8.3 Test Method **C780** is suitable for the evaluation of masonry mortars in the field. However, due to the procedural differences between Specification C270 and **C780**, the compressive strength values resulting from field sampled mortars are not required nor expected to meet the compressive strength requirements of the property specification of Specification C270, nor do they represent the compressive strength of the mortar in the wall.

8.4 Test Method **C1324** is available to determine the proportions of materials in hardened masonry mortars. There is no ASTM method for determining the conformance of a mortar to the property specifications of Specification C270 by testing hardened mortar samples taken from a structure.

NOTE 12—The results of tests using Test Methods **C780** Annex 4 and **C1324** can be compared with Specification C270 proportion requirements; however, precision and bias have not been determined for these test methods.

NOTE 13—The results of tests done using Test Method **C1324** can be compared with the Specification C270 proportion requirements, however, precision and bias have not been determined for this test method.

NOTE 14—Where necessary, testing of a wall or a masonry prism from the wall is generally more desirable than attempting to test individual components.

NOTE 15—The cost of tests to show initial compliance are typically borne by the seller. The party initiating a change of materials typically bear the cost for recompliance.

Unless otherwise specified, the cost of other tests are typically borne as follows:

If the results of the tests show that the mortar does not conform to the requirements of the specification, the costs are typically borne by the seller.

If the results of the tests show that the mortar does conform to the requirements of the specification, the costs are typically borne by the purchaser.

9. Keywords

9.1 air content; compressive strength; masonry; masonry cement; mortar; portland cement-lime; water retention; water retentivity

APPENDIXES
(Nonmandatory Information)
X1. SELECTION AND USE OF MORTAR FOR UNIT MASONRY

X1.1 *Scope*—This appendix provides information to allow a more knowledgeable decision in the selection of mortar for a specific use.

X1.2 *Significance and Use*—Masonry mortar is a versatile material capable of satisfying a variety of diverse requirements. The relatively small portion of mortar in masonry significantly influences the total performance. There is no single mortar mix that satisfies all situations. Only an understanding of mortar materials and their properties, singly and collectively, will enable selection of a mortar that will perform satisfactorily for each specific endeavor.

X1.3 *Function:*

X1.3.1 The primary purpose of mortar in masonry is to bond masonry units into an assemblage which acts as an integral element having desired functional performance characteristics. Mortar influences the structural properties of the assemblage while adding to its water resistance.

X1.3.2 Because portland cement concretes and masonry mortars contain some of the same principal ingredients, it is often erroneously assumed that good concrete practice is also good mortar practice. Realistically, mortars differ from concrete in working consistencies, in methods of placement and in the curing environment. Masonry mortar is commonly used to bind masonry units into a single structural element, while concrete is usually a structural element in itself.

X1.3.3 A major distinction between the two materials is illustrated by the manner in which they are handled during construction. Concrete is usually placed in nonabsorbent metal or wooden forms or otherwise treated so that most of the water will be retained. Mortar is usually placed between absorbent masonry units, and as soon as contact is made the mortar loses water to the units. Compressive strength is a prime consideration in concrete, but it is only one of several important factors in mortar.

X1.4 *Properties:*

X1.4.1 Masonry mortars have two distinct, important sets of properties, those of plastic mortars and those of hardened mortars. Plastic properties determine a mortar's construction suitability, which in turn relate to the properties of the hardened mortar and, hence, of finished structural elements. Properties of plastic mortars that help determine their construction suitability include workability and water retentivity. Properties of hardened mortars that help determine the performance of the finished masonry include bond, durability, elasticity, and compressive strength.

X1.4.2 Many properties of mortar are not quantitatively definable in precise terms because of a lack of measurement standards. For this and other reasons there are no mortar

standards wholly based upon performance, thus the continued use of the traditional prescription specification in most situations.

X1.4.3 It is recommended that Test Method **C780** and assemblage testing be considered with proper interpretation to aid in determining the field suitability of a given masonry mortar for an intended use.

X1.5 *Plastic Mortars:*

X1.5.1 *Workability*—Workability is the most important property of plastic mortar. Workable mortar can be spread easily with a trowel into the separations and crevices of the masonry unit. Workable mortar also supports the weight of masonry units when placed and facilitates alignment. It adheres to vertical masonry surfaces and readily extrudes from the mortar joints when the mason applies pressure to bring the unit into alignment. Workability is a combination of several properties, including plasticity, consistency, cohesion, and adhesion, which have defied exact laboratory measurement. The mason can best assess workability by observing the response of the mortar to the trowel.

X1.5.2 Workability is the result of a ball bearing affect of aggregate particles lubricated by the cementing paste. Although largely determined by aggregate grading, material proportions and air content, the final adjustment to workability depends on water content. This can be, and usually is, regulated on the mortar board near the working face of the masonry. The capacity of a masonry mortar to retain satisfactory workability under the influence of masonry unit suction and evaporation rate depends on the water retentivity and setting characteristics of the mortar. Good workability is essential for maximum bond with masonry units.

X1.5.3 *Flow*—Initial flow is a laboratory measured property of mortar that indicates the percent increase in diameter of the base of a truncated cone of mortar when it is placed on a flow table and mechanically raised ½ in. (12.7 mm) and dropped 25 times in 15 s. Flow after suction is another laboratory property which is determined by the same test, but performed on a mortar sample which has had some water removed by a specific applied vacuum. Water retention is the ratio of flow after suction to initial flow, expressed in percent.

X1.5.3.1 Construction mortar normally requires a greater flow value than laboratory mortar, and consequently possesses a greater water content. Mortar standards commonly require a minimum water retention of 75 %, based on an initial flow of only 105 to 115 %. Construction mortars normally have initial flows, although infrequently measured, in the range of 130 to 150 % (50–60 mm by cone penetration, as outlined in the annex of Test Method **C780**) in order to produce a workability satisfactory to the mason. The lower initial flow requirements for laboratory mortars were arbitrarily set because the low flow

mortars more closely indicated the mortar compressive strength in the masonry. This is because most masonry units will remove some water from the mortar once contact is made. While there may be some discernible relationship between bond and compressive strength of mortar, the relationship between mortar flow and tensile bond strength is apparent. For most mortars, and with minor exceptions for all but very low suction masonry units, bond strength increases as flow increases to where detectable bleeding begins. Bleeding is defined as migration of free water through the mortar to its surface.

X1.5.4 Water Retention and Water Retentivity—Water retention is a measure of the ability of a mortar under suction to retain its mixing water. This mortar property gives the mason time to place and adjust a masonry unit without the mortar stiffening. Water retentivity is increased through higher lime or air content, addition of sand fines within allowable gradation limits, or use of water retaining materials.

X1.5.5 Stiffening Characteristics—Hardening of plastic mortar relates to the setting characteristics of the mortar, as indicated by resistance to deformation. Initial set as measured in the laboratory for cementitious materials indicates extent of hydration or setting characteristics of neat cement pastes. Too rapid stiffening of the mortar before use is harmful. Mortar in masonry stiffens through loss of water and hardens through normal setting of cement. This transformation may be accelerated by heat or retarded by cold. A consistent rate of stiffening assists the mason in tooling joints.

X1.6 *Hardened Mortars:*

X1.6.1 Bond—Bond is probably the most important single physical property of hardened mortar. It is also the most inconstant and unpredictable. Bond actually has three facets; strength, extent and durability. Because many variables affect bond, it is difficult to devise a single laboratory test for each of these categories that will consistently yield reproducible results and which will approximate construction results. These variables include air content and cohesiveness of mortar, elapsed time between spreading mortar and laying masonry unit, suction of masonry unit, water retentivity of mortar, pressure applied to masonry joint during placement and tooling, texture of masonry unit's bedded surfaces, and curing conditions.

X1.6.1.1 Several test methods are available for testing bond strength of mortar to masonry units, normal to the mortar joints. These include Test Methods **C952**, **C1072**, **E518**, and **E72**. Test Method **C952** includes provisions for testing the flexural bond strength of mortar to full-size hollow masonry units, constructed in a prism. It also contains a crossed brick couplet method for testing direct tensile bond of mortar to solid masonry units. Loading of the specimens in Test Method **C952** is such that a single joint is tested in tension. Test Method **C1072** tests the flexural bond strength of hollow and solid units and mortar, constructed in prisms. Individual joints of the prisms are tested for tensile bond strength. Test Method **C1072** is becoming more widely used to test the flexural bond strength than the others, due to the large amount of data produced by relatively small amounts of material. Test Method **C1072** has three distinct methods. The first method, for laboratory pre-

pared specimens, is intended to compare bond strengths of mortars using a standard solid concrete masonry unit constructed in a prism. The second method, for field prepared specimens, is intended to evaluate bond strength of a particular unit/mortar combination. The third method describes procedures to evaluate bond strength of unit/mortar combinations obtained from existing masonry. Test Method **E518** provides a method for testing a masonry prism as a simply supported beam to determine flexural strength. While individual joints are not loaded in the Test Method **E518** procedure, the resulting strength is determined as the prism behaves in flexure. The flexural strength of masonry walls is perhaps best indicated by testing full-scale wall specimens with Test Method **E72** with lateral uniform or point loading applied to the specimen. Research^{4,5} on concrete masonry indicates the flexural bond strength of concrete masonry walls, using Test Method **E72**, may be correlated with results of flexural bond strength of concrete masonry prisms, tested in accordance with Test Method **C1072** and Test Method **E518**.

X1.6.1.2 Extent of bond may be observed under the microscope. Lack of extent of bond, where severe, may be measured indirectly by testing for relative movement of water through the masonry at the unit-mortar interface, such as prescribed in Test Method **E514**. This laboratory test method consists of subjecting a sample wall to a through-the-wall pressure differential and applying water to the high pressure side. Time, location and rate of leakage must be observed and interpreted.

X1.6.1.3 The tensile and compressive strength of mortar far exceeds the bond strength between the mortar and the masonry unit. Mortar joints, therefore, are subject to bond failures at lower tensile or shear stress levels. A lack of bond at the interface of mortar and masonry unit may lead to moisture penetration through those areas. Complete and intimate contact between mortar and masonry unit is essential for good bond. This can best be achieved through use of mortar having proper composition and good workability, and being properly placed.

X1.6.1.4 In general, the tensile bond strength of laboratory mortars increase with an increase in cement content. Because of mortar workability, it has been found that Type S mortar generally results with the maximum tensile bond strength that can practically be achieved in the field.

X1.6.2 Extensibility and Plastic Flow—Extensibility is maximum unit tensile strain at rupture. It reflects the maximum elongation possible under tensile forces. Low strength mortars, which have lower moduli of elasticity, exhibit greater plastic flow than their high moduli counterparts at equal paste to aggregate ratios. For this reason, mortars with higher strength than necessary should not be used. Plastic flow or creep will impart flexibility to the masonry, permitting slight movement without apparent joint opening.

X1.6.3 Compressive Strength—The compressive strength of mortar is sometimes used as a principal criterion for selecting

⁴Thomas, R., Samblanet, P., and Hogan, M., "Research Evaluation of the Flexural Tensile Strength of Concrete Masonry," *Seventh Canadian Masonry Symposium*, June 1995.

⁵Melander, J. and Thomas, R., "Flexural Tensile Strength of Concrete Masonry Constructed with Type S Masonry Cement Mortar," *Eighth Canadian Masonry Symposium*, June 1998.

mortar type, since compressive strength is relatively easy to measure, and it commonly relates to some other properties, such as tensile strength and absorption of the mortar.

X1.6.3.1 The compressive strength of mortar depends largely upon the cement content and the water-cement ratio. The accepted laboratory means for measuring compressive strength is to test 2 in. (50.8 mm) cubes of mortar. Because the referenced test in this specification is relatively simple, and because it gives consistent, reproducible results, compressive strength is considered a basis for assessing the compatibility of mortar ingredients. Field testing compressive strength of mortar is accomplished with Test Method **C780** using either 2 in. (50.8 mm) cubes or small cylindrical specimens of mortar.

X1.6.3.2 Perhaps because of the previously noted confusion regarding mortar and concrete, the importance of compressive strength of mortar is overemphasized. Compressive strength should not be the sole criterion for mortar selection. Bond strength is generally more important, as is good workability and water retentivity, both of which are required for maximum bond. Flexural strength is also important because it measures the ability of a mortar to resist cracking. Often overlooked is the size/shape of mortar joints in that the ultimate compressive load carrying capacity of a typical $\frac{3}{8}$ in. (9.5 mm) bed joint will probably be well over twice the value obtained when the mortar is tested as a 2 in. (50.8 mm) cube. Mortars should typically be weaker than the masonry units, so that any cracks will occur in the mortar joints where they can more easily be repaired.

