International Building Lime Symposium 2005
Orlando, Florida, March 9 -11, 2005

THE MOST IMPORTANT PROPERTY OF CEMENT-LIME MORTAR IN MASONRY CONSTRUCTION IS ….*

Michael Tate[1]

Abstract

Cement-lime (CL) mortar has a number of properties that are beneficial in masonry mortar applications. The most important property of this mortar type is dependent on the user and application. By varying the ratio of cement to lime, the characteristics of CL mortar can be adapted to specific mortar applications. This paper discusses those mortar properties that architects, contractors and owners consider important. For each of these properties, the influence of lime in the mortar is explored. Properties detailed in the paper include bond strength, compressive strength and workability. The flexibility of lime-based mortars to meet a wide range of needs in both new construction and restoration of masonry projects is demonstrated.

Keywords

hydrated lime, mortar, cement, Type S, masonry, bond strength, water penetration

---

[1] Michael J. Tate, Technical Manager, Research & Development, Graymont Inc., USA, mtate@graymont.com.

1 Introduction

Lime-based mortars have been used in building construction for thousands of years. In the 1800s, the development of natural and portland cements provided architects and contractors a range of new properties with which to work. Cement provided the early hardness to speed masonry projects. By varying the level of cement and lime, the workability and strength of mortars could be modified. This paper describes the rational basis for the use of cement-lime mortars in masonry applications today. First, a description will be provided of cement-lime mortars and how they are specified. Key properties of cement-lime mortar will then be discussed. Research used to identify these properties will also be identified and discussed.

2 What is a cement-lime mortar?

The ASTM Standard C270 (Standard Specification for Mortar for Unit Masonry) provides the basis for specifying mortars. Components of mortars permitted by this standard are:

- Cement – Though any of the following cement products can be used within C 270, most applications and research use portland cement:
  - Portland Cement – Type I, IA, II, IIA, III, or IIA of ASTM C 150
  - Blended Hydraulic Cements – Type IS, IS-A, IP, IP-A, I(PM), or I(PM)-A of ASTM C 595
  - Blended Hydraulic Cements – Type GU, HE, MS, HS, MH, or LH of ASTM C 1157
  - Slag Cement (For Use In Property Specifications Only) – Type S or SA of ASTM C 595
- Lime – Any of the following lime products can be used:
  - Hydrated Lime Type S or SA of ASTM C 207. Hydrated Lime Types N or NA are permitted if shown by test to be not detrimental to the soundness of mortar
  - Quicklime of ASTM C 5
  - Lime Putty of ASTM C 1489
- Masonry Cement of ASTM C 91
- Mortar Cement of ASTM C 1329
- Aggregates
  - Aggregates of ASTM C 144
- Water
  - Water shall be clean and free of amounts of oils, acids, alkalies, salts, organic materials, or other substances that are deleterious to mortar or any metal in the wall.

Three mortar products are allowed in ASTM C 270.

- Masonry cement is a blended product meeting the requirements of ASTM C 91. Though this product could contain lime, it normally contains cement, limestone and air-entrainment additives.
- Mortar cement is a blended product similar to masonry cement, but meeting the requirements of ASTM 1329. Mortar cement differs from masonry cement in the following ways:
  - Mortar cement is required to development minimum flexural bond strength, the magnitude of which depends upon the Type of the mortar.
  - The allowable air content in mortar cement is lower than air contents allowed for masonry cement.
  - Water-soluble alkali (0.03%) content is restricted in masonry cement, but is not restricted in the standard specification for mortar cement.
- The third type of mortar is cement-lime. The two components of cement-lime mortars have separate standards that specify chemical and physical characteristics. Standards for cement

focus on the ability of the cement to harden. Lime standards focus on insuring that the lime product will contribute to workability of the mortar. This paper explores the characteristics of cement-lime mortars.

ASTM C 270 contains five different mortar Types (Type K is listed in section X3 of the appendix), based on the strength of mortar needed for an application. The names for these mortar Types, developed in 1954, were derived from alternating letters of the words "**M**A**S**O**N** W**O**R**K**". Type M mortars have the highest compressive strength. Type K mortar has the lowest compressive strength and the highest percentage of lime.

ASTM C 270 provides both a proportion specification and a property specification for Types M, S, N and O mortars.