X1.6.3.3 Compressive strength of mortar increases with an increase in cement content and decreases with an increase in lime, sand, water or air content. Retempering is associated with a decrease in mortar compressive strength. The amount of the reduction increases with water addition and time between mixing and retempering. It is frequently desirable to sacrifice some compressive strength of the mortar in favor of improved bond, consequently retempering within reasonable time limits is recommended to improve bond.

X1.6.4 *Durability*—The durability of relatively dry masonry which resists water penetration is not a serious problem. The coupling of mortars with certain masonry units, and design without exposure considerations, can lead to unit or mortar durability problems. It is generally conceded that masonry walls, heated on one side, will stand many years before requiring maintenance, an indication of mortar's potential longevity. Parapets, masonry paving, retaining walls, and other masonry exposed to freezing while saturated represent extreme exposures and thus require a more durable mortar.

X1.6.4.1 Mortar, when tested in the laboratory for durability, is subjected to repeated cycles of freezing and thawing. Unless a masonry assemblage is allowed to become nearly saturated, there is little danger of substantial damage due to freezing. Properly entrained air in masonry mortar generally increases its resistance to freeze-thaw damage where extreme exposure (such as repeated cycles of freezing and thawing while saturated with water) exists. Air content within the specification limits for mortar, however, may be above the amount required for resistance to freeze-thaw damage. Dura-

bility is adversely affected by oversanded or overtempered mortars as well as use of highly absorbent masonry units.

X1.7 *Composition and Its Effect on Properties:*

X1.7.1 Essentially, mortars contain cementitious materials, aggregate and water. Sometimes admixtures are used also.

X1.7.2 Each of the principal constituents of mortar makes a definite contribution to its performance. Portland cement contributes to strength and durability. Lime, in its hydroxide state, provides workability, water retentivity, and elasticity. Both portland cement and lime contribute to bond strength. Instead of portland cement-lime combinations, masonry cement or mortar cement is used. Sand acts as a filler and enables the unset mortar to retain its shape and thickness under the weight of subsequent courses of masonry. Water is the mixing agent which gives fluidity and causes cement hydration to take place.

X1.7.3 Mortar should be composed of materials which will produce the best combination of mortar properties for the intended service conditions.

X1.7.4 *Cementitious Materials Based on Hydration*—Portland cement, a hydraulic cement, is the principal cementitious ingredient in most masonry mortars. Portland cement contributes strength to masonry mortar, particularly early strength, which is essential for speed of construction. Straight portland cement mortars are not used because they lack plasticity, have low water retentivity, and are harsh and less workable than portland cement-lime or masonry cement mortars.

X1.7.4.1 Masonry cement is a proprietary product usually containing portland cement and fines, such as ground limestone or other materials in various proportions, plus additives such as air entraining and water repellency agents.

X1.7.4.2 Mortar cement is a hydraulic cement similar to masonry cement, but the specification for mortar cement requires lower air contents and includes a flexural bond strength requirement.

X1.7.5 *Cementitious Materials Based on Carbonation*—Hydrated lime contributes to workability, water retentivity, and elasticity. Lime mortars carbonate gradually under the influence of carbon dioxide in the air, a process slowed by cold, wet weather. Because of this, complete hardening occurs very slowly over a long period of time. This allows healing, the recementing of small hairline cracks.

X1.7.5.1 Lime goes into solution when water is present and migrates through the masonry where it can be deposited in cracks and crevices as water evaporates. This could also cause some leaching, especially at early ages. Successive deposits may eventually fill the cracks. Such autogenous healing will tend to reduce water permeance.

X1.7.5.2 Portland cement will produce approximately 25 % of its weight in calcium hydroxide at complete hydration. This calcium hydroxide performs the same as lime during carbonation, solubilizing, and redepositing.

X1.7.6 *Aggregates*—Aggregates for mortar consist of natural or manufactured sand and are the largest volume and weight constituent of the mortar. Sand acts as an inert filler, providing

economy, workability and reduced shrinkage, while influencing compressive strength. An increase in sand content increases the setting time of a masonry mortar, but reduces potential cracking due to shrinkage of the mortar joint. The special or standard sand required for certain laboratory mortar tests may produce quite different test results from sand that is used in the construction mortar.

X1.7.6.1 Well graded aggregate reduces separation of materials in plastic mortar, which reduces bleeding and improves workability. Sands deficient in fines produce harsh mortars, while sands with excessive fines produce weak mortars and increase shrinkage. High lime or high air content mortars can carry more sand, even with poorly graded aggregates, and still provide adequate workability.

X1.7.6.2 Field sands deficient in fines can result in the cementitious material acting as fines. Excess fines in the sand, however, is more common and can result in oversanding, since workability is not substantially affected by such excess.

X1.7.6.3 Unfortunately, aggregates are frequently selected on the basis of availability and cost rather than grading. Mortar properties are not seriously affected by some variation in grading, but quality is improved by more attention to aggregate selection. Often gradation can be easily and sometimes inexpensively altered by adding fine or coarse sands. Frequently the most feasible method requires proportioning the mortar mix to suit the available sand within permissible aggregate ratio tolerances, rather than requiring sand to meet a particular gradation.

X1.7.7 *Water*—Water performs three functions. It contributes to workability, hydrates cement, and facilitates carbonation of lime. The amount of water needed depends primarily on the ingredients of the mortar. Water should be clean and free from injurious amounts of any substances that may be deleterious to mortar or metal in the masonry. Usually, potable water is acceptable.

X1.7.7.1 Water content is possibly the most misunderstood aspect of masonry mortar, probably due to the confusion between mortar and concrete requirements. Water requirement for mortar is quite different from that for concrete where a low water/cement ratio is desirable. Mortars should contain the maximum amount of water consistent with optimum workability. Mortar should also be rettempered to replace water lost by evaporation.

X1.7.8 *Admixtures*—Admixtures for masonry mortars are available in a wide variety and affect the properties of fresh or hardened mortar physically or chemically. Some chemical additions are essential in the manufacture of basic mortar materials. The inclusion of an additive is also necessary for the production of ready mixed mortars. Undoubtedly there are also some special situations where the use of admixtures may be advantageous when added at the job site mixer. In general, however, such use of admixtures is not recommended. Careful selection of the mortar mix, use of quality materials, and good practice will usually result in sound masonry. Improperities cannot be corrected by admixtures, some of which are definitely harmful.

X1.7.8.1 Admixtures are usually commercially prepared products and their compositions are not generally disclosed.

Admixtures are functionally classified as agents promoting air entrainment, water retentivity, workability, accelerated set, and so on. Limited data are available regarding the effect of proprietary admixtures on mortar bond, compressive strength, or water permeance of masonry. Field experience indicates that detrimental results have frequently occurred. For these reasons, admixtures should be used in the field only after it has been established by laboratory test under conditions duplicating their intended use, and experience, that they improve the masonry.

X1.7.8.2 Use of an air entraining admixture, along with the limits on air content in a field mortar, still continues to create controversy. Most masonry cements, all Type “A” portland cements and all Type “A” limes incorporate air entraining additions during their manufacture to provide required minimum as well as maximum levels of air in a laboratory mortar. Such materials should never be combined, nor should admixtures which increase the entrained air content of the mortar be added in the field, except under the most special of circumstances.

X1.7.8.3 The uncontrolled use of air entraining agents should be prohibited. At high air levels, a definite inverse relationship exists between air content and tensile bond strength of mortar as measured in the laboratory. In general, any increase in air content is accompanied by a decrease in bond as well as compressive strength. Data on masonry grouts indicate that lower bond strength between grout and reinforcing steel is associated with high air content. Most highly air entrained mortar systems can utilize higher sand contents without losing workability, which could be detrimental to the masonry if excessive sand were used. The use of any mortar containing air entraining materials, where resulting levels of air are high or unknown, should be based on a knowledge of local performance or on laboratory tests of mortar and masonry assemblages.

X1.7.8.4 Air can be removed from plastic mortar containing air entraining material by use of a defoamer, although its use in the field is strongly discouraged.

X1.7.8.5 Color can be added to mortar using selected aggregates or inorganic pigments. Inorganic pigments should be of mineral oxide composition and should not exceed 10 % of the weight of portland cement, with carbon black limited to 2 %, to avoid excessive strength reduction of the mortar. Pigments should be carefully chosen and used in the smallest amount that will produce the desired color. To minimize variations from batch to batch it is advisable to purchase cementitious materials to which coloring has been added at the plant or to use preweighed individual packets of coloring compounds for each batch of mortar, and to mix the mortar in batches large enough to permit accurate batching. Mortar mixing procedures should remain constant for color consistency.

X1.8 *Kinds of Mortars:*

X1.8.1 *History*—History records that burned gypsum and sand mortars were used in Egypt at least as early as 2690 B.C. Later in ancient Greece and Rome, mortars were produced from various materials such as burned lime, volcanic tuff, and

sand. When the first settlements appeared in North America, a relatively weak product was still being made from lime and sand. The common use of portland cement in mortar began in the early part of the twentieth century and led to greatly strengthened mortar, either when portland cement was used alone or in combination with lime. Modern mortar is still made with from portland cement and hydrated lime, in addition to mortars made from masonry cement or mortar cement.

X1.8.2 Portland Cement-Hydrated Lime—Cement-lime mortars have a wide range of properties. At one extreme, a straight portland cement and sand mortar would have high compressive strength and low water retention. A wall containing such a mortar would be strong but vulnerable to cracking and rain penetration. At the other extreme, a straight lime and sand mortar would have low compressive strength and high water retention. A wall containing such a mortar would have lower strength, particularly early strength, but greater resistance to cracking and rain penetration. Between the two extremes, various combinations of cement and lime provide a balance with a wide variety of properties, the high strength and early setting characteristics of cement modified by the excellent workability and water retentivity of lime. Selective proportions are found in this specification.

X1.8.3 Masonry Cement—Masonry cement mortars generally have excellent workability. Microscopic bubbles of entrained air contribute to the ball bearing action and provide a part of this workability. Freeze-thaw durability of masonry cement mortars in the laboratory is outstanding. Three types of masonry cement are recognized by Specification C91. These masonry cements are formulated to produce mortars conforming to either the proportion or the property specifications of this specification. Such masonry cements provide the total cementitious material in a single bag to which sand and water are added at the mixer. A consistent appearance of mortar made from masonry cements should be easier to obtain because all the cementitious ingredients are proportioned, and ground or blended together before being packaged.

X1.8.4 Portland Cement-Masonry Cement—The addition of portland cement to Type N masonry cement mortars also allow qualification as Types M and S Mortars in this specification.

X1.8.5 Mortar Cement—Three types of mortar cements are recognized by Specification C1329. These mortar cements are formulated to produce mortar conforming to either the proportion or property requirements of this specification. Mortar cement mortars have attributes similar to those of masonry cement mortars while satisfying air content and bond strength requirements of Specification C1329.

X1.8.6 Prebatched or Premixed—Recently, prebatched or premixed mortars have been made readily available in two options. One is a wet, ready mixed combination of hydrated lime or lime putty, sand, and water delivered to the construction project, and when mixed with cement and additional water is ready for use. The other is dry, packaged mortar mixtures requiring only the addition of water and mixing. Special attention should be given to the dry system, in that resulting mortars may have to be mixed for a longer period of time to overcome the water affinity of oven dry sand and subsequent

workability loss in the mortar. The use of ready mixed mortar is also on the increase. These are mixtures consisting of cementitious materials, aggregates, and admixtures, batched and mixed at a central location, and delivered to the construction project with suitable workability characteristics for a period in excess of 2½ h after mixing. Systems utilizing continuous batching of mortar are also available.

X1.8.7 Portland Cement—Mortar Cement—The addition of portland cement to Type N mortar cement mortars also allow qualification as Types M and S Mortars in this specification.

X1.9 Related Items That Have an Effect on Properties:

X1.9.1 The factors influencing the successful conclusion of any project with the desired performance characteristics are the design, material, procedure and craftsmanship selected and used.

X1.9.2 The supervision, inspecting and testing necessary for compliance with requirements should be appropriate and predetermined.

X1.9.3 Masonry Units—Masonry units are absorptive by nature, with the result that water is extracted from the mortar as soon as the masonry unit and the mortar come into contact. The amount of water removal and its consequences effect the strength of the mortar, the properties of the boundary between the mortar and the masonry units, and thus the strength, as well as other properties, of the masonry assemblage.

X1.9.3.1 The suction exerted by the masonry unit is a very important external factor which affects the fresh mortar and initiates the development of bond. Masonry units vary widely in initial rate of absorption (suction). It is therefore necessary that the mortar chosen have properties that will provide compatibility with the properties of the masonry unit being used, as well as environmental conditions that exist during construction and the construction practices peculiar to the job.

X1.9.3.2 Mortar generally bonds best to masonry units having moderate initial rates of absorption (IRA), from 5 to 25 g/min·30 in.² (194 cm²), at the time of laying. More than adequate bond can be obtained, however, with many units having IRA's less than or greater than these values.

X1.9.3.3 The extraction of too much or too little of the available water in the mortar tends to reduce the bond between the masonry unit and the mortar. A loss of too much water from the mortar can be caused by low water retentivity mortar, high suction masonry units, or dry, windy conditions. When this occurs, the mortar is incapable of forming a complete bond when the next unit is placed. Where lowering the suction by prewetting the units is not proper or possible, the time lapse between spreading the mortar and laying of a masonry unit should be kept to a minimum. When a very low suction masonry unit is used, the unit tends to float and bond is difficult to accomplish. There is no available means of increasing the suction of a low suction masonry unit, and thus the time lapse between spreading the mortar and placing the unit may have to be increased.

X1.9.3.4 Mortars having higher water retentivity are desirable for use in summer or with masonry units having high suction. Mortars having lower water retentivity are desirable for use in winter or with masonry units having low suction.

X1.9.3.5 Shrinkage or swelling of the masonry unit or mortar once contact has been achieved affects the quality of the mortar joint. Protection should be provided to prevent excessive wetting, drying, heating or cooling, until the mortar has at least achieved final set.

X1.9.3.6 Mortar bond is less to surfaces having an unbroken die skin or sanded finish than it is to roughened surfaces such as a wire cut or textured finish.

X1.9.4 *Construction Practice*—Careful attention to good practice on the construction site is essential to achieve quality. Cementitious materials and aggregate should be protected from rain and ground moisture and air borne contaminants.

X1.9.4.1 Proper batching procedures include use of a known volume container (such as a one cubic foot batching box) for measuring sand. When necessary, sand quantities should be adjusted to provide for bulking of the sand. Shovel measuring cannot be expected to produce mortar of consistent quality. Alternatively, a combination volumetric measure calibration of a mixer followed by full bag cementitious additions and shovel additions of sand to achieve the same volume of mortar in the mixer with subsequent batches, should prove adequate.

X1.9.4.2 Good mixing results can be obtained where about three-fourths of the required water, one-half of the sand, and all of the cementitious materials are briefly mixed together. The balance of the sand is then charged and the remaining water added. The mixer should be charged to its full design capacity for each batch and completely emptied before charging the next batch.

X1.9.4.3 Mixing time in a paddle mixer should usually be a minimum of 3 and a maximum of 5 min after the last mixing water has been added, to insure homogeneity and workability of the mortar. Overmixing results in changing the air content of the mortar. Worn paddles and rubber scrapers will greatly influence the mixing efficiency. Concern for quality suggests use of an automatic timer on the mixing machine. Mixing time should not be determined by the demand of the working force.

X1.9.4.4 Since all mortar is not used immediately after mixing, evaporation may require the addition of water, retempering the mortar, to restore its original consistency. The addition of water to mortar within specified time limits should

not be prohibited. Although compressive strength of the mortar is reduced slightly by retempering, bond strength is usually increased. For this reason, retempering should be required to replace water lost by evaporation. Because retempering is harmful only after mortar has begun to set, all site prepared mortar should be placed in final position as soon as possible, but always within 2½ h after the original mixing, or the mortar discarded.

X1.9.4.5 Weather conditions also should be considered when selecting mortar. During warm, dry, windy, summer weather, mortar must have a high water retentivity to minimize the effect of water lost by evaporation. In winter, a lower water retentivity has merit because it facilitates water loss from the mortar to the units prior to a freeze. To minimize the risk of reduced bond in cold weather, the masonry units being used as well as the surface on which the mortar is placed should both be brought to a temperature at least above 32°F (0°C) before any work commences. (For more inclusive suggestions, see “Recommended Practices for Cold Weather Masonry Construction” available from the International Masonry Industry All Weather Council.)

X1.9.5 *Workmanship*—Workmanship has a substantial effect on strength and extent of bond. The time lapse between spreading mortar and placing masonry units should be kept to a minimum because the flow will be reduced through suction of the unit on which it is first placed. This time lapse should normally not exceed one minute. Reduce this time lapse for hot, dry and windy conditions, or with use of highly absorptive masonry units. If excessive time elapses before a unit is placed on the mortar, bond will be reduced. Elimination of deep furrows in horizontal bed joints and providing full head joints are essential. Any metal embedded in mortar should be completely surrounded by mortar.

X1.9.5.1 Once the mortar between adjacent units has begun to stiffen, tapping or otherwise attempting to move masonry units is highly detrimental to bond and should be prohibited. The movement breaks the bond between the mortar and the masonry unit, and the mortar will not be sufficiently plastic to reestablish adherence to the masonry unit.

X1.9.5.2 Tooling of the mortar joint should be done when its surface is thumb-print hard utilizing a jointer having a

TABLE X1.1 Guide for the Selection of Masonry Mortars^A

Location	Building Segment	Mortar Type	
		Recommended	Alternative
Exterior, above grade	load-bearing wall	N	S or M
	non-load bearing wall	O ^B	N or S
	parapet wall	N	S
Exterior, at or below grade	foundation wall, retaining wall, manholes, sewers, pavements, walks, and patios	S ^C	M or N ^C
Interior	load-bearing wall	N	S or M
	non-bearing partitions	O	N
Interior or Exterior	tuck pointing	see Appendix X3	see Appendix X3

^AThis table does not provide for many specialized mortar uses, such as chimney, reinforced masonry, and acid-resistant mortars.

^BType O mortar is recommended for use where the masonry is unlikely to be frozen when saturated, or unlikely to be subjected to high winds or other significant lateral loads. Type N or S mortar should be used in other cases.

^CMasonry exposed to weather in a nominally horizontal surface is extremely vulnerable to weathering. Mortar for such masonry should be selected with due caution.

diameter slightly larger than the mortar joint width. Joint configurations other than concave can result in increased water permeance of the masonry assemblage. Striking joints with the same degree of hardness produces uniform joint appearance. Finishing is not only for appearance, but to seal the interface between mortar and masonry unit, while densifying the surface of the mortar joint.

X1.9.5.3 The benefits of the finishing operation should be protected from improper cleaning of the masonry. Use of strong chemical or harsh physical methods of cleaning may be detrimental to the mortar. Colored mortars are especially susceptible to damage from such cleaning. Most chemicals used in cleaning attack the cementitious materials within the mortar system, as well as enlarge cracks between mortar and masonry unit.

X1.9.5.4 With very rapid drying under hot, dry and windy conditions, very light wetting of the in-place masonry, such as fog spray, can improve its quality. Curing of mortar by the addition of considerable water to the masonry assemblage, however, could prove to be more detrimental than curing of mortar by retention of water in the system from its construction. The addition of excess moisture might saturate the masonry, creating movements which decrease the adhesion between mortar and masonry unit.

X1.10 Summary:

X1.10.1 No one combination of ingredients provides a mortar possessing an optimum in all desirable properties. Factors that improve one property generally do so at the

expense of others. Testing of mortars in the laboratory by this specification's referenced methods, and in the field by Test Method C780 is beneficial. Some physical properties of mortar, however, are of equal or greater significance to masonry performance than those properties commonly specified. When selecting a mortar, evaluate all properties, and then select the mortar providing the best compromise for the particular requirements.

X1.10.2 Bond is probably the most important single property of a conventional mortar. Many variables affect bond. To obtain optimum bond, use a mortar with properties that are compatible with the masonry units to be used. To increase tensile bond strength in general, increase the cement content of the mortar (see X1.6.1.4); keep air content of the mortar to a minimum; use mortars having high water retentivity; mix mortar to the water content compatible with workability; allow retempering of the mortar; use masonry units having moderate initial rates of absorption when laid (see X1.9.3.2); bond mortar to a rough surface rather than to a die skin surface; minimize time between spreading mortar and placing masonry units; apply pressure in forming the mortar joint; and do not subsequently disturb laid units.

X1.10.3 Table X1.1 is a general guide for the selection of mortar type for various masonry wall construction. Selection of mortar type should also be based on the type of masonry units to be used as well as the applicable building code and engineering practice standard requirements, such as allowable design stresses, and lateral support.

X2. EFFLORESCENCE

X2.1 Efflorescence is a crystalline deposit, usually white, of water soluble salts on the surface of masonry. The principal objection to efflorescence is the appearance of the salts and the nuisance of their removal. Under certain circumstances, particularly when exterior coatings are present, salts can be deposited below the surface of the masonry units. When this cryptoflorescence occurs, the force of crystallization can cause disintegration of the masonry.

X2.2 A combination of circumstances is necessary for the formation of efflorescence. First, there must be a source of soluble salts. Second, there must be moisture present to pick up the soluble salts and carry them to the surface. Third, evaporation or hydrostatic pressure must cause the solution to migrate. If any one of these conditions is eliminated, efflorescence will not occur.

X2.3 Salts may be found in the masonry units, mortar components, admixtures or other secondary sources. Water-soluble salts that appear in chemical analyses as only a few tenths of 1 % are sufficient to cause efflorescence when leached out and concentrated on the surface. The amount and character of the deposits vary according to the nature of the soluble materials and the atmospheric conditions. A test for the efflorescence of individual masonry units is contained within ASTM standards. Efflorescence can occur with any C270

mortar when moisture migration occurs. There is no ASTM test method that will predict the potential for efflorescence of mortar. Further, there is no ASTM test method to evaluate the efflorescence potential of combined masonry materials.

X2.4 The probability of efflorescence in masonry as related directly to materials may be reduced by the restrictive selection of materials. Masonry units with a rating of "not effloresced" are the least likely to contribute towards efflorescence. The potential for efflorescence decreases as the alkali content of cement decreases. Admixtures should not be used in the field. Washed sand and clean, potable water should be used.

X2.5 Moisture can enter masonry in a number of ways. Attention must be paid to the design and installation of flashing, vapor barriers, coping and caulking to minimize penetration of rainwater into the masonry. During construction, masonry materials and unfinished walls should be protected from rain and construction applied water. Full bed and head joints, along with a compacting finish on a concave mortar joint, will reduce water penetration. Condensation occurring within the masonry is a further source of water.

X2.6 Although selection of masonry construction materials having a minimum of soluble salts is desirable, the prevention of moisture migration through the wall holds the greatest

potential in minimizing efflorescence. Design of masonry using the principle of pressure equalization between the outside and a void space within the wall will greatly reduce the chances of water penetration and subsequently efflorescence.

X2.7 Removal of efflorescence from the face of the masonry can frequently be achieved by dry brushing. Since many salts

are highly soluble in water, they will disappear of their own accord under normal weathering processes. Some salts, however, may require harsh physical or even chemical treatment, if they are to be removed.

X3. TUCK POINTING MORTAR

X3.1 General:

X3.1.1 Tuck pointing mortars are replacement mortars used at or near the surface of the masonry wall to restore integrity or improve appearance. Mortars made without portland cement may require special considerations in selecting tuck pointing mortars.

X3.1.2 If the entire wall is not to be tuck pointed, the color and texture should closely match those of the original mortar. An exact match is virtually impossible to achieve.

X3.2 Materials:

X3.2.1 Use cementitious materials that conform to the requirements of this specification (C270).

X3.2.2 Use sand that conforms to the requirements of this specification (C270). Sand may be selected to have color, size, and gradation similar to that of the original mortar, if color and texture are important.

X3.3 *Selection Guide*—Use tuck pointing mortar of the same or weaker composition as the original mortar. See [Table X3.1](#).

X3.4 *Materials*—Mortar shall be specified as one of the following:

X3.4.1 The proportion specification of C270, Type ____.

X3.4.2 *Type K*—One part portland cement and 2½ to 4 parts hydrated lime. Aggregate Ratio of 2¼ to 3 times sum of volume of cement and lime.

TABLE X3.1 Guide for Selection of Tuck Pointing Mortar^A

Location or Service	Mortar Type	
	Recommended	Alternate
interior	O	K,N
exterior, above grade exposed on one side, unlikely to be frozen when saturated, not subject to high wind or other significant lateral load	O	N,K
exterior, other than above	N	O

^A In some applications, structural concerns may dictate the use of mortars other than those recommended. This table is not applicable to pavement applications.

NOTE X3.1—Type K mortar proportions were referenced in this specification (C270) prior to 1982.

X3.5 Mixing:

X3.5.1 Dry mix all solid materials.