The **proportion specification** provides a recipe based on relative volumes of the constituent materials. For cement-lime mortars, the proportion specification will indicate the volume of cement followed by the volume of hydrated lime and finally the volume of sand. For example, a 1: ½:4-½ mix contains 1 cubic foot of cement plus ½ cubic foot of hydrated lime and 4-½ cubic feet of sand. For the purposes of determining volumes, ASTM C 270 provides typical bulk densities for cement, hydrated lime and sand. These densities are seen in Table 1. Table 2 details the recipes for each mortar type defined in ASTM C 270.

Table 1 Mortar Component Densities

Mortar Component	Bulk Density (lbs/ft^3)
Portland Cement	94
Blended Cement	Obtain From Manufacturer
Hydraulic Cement	Obtain From Manufacturer
Hydrated Lime	40
Lime Putty	80
Masons Sand	80

The **property specification** requires that the mortar exhibit certain characteristics when tested under laboratory conditions. As seen in Table 3, compressive strength, water retention and air content tests are required to be performed on the mortar mixed in the laboratory. Since jobsite water additions may not be the same as those in the laboratory, the properties of field-mixed mortar cannot be compared to the property requirements of ASTM C 270.

Table 2 ASTM C 270 Proportion Specifications

Mortar Type	Proportions by volume (cementitious materials)		Aggregate Ratio – Measured in damp, loose conditions
	Portland Cement	Hydrated Lime	
M	1	¼	Not less than 2 ¼ and not more than 3 times the sum of the separate volumes of cementitious materials
S	1	Over ¼ to ½	
N	1	Over ½ to 1 ¼	
O	1	Over 1 ¼ to 2 ½	

Cement-lime mortars should be specified by either the proportion or the property specification, but not by both. When neither the proportion or property specifications are specified, the proportion specifications govern.

3 Properties of cement-lime mortars

ASTM C 270 focuses on three masonry properties to define the quality of mortar: water retention, air content, and compressive strength. These parameters by themselves, however, present only a limited view of the characteristics of cement-lime mortar. Brown and Robinson (1986) write "The most rigorous mortar requirements are to provide adequate and uniform bond strength and to prevent wall leakage." Other parameters, such as workability of the mortar and durability are also important. Two

Table 3 ASTM C 270 Property Specifications[A]

Mortar Type	Average Compressive Strength at 28 Days (psi)	Water Retention (%)	Air Content max. %	Aggregate Ratio
M	2,500	75	12	Not less than 2 ¼ and not more than 3½ times the sum of the separate volumes of cementitious materials
S	1,500	75	12	
N	750	75	14[B]	
O	350	75	14[B]	

A – Laboratory-prepared mortar only
B – When structural reinforcement is incorporated in cement-lime mortar, the maximum air content shall be 12%.

types of properties should be considered. Plastic mortar properties pertain to the mortar from the time of mixing until it chemically hardens in the wall. Hardened mortar properties develop as the mortar cures after the initial chemical set. Both types of properties are important in determining the quality of the masonry application.

3.1 Plastic mortar properties

3.1.1 Workability (Plasticity)

One of the most important properties of plastic mortar is its workability. Lime is the primary contributor to workability of cement-lime mortars.

Quantifying the contribution of lime to mortar workability in the laboratory has proven to be difficult. After much experimentation, a chemist with the National Bureau of Standards, Warren Emley, developed a test method that measured the workability (plasticity) of lime putty (Godbey et al 2002). The Emley apparatus, seen in Figure 1, determines the ability of hydrated lime to minimize the work required to spread lime putty when it is in contact with an absorptive base. This simulates the "drag" experienced when towelling the mortar on a brick or block unit.

The Emley test provides a quality control procedure to ensure that Type S hydrated lime products enhance workability of mortars. Type S hydrated lime products provide good workability without the addition of excessive amounts of air entrainment additives that could negatively impact bond strength.

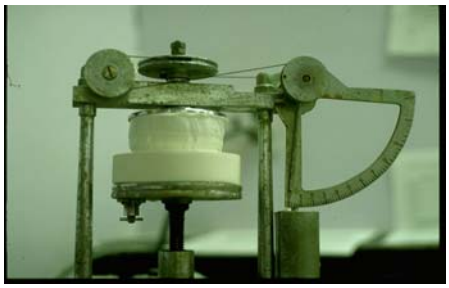

Figure 1: Emley Test Apparatus

Hedin (Hedin et al, 1962) identified one factor, hydrated lime particle shape, that can influence workability as measured by plasticity. The hexagonal platelet particle shape of Type S hydrated lime can act like a deck of cards by sliding in one direction, yet remaining in contact with the particle above. This provides lubrication and, at the same time, a stickiness to the mortar (Gutschick, et al1988). If additional workability is needed, Type SA hydrated lime products, which provide enhanced workability and board life with moderate levels of air entrainment, can be used.