X3.5.2 Add sufficient water to produce a damp mix that will retain its shape when pressed into a ball by hand. Mix from 3 to 7 min, preferably with a mechanical mixer.

X3.5.3 Let mortar stand for not less than 1 h nor more than 1½ h for prehydration.

X3.5.4 Add sufficient water to bring the mortar to the proper consistency for tuck pointing, somewhat drier than mortar used for laying the units.

X3.5.5 Use the mortar within 2½ h of its initial mixing. Permit tempering of the mortar within this time interval.

X4. EXAMPLES OF MATERIAL PROPORTIONING FOR TEST BATCHES OF MORTAR

X4.1 *Example A*—A mortar consisting of one part portland cement, 1¼ parts lime, and 6¾ parts of sand is to be tested. The weights of the materials used in the mortar are calculated as follows:

$$\text{Batch factor} = 1440 / (80 \times 6.75) = 2.67 \quad (\text{X4.1})$$

$$\text{Weight of portland cement} = 1 \times 94 \times 2.67 = 251$$

$$\text{Weight of lime} = 1\frac{1}{4} \times 40 \times 2.67 = 133$$

$$\text{Weight of sand}^A = 6\frac{3}{4} \times 80 \times 2.67 = 1440$$

	Portland Cement	Lime	Sand
Proportions by volume	1	1 ¼	6¾
Unit weight (lb/ft ³)	94	40	80
Batch factor	2.67	2.67	2.67
Weight of material ^B (in g)	251	133	1440

^ATotal sand content is calculated as: (1 volume part of portland cement plus 1¼ volume parts of hydrated lime) times three = 6¾ parts of sand.

^BWeight of material = volume proportion times unit weight times batch factor.

X4.2 *Example B*—A mortar consisting of one part masonry cement, three parts sand is to be tested. The weights of the

materials used in the mortar are calculated as follows:

$$\text{Batch factor} = 1440 / (80 \times 3) = 6.00 \quad (\text{X4.2})$$

$$\text{Weight of masonry cement} = 1 \times 70 \times 6.00 = 420$$

$$\text{Weight of sand}^A = 3 \times 80 \times 6.00 = 1440$$

	Masonry Cement	Sand
Proportions by volume	1	3
Unit weight (lb/ft ³)	70	80
(Weight printed on bag for masonry cement)		
Batch factor	6.00	6.00
Weight of material ^B (in g)	420	1440

^ATotal sand content is calculated as: (1 volume part of masonry cement) times three = 3 parts of sand.

^BWeight of material = volume proportion times unit weight times batch factor.

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Standard Specification for Hydrated Lime for Masonry Purposes¹

This standard is issued under the fixed designation C207; 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.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 This specification covers four types of hydrated lime. Types N and S are suitable for use in mortar, in scratch and brown coats of cement plaster, for stucco, and for addition to portland-cement concrete. Types NA and SA are air-entrained hydrated limes that are suitable for use in any of the above uses where the inherent properties of lime and air-entrainment are desired. The four types of lime sold under this specification shall be designated as follows:

1.1.1 *Type N*—Normal hydrated lime for masonry purposes.

1.1.2 *Type S*—Special hydrated lime for masonry purposes.

1.1.3 *Type NA*—Normal air-entraining hydrated lime for masonry purposes.

1.1.4 *Type SA*—Special air-entraining hydrated lime for masonry purposes.

NOTE 1—Type S, special hydrated lime, and Type SA, special air-entraining hydrated lime, are differentiated from Type N, normal hydrated lime, and Type NA, normal air-entraining hydrated lime, principally by their ability to develop high, early plasticity and higher water retentivity, and by a limitation on their unhydrated oxide content.

NOTE 2—For normal (Type N) and special (Type S) finishing hydrated lime, refer to Specification C206.

NOTE 3—Some building codes prohibit the use of air-entraining materials in mortar, because of the accompanying reduction in bond and compressive strength. Where increased freeze-thaw resistance is important, air-entraining may be beneficial. Air-entraining lime should not be used as a finishing lime.

NOTE 4—For lime putty, refer to Specification C1489.

1.2 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

¹ This specification is under the jurisdiction of ASTM Committee C07 on Lime and is the direct responsibility of Subcommittee C07.02 on Specifications and Guidelines.

Current edition approved June 1, 2011. Published July 2011. Originally approved in 1946. Last previous edition approved in 2006 as C207–06. DOI: 10.1520/C0207-06R11.

2. Referenced Documents

2.1 *ASTM Standards*:²

C25 Test Methods for Chemical Analysis of Limestone, Quicklime, and Hydrated Lime

C50 Practice for Sampling, Sample Preparation, Packaging, and Marking of Lime and Limestone Products

C110 Test Methods for Physical Testing of Quicklime, Hydrated Lime, and Limestone

C206 Specification for Finishing Hydrated Lime

C226 Specification for Air-Entraining Additions for Use in the Manufacture of Air-Entraining Hydraulic Cement

C778 Specification for Sand

C1489 Specification for Lime Putty for Structural Purposes

3. Terminology

3.1 *Definitions*:

3.1.1 *standard mortar, n*—a mortar containing only hydrated lime and sand meeting the requirements of Specification C778.

The mortar proportions are one part hydrated lime to three parts of sand by volume as indicated in Table 4 of Test Methods C110.

4. Additions

4.1 Types NA and SA hydrated lime covered by this specification shall contain additives for the purpose of entraining air, and such additives shall conform to the requirements of Specification C226.

5. Manufacturer's Statement

5.1 At the request of the purchaser, the manufacturer shall state in writing the nature, amount, and identity of the air-entraining agent used and of any processing addition that may have been used, and also, if requested, shall supply test

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.

data showing compliance of such air-entraining addition with the provisions of Specification C226.

6. Chemical Composition

6.1 Hydrated lime for masonry purposes shall conform to the following requirements as to chemical composition:

	Hydrate Types:			
	N	NA	S	SA
Calcium and magnesium oxides (nonvolatile basis), min, %	95	95	95	95
Carbon dioxide (as-received basis), max, %:				
If sample is taken at place of manufacture	5	5	5	5
If sample is taken at any other place	7	7	7	7
Unhydrated oxides (as-received basis), max, %	...	...	8	8

7. Residue, Popping, and Pitting

7.1 The four types of hydrated lime for masonry purposes shall conform to one of the following requirements:

7.1.1 The residue retained on a No. 30 (600- μ m) sieve shall not be more than 0.5 %, or

7.1.2 If the residue retained on a No. 30 (600- μ m) sieve is over 0.5 %, the lime shall show no pops or pits when tested in accordance with the method prescribed in 12.1.2.

8. Plasticity

8.1 The putty made from Type S, special hydrate, or Type SA, special air-entraining hydrate, shall have a plasticity figure of not less than 200 Elmev units when tested within 30 min after mixing with water using Test Methods C110.

9. Water Retention

9.1 Hydrated lime mortar made with Type N (normal hydrated lime) or Type NA (normal air-entraining hydrated lime), after suction for 60 s, shall have a water retention value of not less than 75 % when tested in a standard mortar made from the dry hydrate or from putty made from the hydrate which has been soaked for a period of 16 to 24 h.

9.2 Hydrated lime mortar made with Type S (special hydrated lime) or Type SA (special air-entraining hydrated lime), tested in accordance with Section 10 of Test Methods C110, shall have a water retention value of not less than 85 % when tested in a standard mortar made from the dry hydrate using Test Methods C110.

10. Air-Entrainment

10.1 The hydrated lime covered by Types N or S in this specification shall contain no additives for the purpose of entraining air. The air content of a standard mortar made with Types N or S shall not exceed 7 % as determined in accordance with the requirements of Section 8 of Test Methods C110. The air content of standard mortar made with Types NA or SA shall have a minimum of 7 % and a maximum of 12 % when tested in accordance with the requirements of Section 8 of Test Methods C110.

11. Sampling and Inspection

11.1 The sampling, inspection, rejection, retesting, packaging, and marking shall be conducted in accordance with Practice C50.

12. Test Methods

12.1 Determine the properties enumerated in this specification in accordance with the following methods:

12.1.1 *Chemical Analysis*—Test Methods C25.

12.1.2 *Physical Tests*—Test Methods C110.

13. Special Package Marking

13.1 When Types NA or SA air-entraining hydrated lime are delivered in packages, the name and brand of the manufacturer, the type under this specification, and the words “AIR-ENTRAINING” shall be plainly indicated thereon or in case of bulk shipments, so indicated on shipping notices.

14. Keywords

14.1 hydrated lime; masonry; mortar; plasticity; popping and pitting; residue; stucco; Type N; Type NA; Type S; Type SA; unhydrated oxides; water retention; air entraining

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Standard Specification for Finishing Hydrated Lime¹

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This standard has been approved for use by agencies of the U.S. Department of Defense.

1. Scope*

1.1 This specification covers two types of finishing hydrated lime that are suitable for use in the scratch, brown, and finish coats of plaster, for stucco, for mortar, and as an addition to portland-cement concrete. The two types of lime sold under this specification shall be designated as follows:

1.1.1 *Type N*—Normal hydrated lime for finishing purposes, and

1.1.2 *Type S*—Special hydrated lime for finishing purposes.

NOTE 1—Type N, normal finishing hydrated lime, is differentiated from Type S, special finishing hydrated lime, in that no limitation on the amount of unhydrated oxides is specified for Type N hydrate, and the plasticity requirement for Type N hydrate shall be determined after soaking for 16 to 24 h.

NOTE 2—For lime putty, refer to Specification C1489.

1.2 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

2. Referenced Documents

2.1 *ASTM Standards*:²

C25 Test Methods for Chemical Analysis of Limestone, Quicklime, and Hydrated Lime

C50 Practice for Sampling, Sample Preparation, Packaging, and Marking of Lime and Limestone Products

C51 Terminology Relating to Lime and Limestone (as used by the Industry)

C110 Test Methods for Physical Testing of Quicklime, Hydrated Lime, and Limestone

C842 Specification for Application of Interior Gypsum Plaster

C1271 Test Method for X-ray Spectrometric Analysis of

¹ This specification is under the jurisdiction of ASTM Committee C07 on Lime and Limestone and is the direct responsibility of Subcommittee C07.02 on Specifications and Guidelines.

Current edition approved Dec. 1, 2014. Published December 2014. Originally approved in 1946. Replaces C6 – 49 (1974). Last previous edition approved in 2009 as C206 – 03 (2009). DOI: 10.1520/C0206-14.

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.

Lime and Limestone

C1301 Test Method for Major and Trace Elements in Limestone and Lime by Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP) and Atomic Absorption (AA)

C1489 Specification for Lime Putty for Structural Purposes

3. Terminology

3.1 *Definitions*—For definitions of terms relating to hydrated lime, refer to Terminology C51.

4. Chemical Composition

4.1 Hydrated lime for finishing purposes shall conform to the following requirements as to chemical composition:

	Type N 95	Type S 95
Calcium and magnesium oxides (LOI-free basis), min, %		
Carbon dioxide (as-received basis), max, %		
If sample is taken at the place of manufacture	5	5
If sample is taken at any other place	7	7
Unhydrated oxides (as-received basis), max, %	...	8

5. Residue

5.1 The percentage residue of finishing hydrated lime shall conform to the following requirements:

Residue retained on 600-µm (No. 30) sieve, max, %	0.5
Residue retained on 75-µm (No. 200) sieve, max, %	15

6. Popping and Pitting

6.1 Finishing hydrated lime shall show no pops or pits when tested in accordance with the method prescribed in 10.1.2.

7. Plasticity

7.1 The putty made from Type N, normal finishing hydrated lime, shall have a plasticity figure of not less than 200 when soaked for a period of not less than 16 h nor more than 24 h.

7.2 The putty made from Type S, special finishing hydrated lime, shall have a plasticity figure of not less than 200 when tested commencing within 30 min after mixing with water.

8. Application of Interior Gypsum Plaster

8.1 For recommended application procedures refer to Specification C842.

*A Summary of Changes section appears at the end of this standard

9. Sampling, Inspection, and so forth

9.1 The sampling, inspection, rejection, retesting, packing, and marking shall be conducted in accordance with Methods **C50**.

10. Test Methods

10.1 The properties enumerated in this specification shall be determined in accordance with the following methods:

10.1.1 *Chemical Analysis*—Test Methods **C25** or, for total calcium and magnesium oxides, Test Methods **C1271** or **C1301**.

10.1.2 *Physical Tests*—Test Methods **C110**.

11. Package Marking

11.1 Type N hydrated lime, in bags, conforming to this specification, shall be soaked for a minimum of 16 h prior to use.

12. Keywords

12.1 finishing lime; masonry; plaster; plasticity; popping and pitting; residue; Type N; Type S; unhydrated oxides

SUMMARY OF CHANGES

Committee **C07.02** has identified the location of selected changes to this standard since the last issue (C206 – 03 (2009)) that may impact the use of this standard. (Approved Dec. 1, 2014.)

(1) Added Test Methods **C1271** and **C1301** to Section 2.

(2) Revised 4.1, 5.1, and 10.1.1.

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Standard Specification for Mortars for the Repair of Historic Masonry¹

This standard is issued under the fixed designation C1713; 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 mortar for the repair of masonry that was constructed with methods and materials that pre-date the origination of current standards of construction that are compatible with it. The mortar may be used for non-structural purposes such as repointing of the masonry, or for structural purposes such as, but not restricted to, reconstruction or repair of mortar joints that contribute to the structural integrity of the masonry.

1.2 Masonry includes the following units laid in mortar: (1) cast stone, (2) clay masonry units/brick and clay tile, (3) concrete masonry units, (4) natural stone, and (5) terra cotta.

1.3 This specification may be used to pre-qualify mortar for a project.

1.4 Mortars tested using this specification are laboratory-prepared mortars and do not represent in-place, site mortars.

1.5 Use of this specification should be based on a thorough understanding of the function, maintenance, and repair requirements for the preservation and continued performance of the masonry in the context of the building structure and long-term performance. The user of this specification is responsible for examining all criteria and selecting the appropriate mortar formulation and properties required.

1.6 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

¹ This specification is under the jurisdiction of ASTM Committee C12 on Mortars and Grouts for Unit Masonry and is the direct responsibility of Subcommittee C12.03 on Specifications for Mortars.

Current edition approved Dec. 1, 2015. Published January 2016. Originally approved in 2010. Last previous edition approved in 2012 as C1713 – 12. DOI: 10.1520/C1713-15.

2. Referenced Documents

2.1 ASTM Standards:²

- C5 Specification for Quicklime for Structural Purposes
- C10 Specification for Natural Cement
- C61 Specification for Gypsum Keene's Cement
- C91 Specification for Masonry Cement
- C109/C109M Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)
- C110 Test Methods for Physical Testing of Quicklime, Hydrated Lime, and Limestone
- C136 Test Method for Sieve Analysis of Fine and Coarse Aggregates
- C141 Specification for Hydraulic Hydrated Lime for Structural Purposes
- C144 Specification for Aggregate for Masonry Mortar
- C150 Specification for Portland Cement
- C207 Specification for Hydrated Lime for Masonry Purposes
- C216 Specification for Facing Brick (Solid Masonry Units Made from Clay or Shale)
- C270 Specification for Mortar for Unit Masonry
- C305 Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency
- C511 Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes
- C595 Specification for Blended Hydraulic Cements
- C780 Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry
- C948 Test Method for Dry and Wet Bulk Density, Water Absorption, and Apparent Porosity of Thin Sections of Glass-Fiber Reinforced Concrete
- C979 Specification for Pigments for Integrally Colored Concrete
- C1072 Test Methods for Measurement of Masonry Flexural Bond Strength

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.

[C1093 Practice for Accreditation of Testing Agencies for Masonry](#)
[C1157 Performance Specification for Hydraulic Cement](#)
[C1180 Terminology of Mortar and Grout for Unit Masonry](#)
[C1329 Specification for Mortar Cement](#)
[C1384 Specification for Admixtures for Masonry Mortars](#)
[C1400 Guide for Reduction of Efflorescence Potential in New Masonry Walls](#)
[C1403 Test Method for Rate of Water Absorption of Masonry Mortars](#)
[C1489 Specification for Lime Putty for Structural Purposes](#)
[C1506 Test Method for Water Retention of Hydraulic Cement-Based Mortars and Plasters](#)
[C1707 Specification for Pozzolanic Hydraulic Lime for Structural Purposes](#)
[E96/E96M Test Methods for Water Vapor Transmission of Materials](#)
[E2260 Guide for Repointing \(Tuckpointing\) Historic Masonry](#)

3. Terminology

3.1 The terms used in this specification are identified in Terminology [C1180](#).

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *aggregate, n*—material as defined in Terminology [C1180](#), but limited to the material groups listed under Section 4 of this specification.

3.2.2 *binder, n*—material as defined in Terminology [C1180](#), but limited to the cementitious material groups listed under Section 4 of this specification to be mixed with potable water.

3.2.3 *curing, n*—process by which a mortar gains its long-term, final-state properties.

3.2.4 *curing time (CT), n*—number of days in which a hardened state sample is cured before testing.

3.2.5 *historic masonry, n*—masonry that may have been constructed with methods and materials that pre-date the origination of current standards.

3.3 *Properties*, as determined by Section 8 of this specification:

3.3.1 *absorption rate (AR), n*—a measure of the hardened mortar's ability to absorb water from a dry condition, measured as the initial flow of water into the mortar, as defined under Test Method [C1403](#) and evaluated at the specified curing time (CT).

3.3.2 *air content, n*—cumulative volume of air in a mortar, as a percentage of the total volume of mortar in its plastic state.

3.3.3 *flexural bond strength (FBS), n*—maximum flexural tensile stress that causes failure of the bond between the mortar and masonry unit in a tested assembly at the specified curing time (CT).

3.3.4 *maximum compressive strength (F_{cmx}), n*—upper allowable limit on the ultimate strength of a hardened mortar sample subjected to compression measured as force per unit area at the specified curing time (CT).

3.3.5 *minimum compressive strength (F_c), n*—lower allowable limit on the ultimate strength of a hardened mortar sample subjected to compression measured as force per unit area at the specified curing time (CT).

3.3.6 *total porosity, n*—volume percentage of all pores or void space in the mortar at the specified curing time (CT).

3.3.7 *water retention, n*—as defined in Terminology [C1180](#). Test shall be conducted on a sample in its plastic state.

3.3.8 *water vapor permeability (WVP), n*—ability of a mortar to pass water through it in vapor form at the specified curing time (CT).

4. Constituent Materials

4.1 *Binder Materials* shall be classified into the following groups:

4.1.1 *Group L*—Lime (non-hydraulic) shall conform to the following specifications:

4.1.1.1 Hydrated Lime shall conform to Specification [C207](#), Types S or SA. Types N and NA hydrated limes are permitted if soaked or shown by test or performance record to be not detrimental to the mortar.

4.1.1.2 Lime putty shall conform to Specification [C1489](#).

NOTE 1—Specification [C5](#), Appendix 1, may be used, and the resulting putty should meet the requirements of Specification [C1489](#).

4.1.2 *Group HL*—Hydraulic Lime shall conform to the following specifications:

4.1.2.1 *Hydraulic Hydrated Lime*—shall conform to Specification [C141](#).

4.1.2.2 *Pozzolanic Hydraulic Lime*—shall conform to Specification [C1707](#).

4.1.3 *Group HC*—Hydraulic Cements shall conform to the following specifications:

4.1.3.1 *Blended Hydraulic Cement*—shall conform to Specification [C595](#).

NOTE 2—Blended hydraulic cement may not be appropriate for structures built before the second half of the 20th century.

4.1.3.2 *Performance Hydraulic Cement*—shall conform to Specification [C1157](#).

NOTE 3—Performance hydraulic cement may not be appropriate for structures built before the second half of the 20th century.

4.1.3.3 *Masonry Cement*—shall conform to Specification [C91](#).

4.1.3.4 *Mortar Cement*—shall conform to Specification [C1329](#).

4.1.3.5 *Natural Cement*—shall conform to Specification [C10](#).

4.1.3.6 *Portland Cement*—shall conform to Specification [C150](#).

NOTE 4—For interior gypsum mortar based systems requiring gypsum cement refer to Specification [C61](#) and consult with the product manufacturer regarding exposure suitability.

4.2 *Aggregates*—Aggregate shall conform to Specification [C144](#). Aggregates that conform to all aspects of Specification [C144](#) except for the gradation limits are permitted if demonstrated by their history of performance under equivalent conditions and mortar formulation to be non-detrimental to the mortar. To determine aggregate gradation, use Test Method [C136](#).

NOTE 5—The need to aesthetically match the color and texture of an existing mortar may be justification for deviating from the gradation limits of Specification [C144](#).

4.3 *Water*—Water shall be clean and free of oils, acids, alkalis, salts, organic materials, or other substances that are deleterious to mortar or any metal used in the masonry.

4.4 *Admixtures*:

4.4.1 *Admixtures*—shall meet the requirements of Specification **C1384**. Calcium chloride is not permitted. Other admixtures that are outside the scope of Specification **C1384** are permitted if they contain no more than 0.3 % water-soluble alkali and if demonstrated by their history of performance under equivalent conditions and mortar formulation to be non-detrimental to the mortar and items in contact.

4.4.2 *Pigments*—Pigments shall meet the requirements of Specification **C979**. Pigments which are not described by Specification **C979** are permitted if demonstrated by their history of performance under equivalent conditions and mortar formulation to be non-detrimental to the mortar. Pigment addition shall not exceed 10 % by weight of the binder materials except for carbon black which is limited to 2 % unless otherwise demonstrated by history of performance under equivalent conditions and mortar formulation to be non-detrimental to the mortar.

5. Mortar Proportioning

5.1 *Binder/Aggregate Ratio*:

5.1.1 Combine the mortars in volume ratios of 1 part total binder materials to 2 to 3½ parts aggregate.

5.1.2 Mortars specified outside volume ratios of 1 part total binder materials to 2 to 3½ parts aggregate shall be permitted if shown by history of use or by mortar testing per this specification to be not detrimental to the mortar.

NOTE 6—Most common mortars have total binder to aggregate ratios of 1 part total cementitious materials to 2½ to 3 part aggregate, whereas some earlier mortars may have ratios as high as 1 to 1.

5.2 *Air Entraining Binders*—Air entraining binders shall not be used in combination with other air entraining binders or with a separate air entrainment admixture.

6. Requirements

6.1 *Establishing Mortar Proportions*:

6.1.1 Specify mortars by (1) proportion specification, constituent materials and their respective volume proportions, or (2) property specification, constituent materials (or proprietary products names) and required properties, in accordance with **Table 1**.

6.1.1.1 Specifiers using the proportion specification shall select binder and aggregate proportions based upon an established history of performance or testing that documents satisfactory performance of the combinations and proportions specified, and in conformance with Section 5 of this specification.

NOTE 7—WVP of the mortar should be greater than that of the masonry units, and equal to or greater than that of the substrate mortar where present.

NOTE 8—Vapor permeability will generally decrease with increasing hydraulic constituents; however, aggregate gradation and admixtures can greatly influence the value.

7. Test Samples and Preparation

7.1 *Material Proportioning*—Laboratory mixed mortar specified by volume proportions shall contain the mortar

materials as indicated in the mortar specification. Volume proportions shall be converted to weights using the batch factor calculated as follows:

7.1.1 *Material Proportioning for Test Batches of Mortar*:

7.1.1.1 Batch factor = $1440 / [1280 \text{ kg/m}^3 \text{ (bulk density of aggregate) times total aggregate volume proportion}]$.

NOTE 9—A batch size using 1440 g of aggregate will typically result in enough mortar for water retention testing and one set of three 2-in. cubes for compressive strength testing. Several batches with the same water to binder ratio may be necessary to complete all tests.

7.1.1.2 Oven dry and cool to room temperature all aggregate used for test mortars. Mortars preblended with aggregate require no proportioning.

7.1.2 Constituent materials shall have the bulk densities as noted in **Table 2**.

7.2 *Masonry Units for Use in Water Vapor Permeability and Bond Strength*—Masonry units shall be the actual masonry units to be used in the field, or if unavailable, a brick meeting Specification **C216**, Grade SW with absorption properties similar to the in-situ masonry units, if known.

7.3 *Mortar Mixing*—Mix the mortar in accordance with Practice **C305** with the exception that for Group L and Group HL mortars and those combined mortars at or greater than 45 % lime by binder volume the initial mixing time is extended to 1 min and the resting time is extended to 1.5 min.

NOTE 10—These time extensions allow for the full wetting of the mortar constituents.

7.4 *Test Sample Molding*:

7.4.1 For total porosity, absorption rate and compressive strength testing, mold the 2-in. (50 mm) cubes in accordance with Test Method **C109/C109M**, subsections on Specimen Molds and Molding Test Specimens. For mortars to be used as unit bedding, add enough water to obtain flow of $110 \pm 5 \%$. For mortars to be used as repointing mortars, add enough water to obtain a Vicat Cone Penetrometer value (Test Method **C780**, Annex A1, Consistency by Cone Penetration Test Method) of $15 \text{ mm} \pm 5 \%$.

7.4.2 For vapor transmission and bond strength testing mold the samples according to Test Method **C1072**, with the exception that for the vapor transmission the specimen is two brick, and cheese cloth is to be used as a bond break, and mortar is to have flow values of $120 \pm 5 \%$. If the binder material to aggregate volume ratio has not been specified, use a value of 1:3 binder to aggregate ratio measured by volume with sand meeting Specification **C144**.

7.5 *Sample Demolding*—**Table 3** summarizes the demolding time required for different binder combinations.

7.6 *Specimen Storage and Curing*—The storage and curing conditions in **Table 3** shall be maintained both before and after demolding, for the duration of the specified Curing Time (CT).

7.6.1 Test specimens stored at $70 \pm 5 \%$ RH shall be placed in a cabinet or environmental chamber where the relative humidity and ambient CO₂ level can be maintained and documented.

7.6.2 Test specimens stored at 100 % RH shall be placed in a moist room or cabinet following Specification **C511**.

TABLE 1 Specification Requirements

Requirement	Proportion Specification	Property Specification
<i>Water Retention (%)</i> —Water retention value shall not be less than 75 %.	Mandatory requirement for all mortar formulations in their plastic states	Mandatory requirement for all mortar formulations in their plastic states
<i>Air Content (%)</i> —When an air entraining admixture is used, the air content of the mortar shall not exceed 12 %, with the exceptions of mortar cement which shall not exceed 17 % and masonry cement mortar which shall not exceed 21 %.	Mandatory requirement for all mortar formulations	Mandatory requirement for all mortar formulations
<i>Curing Time (CT, days)</i> —Laboratory Test Samples shall be cured according to Section 7. The minimum CT for mortars with Group L and Group HL as binders, and those that combine Group HC with greater than or equal to 45 volume % Group L shall be 120 days. The minimum CT for mortars with Group HC as binder and those that combined Group HC with Group L with less than 45 volume % Group L shall be 28 days. Longer CTs or multiple CTs may be required at the discretion of the specifier. The above is for Laboratory Sample Testing Only.	Mandatory minimum curing requirement for all hardened state mortar test samples	Mandatory minimum curing requirement for all hardened state mortar test samples
<i>Total Porosity (TP, %)</i> —Where a target value has been established by the specifier or the manufacturer, the total porosity % shall not range more than 0.75 to 1.25 times the target value.	Report if specified.	Mandatory if specified. Previously determined TP values obtained using this specification within the last five years from at least five same mortar formulations are permitted to be used.
<i>Water Vapor Permeability (WVP, perms)</i> —Where a target value has been established by the specifier or the manufacturer the water vapor permeability value shall not range more than $\pm 25\%$ of the target value.	Report if specified.	Mandatory to report. Previously determined WVP values obtained under this specification within the last five years for at least five samples from the same mortar formulation are permitted to be used.
<i>Minimum Compressive Strength (Fc, psi)^A</i>	Report if specified.	Mandatory requirement.
<i>Maximum Compressive Strength (Fcmx, psi)</i> —Where needed to establish material quality control. Where minimum compressive strength is specified, the value shall not be more than $100 \pm 20\%$ greater than the minimum compressive strength. ^B	Report if specified.	Mandatory if specified.
<i>Flexural Bond Strength (FBS, psi)</i> —Where bond strength of the mortar to masonry unit is critical. In mortars containing more than 50 % of Group HC binder, the FBS average shall be not less than 29 psi.	Report if specified.	Mandatory if specified.
<i>Absorption Rate (AR, g/min/30 in.²)</i> , shall be appropriate for the masonry units employed.	Report if specified.	Mandatory if specified.

^A This property can be critical to physical compatibility with the surrounding construction, and the structural safety and/or stability of the system.

^B This property can be critical to physical compatibility with the surrounding construction, as limited by structural safety and/or stability of the system.

TABLE 2 Bulk Density of Constituent Materials

Binder	Material	Bulk Density
Group L	Hydrated Lime	40 pcf (640 kg/m ³)
	Lime Putty	80 pcf (1280 kg/m ³)
Group HL	Hydrated Hydraulic Lime	Obtain from bag or manufacturer
Group HC	Portland Cement	Obtain from bag or manufacturer
	Masonry Cement	Obtain from bag or manufacturer
	Mortar Cement	Obtain from bag or manufacturer
	Natural Cement	Obtain from bag or manufacturer
	Blended Hydraulic Cement	Obtain from manufacturer
	Hydraulic Cement	Obtain from manufacturer
Pre-blended binder	Any or all of the above Aggregate	Obtain from manufacturer 80 pcf

TABLE 3 Storage Time in Molds

Binder Type	Time in Molds	Specimen Storage Conditions
Group L and Group HL only and combined mortars with 45 % or more lime by binder volume	Minimum 5 days or until the sample is sufficiently stable to demold	70 ± 5 % RH for Group L 90 ± 5 % RH for Group HL
Group HC only and combined mortars with less than 45 % lime by binder volume	2 to 5 days as needed	100 % RH

8. Test Methods

8.1 *Water Retention*—Determine water retention in accordance with the Test Method **C1506**.

NOTE 11—Water retention cannot be determined for repointing mortars at low flow values. Enough water must be added to obtain a flow of 110 ± 5 %.

8.2 *Air Content*—Determine air content in accordance with Specification **C270** or with the air meter technique of Test Method **C110**.

8.3 *Total Porosity*—determine total porosity in accordance with Test Method **C948**, on a set of three 2-in. samples.

8.4 *Absorption Rate*—determine absorption rate in accordance with Test Method **C1403** using three 2-in. cubes, performing weight measurements at 1 and 3 min in addition to the times specified therein, with reported units converted to g/min/30 in.².

8.5 *Water Vapor Permeability*—determine in accordance with Test Method **E96/E96M**. The mortar shall be prepared according to **7.3**. At the time of testing, samples will be cut to fit over a testing cup measuring 50 ± 2.5 mm on a side, in a manner so as not to adversely affect the result.

8.6 *Compressive Strength*—determine in accordance with Test Method **C109/C109M** (using 2-in. or 50-mm cube

specimens), except that samples shall be cured in accordance with **7.6** of this specification.

8.7 *Flexural Bond Strength*—determine in accordance with Test Method **C1072** using masonry units as described in **7.2**. Assembly shall be cured in accordance with **7.6** of this specification.

9. Quality Assurance

9.1 Compliance of volume specified mortars to this specification shall be verified by:

9.1.1 Confirmation that the materials in Section 4 of this specification are used shall be verified by letters of certification or mill reports from the manufacturer.

9.1.2 Proportions of material shall be verified by weigh scale certificates or described procedures for proportioning and mixing the approved materials.

NOTE 12—The testing laboratories performing the testing specified herein should be evaluated in accordance with Practice **C1093**.

10. Keywords

10.1 absorption rate; air content; compressive strength; flexural bond strength; hydrated lime; hydraulic cement; hydraulic lime; lime putty; masonry; natural cement; portland cement masonry cement; preservation; repointing; total porosity; water retention; water vapor permeability

APPENDIXES

(Nonmandatory Information)

X1. EVALUATION, SELECTION AND USE OF MORTAR FOR REPAIR OF HISTORIC MASONRY

X1.1 *Scope*—This specification covers mortar for the repair of masonry that was constructed with methods and materials that pre-date the origination of current standards of construction. The mortar may be used for non-structural purposes such as repointing of the masonry, or for structural purposes such as, but not restricted to, reconstruction or repair of mortar joints that contribute to the structural integrity of the masonry. This appendix is a guide to the use of this specification and provides additional information for use in evaluating and specifying mortars for the repair of historic masonry. Repeated reference is made to the Appendix X1 of Specification **C270**, which provides nonmandatory information that can be used as a supplement to this appendix. The reader is encouraged to read all of Appendix X1 and X2 in Specification **C270** as well as the other appendices in Specification **C270** as they will provide

helpful information beyond what is specifically referenced herein.

X1.2 *Significance and Use*—Masonry mortar is a versatile material capable of satisfying a variety of diverse requirements and significantly influences the performance of the masonry assembly as a whole. In the repair of existing masonry, it is critical that the mortar being used in the repair is both aesthetically and physically compatible with the existing mortar, as well as the masonry assembly as a whole. In many cases, this may be achieved with nearly equal success by a variety of different mortar types that all satisfy the same requirements. A thorough understanding of both existing mortar materials and those used in the repair and their properties, and their relation to the historic masonry assembly being

repaired will enable selection of a mortar that will perform satisfactorily.

X1.3 *Specifying Mortars for Repair of Historic Masonry:*

X1.3.1 *Understanding the Existing Masonry Assembly and Functional Requirements of Mortar for Repair*—In order to properly specify a mortar that is appropriate for the repair of an historic masonry assembly, the user of this specification (specifier) must first understand the materials and functional requirements of the existing masonry assembly, the way in which the assembly has and will behave, how well it has performed, and how appropriate the existing mortar and masonry units have been for the assembly's usage requirements and environment. Based upon this understanding, the specifier must then determine what materials and mortar properties are most appropriate for the mortar that will be used for the repairs.

X1.3.2 *Proportion vs. Property Specification*—This specification provides two ways of specifying mortars: (1) by proportion and (2) by property, whichever better suits the requirements of the work. The specifier may also designate or restrict allowed material types to be used in a property-specified mortar, and require verification of expected properties on a proportion-specified mortar. In all cases, the proportion-specifier must have a thorough understanding of the available materials, which include binders (cementitious materials), aggregate, water and sometimes admixtures, and their role in the mortar properties that will result. The property-specifier must have a thorough understanding of the properties that are required, as well as the properties that can be achieved with the available materials. The specifier is cautioned not to intermix the requirements of the proportion specification and the property specification in such a way as creates unachievable requirements for given formulations, but must rather, base the use of all overlapping requirements on a thorough understanding of the properties that will result from the specified proportions.

X1.3.3 *Proportion Specification* can be useful for projects where manufactured property-specified mortars are not available or may not best suit the requirements of the work, or where the size of the project is such that it is not expedient for a contractor or manufacturer to produce a pre-tested, prequalified mortar for the specific requirements of the job, as well as in cases where mortar formulations have been developed by the specifier for mixing on site.

NOTE X1.1—It is the intent of this specification to encourage the growth of a public domain repository of mortar formulations and their correlated properties that will be helpful in guiding the process for selection of mortar formulations that must satisfy the specific needs of the project.

X1.3.3.1 *Examples of Proportion Specification*—When using proportion specification, the specifier must list the constituent materials in the mortar with their relative proportions by volume. For example:

“Mortar A and its constituents shall meet the requirements of ASTM C1713, and shall consist of 1 part portland cement, 3 parts hydrated lime and 12 parts bulked sand by volume.”

or:

“Mortar B and its constituents shall meet the requirements of ASTM C1713 and shall consist of 2 parts natural cement, 1 part hydrated lime and 7 parts bulked sand by volume with an air content of 8 % plus or minus 2 %.”

or:

“Mortar C and its constituents shall meet the requirements of ASTM C1713, and shall consist of 2 parts lime putty and 5 parts bulked sand by weight.”

X1.3.3.2 Additional requirements can be put into the specification regarding sand gradation, additives and pigments for exposed applications, such as:

“For architecturally exposed mortar, the aggregate type and gradation shall match the existing exposed original mortar sand and, where necessary, mineral oxide pigments may be added by up to ten percent by weight of binder to adjust the paste color to match the original.”

X1.3.3.3 The specifier may also require certain properties to be attained or reported as verification of the formulation (but must allow a mechanism for adjustment of the proportions in order to meet required properties if the original formulation does not), such as:

“Mortar A shall have an Fc of 750 psi and an Fomx of 1500 psi subject to verification by test in accordance with ASTM C1713. Constituent proportions may be adjusted by up to 25 percent to meet these property requirements, but only with written authorization of the [specifier].”

or:

“The water vapor permeability (WVP) of Mortars B and C shall be determined in accordance with ASTM C1713 and shall be reported in writing.”

X1.3.4 *Property Specification* can be useful in projects where pre-blended mortars are available to suit the requirements of the work, or where the size of the project is such that it is expedient for a manufacturer or contractor to produce a pre-tested, prequalified mortar for the specific requirements of the job, as well as cases where the performance requirements of the project are so critical that the specific property requirements drive the design.

X1.3.4.1 *Example of Property Specification*—When using property specification, the specifier should state the allowed constituent types but not the proportions, leaving the determination of proportions to the contractor or manufacturer, to be verified by test (tests shall be batch specific in the case of custom designed mortars or where permitted from previous

tests within the last five years for pre-manufactured pre-blended standardized mortars). For example:

“Mortar A and its constituents shall meet the requirements of ASTM C1713, and shall consist of a mix of Group HC and L binders and sand with the following properties as determined in accordance with ASTM C1713 at the required CT: air content of 8 % plus or minus 2 %, $F_c=750$ psi, $F_{cmx}=1500$ psi. The WVP shall be determined in accordance with ASTM C1713 and shall be reported in writing.”

or, if more specificity is desired:

“Mortar B and its constituents shall meet the requirements of ASTM C1713 and shall consist of a mix of natural cement and hydrated lime binders and sand following properties as determined in accordance with ASTM C1713 at the required CT: $F_c=2500$ psi, $FBS>50$ psi. The WVP shall be determined in accordance with ASTM C1713 and shall be reported in writing.”

or:

“Mortar C and its constituents shall meet the requirements of ASTM C1713 and shall consist of a mix of lime putty and sand with an F_c of 350 psi as determined in accordance with ASTM C1713 at the required CT. The WVP shall be determined in accordance with ASTM C1713 and shall be reported in writing.”

X1.3.4.2 Additional requirements can be put into the specification regarding sand gradation, additives and pigments for exposed applications, such as:

“For architecturally exposed mortar, the aggregate type gradation shall match that of the existing exposed original mortar and where necessary, up to 10 percent mineral oxide pigment may be added to adjust the paste color to match the original.”

X1.3.5 *Binder Materials and Historical Context*—The specification allows a wide range of binder materials because of the many time periods of construction it covers. Lime putty and, to a lesser extent, clay, hydraulic lime, and lime hydrate were the predominant binder materials used up until the mid-to late-19th century. Natural cement was first used in England in 1756 and then North America in 1818, and then became increasingly common throughout duration of the 19th century, particularly in large urban centers and in significant public works, transportation and industrial projects. Portland cement production began in England in the 1820s and began to be exported shortly thereafter, not being produced in North America until the 1870s. By the beginning of the 20th century, portland cement had gained market dominance, becoming one of the primary building materials of the modern industrialized world. Masonry cement was first introduced as a patented product in 1918 and generic masonry cements gained sufficient use in the marketplace to warrant issuing of ASTM , Tentative Specification for Masonry Cement in 1932. Much of this more recent, modern-era construction that was built during the first half of the 20th century, is now old enough that it too can be considered “historic”.

X1.3.6 *Differences in Curing Times* in the specification were developed to account for the differences between carbonation-curing, which takes place in Group L and to some extent HL binders, and hydration curing which takes place in Goup HC and HL binders. In simplistic terms, carbonation-curing generally starts from the exposed surface of a mortar and slowly works its way inward (requiring sample testing at up to 120 days), while hydration curing takes place from within (requiring sample testing at only 28 days).

X1.3.6.1 The curing times in hydrating laboratory samples are generally analogous to the curing times that might be experienced in the field, whereas curing times in carbonating samples are usually not analogous to field curing times, because the actual time that it takes to cure a carbonating mortar is dependent upon the mode and pathway of carbon transport from the atmosphere. For example, mortar that is in the core of a granite faced wall with tight joints will carbonate more slowly than the same mortar used in pointing the exposed surfaces of the joints because it takes longer for sufficient carbon to reach the wall’s core than the surface. Carbonation is promoted through repeated cycles of wet and dry where care is taken in the early stages to ensure the mortar is not allowed to completely dry out. The unit material, construction sequencing and joint detailing in a masonry assembly along with wetting and drying frequency of the completed work will affect the curing time. The geometric relationship of the mortar, the masonry units and the free air surface, however, will often have an even bigger effect on the in-situ curing time of the mortar, this being a function of the unexposed mortar volume multiplied by the distance from the surface divided by the surface-exposed area.

X1.4 *Function of Mortar in Historic Masonry Assemblies:*

X1.4.1 The purposes of mortar in historic masonry are to bond masonry units together, provide for load-bearing support, weather resistance, vapor transport, architectural expression, and constructability as an integral element having the desired functional performance characteristics. Mortar influences the performance of the assembly in many ways.

X1.4.2 *Functional Requirements*—A masonry assembly may be subjected to numerous external conditions under which it must successfully perform. These include structural loading, induced strains and forced displacements, environmental abrasion, wetting and drying, freezing and thawing, and salt transport. The ability of an historic masonry assembly to perform under these conditions must be maintained or, if needed improved, with the proper selection of materials that will be used in their repair.

X1.4.2.1 *Structural Loading* includes the combined weight of built-in, stationary elements (dead loads), and non-built-in often non-stationary elements (live loads) and the weight of the masonry itself. Moving structural loads, such as vehicles or swinging bells, can also cause dynamic impact live loads. Other structural live loads include wind forces, earthquake forces, and even in rare cases bomb blasts. The masonry assembly, of which mortar is a key component, must be sufficiently strong to support such loads without failure or excessive deformation. The minimum strength (F_c , F_{bs}) of the mortar must be adequate to properly stabilize and support the masonry units within the loaded assembly whereas the maximum strength (F_{cmx}) must be less than the units in order to maintain strain compatibility within the assembly (see X1.4.2.2). Generally, mortars with greater quantities of group HC binder materials have higher compressive strengths than those without. Bond strength is a property of mortars in combination with masonry units. Selection and combination of

mortar binders can significantly affect bond strength (FBS), however this is also a function of workability, water retentivity, air content, workmanship, curing, and unit properties. Reference may also be made to Appendix X1 of Specification C270, which provides additional information that is useful in understanding the development of strength properties in portland cement and hydrated lime-based mortars.

X1.4.2.2 Induced Strains and Forced Displacements—can be caused by heating and cooling cycles where the masonry thermally expands and contracts, as well as moisture growth where some types of masonry units expand upon absorbing water. Strains and forced displacements can also be caused by external structural influences such as lintel deflections, foundation settlements and rust jacking. A masonry assembly will deform elastically until a level of deformation is reached where either plastic yielding occurs, or the assembly fails and a crack is formed. Both the mortar and the masonry units undergo elastic deformation, however when elastic limits are exceeded, then the weaker of the two materials responds. Mortar, the more easily replaceable component, is the preferred sacrificial respondent and must be weaker than the masonry units for this to occur. At equal binder-to-aggregate ratios, lower strength mortars, such as those containing greater amounts of Group L binders, have lower moduli of elasticity, exhibit greater plastic flow, and are therefore more flexible and able to deform plastically than those with higher concentrations of Group HC binders. The properties of mortars with Group HL binders fall in between. When the mortar can no longer deform plastically and a crack occurs, this crack may be within the mortar (joint failure), between the mortar and the masonry unit (bond failure), or through the masonry unit (unit failure). Upper limits on maximum compressive strength (F_{mx}) help prevent unit failure from occurring. Optimization of flexural bond strength (FBS) helps the masonry assembly withstand higher tensile stress without premature bond failure. Extensibility is the maximum unit tensile strain just prior to rupture, indicative of the maximum elongation under tensile forces, and is discussed in Appendix X1 of Specification C270. Depending upon the location and geometry, where joint failure does occur, hydrated lime provided by Group L and HL binders or released during hydration of Group HC binders can sometimes autogenously heal hairline cracks as the lime migrates to the crack location and carbonates.

X1.4.2.3 Environmental Abrasion occurs where wind, water flow, or other environmental dynamics tend to wear away the surface of the masonry. In such cases a harder mortar, such as one containing higher amounts of Group HC binders and the stronger of the HL binders, will be more resistant than mortars with lesser amounts of the same.

X1.4.2.4 Wetting and Drying occurs during normal weather cycles, rising dampness and day-to-day functioning of a building. Unlike modern building assemblies, which are designed as impenetrable barriers to water, historic masonry assemblies were intended to depend upon their mass to protect the interiors of structures, as they would absorb and store water that entered them before it could reach the interiors, and then allow the water to drain and evaporate out before the next wetting. The assembly must be able to dry in order to have

storage capacity for the next cycle of wetting; and it is usually critical that most of this take place through the mortar joints. Maintaining the ability for sufficient drainage and evaporation through porosity and water vapor permeability (WVP) is thus necessary for the success of the masonry assembly and protection of the structures' interior. Mortars that have greater concentrations of Group L and HL binders tend to higher porosity and WVP.

X1.4.2.5 Freezing and Thawing—Damage can occur when expansive forces induced by absorbed water turning to ice exerts pressure within the masonry assembly; and after many ratcheting cycles can begin to cause cracks. Effective drying of the masonry assembly (described in X1.4.2.4) helps minimize the volume of water that can freeze within it. When air entrained mortars are used, the entrained air bubbles in the mortar help give expanding water a place to go.

X1.4.2.6 Salt Transport—occurs when there is a flow of water through the mortar created by the wetting and drying process, and dissolved solids, such as salts, are transported in solution within the water. These solids can come from contaminated rainwater runoff or salt-spray, from wicking groundwater or seawater, or even from the masonry itself. When this water evaporates at the surface of the masonry mass, salts are deposited on the surface and evidence themselves as efflorescence. When this water evaporates under the surface of the masonry, damage can occur through cryptoflorescence, where expanding crystals form within the outer shell of the masonry and cause it to unavoidably flake off. It is generally helpful to protect masonry assemblies from environment conditions that can inundate them with salts. Given the fact that there are some situations where the transport of soluble compounds is unavoidable, it is critical that the mortar, which is intended to be replaceable, act sacrificially to the masonry units, which are not. A higher water vapor transmission rate (WVT) in the mortar compared to the masonry units will channel the evaporating water through the joints; and a lower strength (F_{cmx} , FBS) of the mortar than the units will allow the mortar to spall without damaging the units. Air entrainment within the mortar mass will postpone surface mortar failure by giving the solids, at least for a while, a place to grow. In cases of significant flow, efflorescing salts can also come from within the masonry assembly. This effect is reduced with lower alkali contents in the binder constituents. Refer to Guide C1400 as well as Appendix X2 in Specification C270 for additional information.

X1.4.3 Constructability—A masonry assembly must be readily constructible within the limits of time, economy and scale. Earlier mortars containing primarily Group L-based binders and to a lesser extent Group HL binders had limited strength and took a long time to cure. This limited the heights and spans of structures that could feasibly be built, both due to the resulting lower strengths of the masonry assemblies, and the impractical timeframe that would be required in more heavily loaded construction. The development of Group HC binders during the 19th century allowed for larger and higher strength construction which could be built with ever increasing speed.

X1.4.4 *Workability* is the degree by which the physical properties of a mortar in its plastic state aid or hinder the efficiency or quality of the work, and is determined by the binder and aggregate combinations and ratios, the aggregate type and gradation, and the water content. Appendix X1 in **C270** provides additional helpful information regarding workability as well as other plastic properties.

X1.4.5 *Architectural Integrity*—Until the Modern Era of the late 20th century, mass masonry served as both the structure and the architectural feature, with many structural components such as flying buttresses, pinnacles, and arches performing critical load-carrying functions while at the same time serving as ornamental features. For example, during the mid-to-late 19th century pigments and multi-colored aggregates were often carefully blended to provide the desired aesthetic effects on exposed surfaces of mortar joints that were part of structural load carrying elements, sometimes with two intentionally distinct colors appearing in the same inter-unit joint. The aesthetic and environmental demands that were placed upon historic masonry assemblies were specific to each structure’s developmental and architectural time period and locality.

X1.5 *Selection and Function of Mortar for Repair of Historic Masonry:*

X1.5.1 Many historic materials that were used in the construction of masonry structures, such as natural and portland cement, hydrated lime and lime putty, hydraulic lime, and clay are presently available in the market today in replicated form, and many of these have ASTM specifications. Mortar used for the repair of historic masonry is typically used for re-setting masonry units or for repointing joints, and often for both simultaneously. Rebuilding is done using basically the same methods that the original builders used, methods that are still used today; and repointing should be done as described in Guide **E2260**. Beyond aesthetics and in-situ performance, application methods, curing requirements, environmental conditions, and speed of construction will be affected by the mortar selection.

X1.5.2 *Selection of Mortar for Repair*—Mortar that is used for the repair of historic masonry should (1) be functionally compatible with the existing masonry assembly and maintain or improve the longevity and performance of the assembly, (2) be aesthetically appropriate and consistent with the existing mortar, (3) have the ability to be installed properly and within the timeframe available for the work, and (4) where possible, be authentic to the history of the structure.

X1.5.3 *Functional Compatibility*—When selecting the most appropriate mortar for a repair, there is the option of simply using the same formulation as the original or the option of matching all of the properties of the original mortar that was used. In the case of existing masonry that has performed poorly or prematurely failed, there also is the need to investigate the cause of the failure, and to consider improving upon the properties of the original mortar in order to enhance the longevity and performance of the assembly. Every historic structure has its own history of performance, and most older structures that still survive do so either because they were

appropriately constructed and performed well, or because they served an important function and were painstakingly repaired and maintained, or maybe a combination of both. Just because an historic masonry structure exists does not mean that it was necessarily the most suited for the conditions that it has endured. The best way to evaluate the level appropriateness of an existing structure or assembly is to evaluate how successfully it has performed or how often it needed to be repaired.

X1.5.3.1 *Matching Formulations*—Many in the preservation field believe that simply using the same materials as the original is the best way to ensure compatibility and continued successful performance of a well-performing masonry assembly. Although this is logically consistent, the reality is that materials produced today may not have the same performance characteristics as the original materials they are trying to match. The specifier should be aware of and understand these differences and the effects they will have on the masonry assembly, and may need to deviate from the historical proportions accordingly.

X1.5.3.2 *Matching Properties*—Matching the properties of the existing mortar is an effective way of maintaining the same level of performance of a successfully performing assembly. This specification was written so that the tested hardened mortar properties listed in Table 1 can also be applied to the evaluation of the existing mortar, with the intent of allowing comparison. The specifier should be cautioned, however, regarding the potential for deviations in test results between in-situ or retrieved specimens, and laboratory specimens that are indirectly representative of mortars that will be used and cured in the field. While every attempt should be made to reduce these deviations as much as possible through effective sampling and testing techniques, some level of deviation will always exist.

X1.5.3.3 *Improving Properties*—The prospect of successfully “improving” properties of mortar to enhance the performance of the assembly should be tempered with the caution that the specifier should be certain which specific properties actually need to be improved and the consequences of doing so. One classic example was the predominant use of intentionally dense and impervious pointing mortars starting the early to mid-20th century. Common knowledge at the time was that these “improved” mortars would prevent water from entering the masonry; however the reality was that water entered the masonry anyway but could not evaporate back out, resulting in damage.

X1.5.4 *Aesthetic Appropriateness*—Mortar used in the repair of exposed masonry must be aesthetically appropriate for the application. Most commonly, this means color- and texture-matching an existing mortar. In the case of complete repointing or reconstruction this would typically mean matching the original. In the case of partial repointing or rebuilding of elements that were earlier repointed with a non-matching mortar, the difficult decision must be made as to whether it is better to match the inappropriate repointing mortar so that repairs are less visible or to match the original mortar so the historical integrity of the work is maintained but repairs stand out. Also, there are many cases where the historic mortars’ pigments and aggregate gradations that did not fall within the

limits of currently accepted standards. Such deviations as replicated in the mortar for repairs may be acceptable per this specification as long as it can be demonstrated that the original in-situ mortar performed satisfactorily.

X1.5.5 Ease and Speed of Construction—Appropriate plastic properties are critical to ensuring high quality results in the repair work, along with stiffening time and strength gain, which determine how quickly the work can be considered serviceable. Much of the work involving the repair of historic masonry is done in a retrofit situation where the work schedule is driven by the fact that an existing structure has been opened or partially dismantled while in service or temporarily out of service, and needs to be restored to a fully functioning condition as quickly as possible. In the case of structural repairs, there may be damage at the bottom of a structure that requires reconstruction while the upper portion of the structure is still bearing upon it. This can require that the work is done in a sequential, multi-step process and that the work reach its required strength before the next sequential operation is started. In these cases the more rapid strength development ability of mortar with Group HC binders and to a lesser extent Group HL binders, must be weighed against other requirements affecting the selection of mortar.

X1.6 Important Properties of Mortar for Repair of Historic Masonry:

X1.6.1 Plastic Properties per this Specification include curing time, air content and water retention.

X1.6.1.1 Curing Time determines how soon mortar samples can be tested but also affects how quickly mortar can be put into service. The specifier should be cautioned that in mortars with Group L, and to a lesser extent HL binders, the amount of time for an in-place mortar to be considered fully cured will relate to but not be the same as the minimum CT values given in **Table 1**, with pointing applications sometimes close but re-setting applications usually longer.

X1.6.1.2 Air Content is measured while the mortar is in its plastic state. It will ultimately affect the ability of the mortar to withstand freezing and thawing cycles and cryptofluorescing salts, and improves workability. Excessive air content in mortar may lead to decreased compressive strength.

X1.6.1.3 Water Retention is the ability of a mortar to retain mixing water when subject to the “suction” of a masonry unit,

which is the capillary action in masonry units that draws water out of the freshly placed mortar. Appendix X1 in Specification **C270** provides additional helpful information on this subject.

X1.6.2 Other Plastic Properties to Consider include workability, flow, water retentivity, and stiffening characteristics will all affect the quality of the construction, and are discussed in Appendix X1 of Specification **C270**.

X1.6.3 Hardened Properties per this Specification include total porosity, water vapor permeability (WVP), minimum compressive strength (F_c), maximum compressive strength (F_{cmx}), flexural bond strength (FBS) and absorption rate (AR).

X1.6.3.1 Total Porosity and Absorption reflect the mortar’s ability to absorb, hold and release water. These properties in a mortar used for repair should be equivalent to or greater than those of the existing mortar, and greater than that of the masonry units.

X1.6.3.2 Water Vapor Permeability is the ability of the mortar to allow water vapor transport. This property in a mortar used for repair should be equivalent to or greater than that of the existing mortar, and greater than that of the masonry units.

X1.6.3.3 Minimum Compressive Strength is the lower allowable limit to be placed on a mortar and directly contributes, along with unit strength, to the strength of the masonry assembly, which must be able to support required loads within code-mandated factors of safety.

X1.6.3.4 Maximum Compressive Strength is the upper allowable limit on compressive strength of the mortar. This should always be less than the strength of the masonry units to ensure that the mortar sacrificially fails before the masonry units.

X1.6.3.5 Flexural Bond Strength is a good indicator of the bond strength between mortar and a masonry unit and is usually less than the internal tensile strength of the mortar, and therefore a safe measure of the perpendicular-to-plane tensile strength of the mortar joint. This value should always be less than the tensile strength of the masonry units.

X1.6.3.6 Absorption Rate is the affinity of a mortar to take up water during wetting cycles and should be appropriate for the masonry units.

X1.6.4 Other Hardened Properties to Consider include extensibility, plastic flow, and durability are discussed in Appendix X1 of Specification **C270**.

X2. SAMPLING, LABORATORY TESTING AND USE

X2.1 It is the intent of the task group to write a second Appendix to this specification with the purpose of providing supplemental guidance for testing and evaluation of new and existing mortars, and later to provide an Annex with public domain target values of common mortar formulations to act as a guideline for use.

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Standard Specification for Aggregate for Masonry Mortar¹

This standard is issued under the fixed designation C144; 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.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 This specification covers aggregate for use in masonry mortar.

1.2 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.3 The following precautionary caveat pertains only to the test methods portion, Section 7, of this standard. *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*²

- [C40 Test Method for Organic Impurities in Fine Aggregates for Concrete](#)
- [C87 Test Method for Effect of Organic Impurities in Fine Aggregate on Strength of Mortar](#)
- [C88 Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate](#)
- [C117 Test Method for Materials Finer than 75-µm \(No. 200\) Sieve in Mineral Aggregates by Washing](#)
- [C123 Test Method for Lightweight Particles in Aggregate](#)
- [C128 Test Method for Density, Relative Density \(Specific Gravity\), and Absorption of Fine Aggregate](#)
- [C136 Test Method for Sieve Analysis of Fine and Coarse Aggregates](#)
- [C142 Test Method for Clay Lumps and Friable Particles in Aggregates](#)

¹ This specification is under the jurisdiction of ASTM Committee C12 on Mortars and Grouts for Unit Masonry and is the direct responsibility of Subcommittee C12.04 on Specifications for Aggregates for Mortars.

Current edition approved July 1, 2011. Published July 2011. Originally approved in 1939. Last previous edition approved in 2004 as C144–04. DOI: 10.1520/C0144-11.

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.

- [C270 Specification for Mortar for Unit Masonry](#)
- [C404 Specification for Aggregates for Masonry Grout](#)
- [D75 Practice for Sampling Aggregates](#)

3. Materials and Manufacture

3.1 Aggregate for use in masonry mortar shall consist of natural sand or manufactured sand. Manufactured sand is the product obtained by crushing stone, gravel, or air-cooled iron blast-furnace slag specially processed to ensure suitable gradation.

NOTE 1—Care should be taken to ensure a suitable particle shape, since excessive quantities of flat and elongated particles have historically caused problems with workability.

4. Grading

4.1 Aggregate for use in masonry mortar shall be graded within the following limits, depending upon whether natural sand or manufactured sand is to be used:

Sieve Designation	Percent Passing	
	Natural Sand	Manufactured Sand
4.75-mm (No. 4)	100	100
2.36-mm (No. 8)	95 to 100	95 to 100
1.18-mm (No. 16)	70 to 100	70 to 100
600-µm (No. 30)	40 to 75	40 to 75
300-µm (No. 50)	10 to 35	20 to 40
150-µm (No. 100)	2 to 15	10 to 25
75-µm (No. 200)	0 to 5	0 to 10

4.2 The aggregate shall not have more than 50 % retained between any two consecutive sieves of those listed in 4.1 nor more than 25 % between 300-µm (No. 50) and the 150-µm (No. 100) sieve.

4.3 If the fineness modulus varies by more than 0.20 from the value assumed in selecting proportions for the mortar, the aggregate shall be rejected unless suitable adjustments are made in proportions to compensate for the change in grading.

NOTE 2—For heavy construction employing joints thicker than 12.5 mm (½ in.), a coarser aggregate may be desirable; for such work a fine aggregate conforming to Specification C404 is satisfactory.

4.4 When an aggregate fails the gradation limits specified in 4.1 and 4.2, its use is permitted provided the mortar can be prepared to comply with the aggregate ratio, water retention,

air content, and compressive strength requirements of the property specifications of Specification **C270**.

5. Composition

5.1 *Deleterious Substances*—The amount of deleterious substances in aggregate for masonry mortar, each determined on independent samples complying with the grading requirements of Section 4, shall not exceed the following:

Item	Maximum Permissible Weight Percent
Friable particles	1.0
Lightweight particles, floating on liquid having a specific gravity of 2.0	0.5 ^A

^A This requirement does not apply to blast-furnace slag aggregate.

5.2 Organic Impurities:

5.2.1 The aggregate shall be free of injurious amounts of organic impurities. Except as herein provided, aggregates subjected to the test for organic impurities and producing a color darker than the standard shall be rejected.

5.2.2 Aggregate failing in the test may be used, provided that the discoloration is due principally to the presence of small quantities of coal, lignite, or similar discrete particles.

5.2.3 Aggregate failing in the test may be used provided that, when tested for the effect of organic impurities on strength of mortar, the relative strength at seven days calculated in accordance with the Procedure Section of Test Method **C87**, is not less than 95 %.

6. Soundness

6.1 Except as herein provided, aggregate subjected to five cycles of the soundness test shall show a loss, weighted in accordance with the grading of a sample complying with the

limitations set forth in Section 4, not greater than 10 % when sodium sulfate is used or 15 % when magnesium sulfate is used.

6.2 Aggregate failing to meet the requirements of 6.1 may be accepted, provided that mortar of comparable properties made from similar aggregates from the same source has been exposed to weathering, similar to that to be encountered, for a period of more than five years without appreciable disintegration.

7. Test Methods for Sampling and Testing

7.1 Sample and test the aggregate in accordance with the following standards, except as otherwise provided in this specification:

7.1.1 *Sampling*—Practice **D75**.

7.1.2 *Sieve Analysis and Fineness Modulus*—Method **C136**.

7.1.3 *Amount of Material Finer Than (75- μ m) No. 200 Sieve*—Test Method **C117**.

7.1.4 *Organic Impurities*—Test Method **C40**.

7.1.5 *Effect of Organic Impurities on Strength*—Test Method **C87**.

7.1.6 *Friable Particles*—Test Method **C142**.

7.1.7 *Lightweight Constituents*—Test Method **C123**.

7.1.8 *Soundness*—Test Method **C88**.

7.1.9 *Density*—Determine the density of the fine aggregate in accordance with Test Method **C128**. In calculating the air content of mortars, use the method described in Specification **C270**.

8. Keywords

8.1 aggregate; fine aggregate; masonry; mortar; sand; soundness

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