3.1.2 Water Retention

The fine particle size of Type S hydrated lime particles enhance the ability of plastic mortar to retain water when applied to an absorptive base. Water retention is important, not only to enhance workability (plasticity), but also to extend board life and assure that adequate water is available to hydrate cementitious components of the mortar. Though research has shown that plasticity is a good predictor of water retention, water retention by itself is not a predictor of plasticity (Levin et al 1956). Water retention of the mortar becomes more important as the absorption rate of the masonry increases or the temperature during installation increases (Palmer et al 1934).

3.1.3 Air Content

Air-entrainment additives can be added to mortar to enhance water retention and plasticity. The maximum level of air allowed for air-entrained cement-lime mortar is 12% when structural reinforcement is incorporated into the masonry or when Type S or Type M mortar is used, and 14% when structural reinforcement is not used and Type N or Type O cement-lime mortar is used. Research has shown, however, that high levels of air entrainment can significantly reduce bond strength. Copeland et al (1964) found that if mortar air content is increased from 5% to 20%, a 79% decline in mortar bond strength results. Fishburn (1961) found that bond strength decreases by 50% when mortars with 10% to 20% air-entrainment are tested. The water-retentive property of Type S hydrated lime allows for workable mortars at low to moderate air entrainment levels.

3.1.4 Uniformity

Cement-lime mortars provide uniform performance characteristics in the field. ASTM C 270 provides recommended proportions for Type M, S, N and O cement-lime mortars. This specification also requires that hydrated lime products meet ASTM C 207 criteria, and that the cement product meet ASTM C 150, C 595 or C 1157. ASTM C 207 and the cement standards all specify chemical composition as well as physical product qualities. The chemistry of each cement-lime blend is defined and contains a high percentage of materials that contribute to the short- and long-term development of strength in mortars. Since the chemistry is well-defined, performance characteristics, such as compressive strength and flexural bond strength, are predictable at given proportion levels. Tighter limits on air content also help to minimize variation between batches.

Many manufactures produce pre-bagged mixtures of cement-lime or cement-lime-sand mortars. These preblended cement-lime mortars are available in most markets in 65-75 lb. bags, bulk bags or silo systems. Preblended cement-lime mortars eliminate the mixing of separate bags of lime and cement at the jobsite and, therefore, reduce variability in the field-mixed proportions.

3.2 Hardened Mortar Properties

3.2.1 Bond Strength

Portland cement and Type S hydrated lime mortars have been shown to have high levels of flexural bond strength. Grimm (1988) indicated that "*Bond strength between mortars and masonry units is the most important physical property of the masonry*." The appendix to ASTM C 270 (2004) and Brick Industry Association (2003) literature also emphasize the importance of bond. A survey of architects (Wallace 1991) has also indicated that bond strength was the most important characteristic in their specification of mortars. Bond strength is enhanced by properties of cement-lime mortars that are discussed below.

Tensile bond strength is the ability of the mortar to hold the masonry units together despite the presence of a force that tries to pull them apart. High tensile bond strength is enhanced by the following plastic mortar characteristics:

- High water retention in cement-lime mortar, which allows for maximum early curing of the cementitious materials (Palmer et al 1934). Water chemically combines with cement to produce the crystals that harden mortars. Water facilitates the reaction between carbon dioxide and lime, which results in hardening through the formation of limestone.
- High initial flow, which permits easy complete coverage of masonry units (Ritchie et al 1964).
- Low air content of cement-lime mortar systems increases bond strength (Grimm), (Redmond 1962). Air bubbles trapped at the interface between the mortar and masonry unit prevent a good mechanical key between the two materials. Since lime is water-retentive, the amount of air-entrainment needed is minimal.

There are a number of studies that demonstrate the superior bond strength of cement-lime mortars. Work performed by Brown et al (1987) at Clemson University concluded that flexural strength of prisms build with cement-lime mortars was substantially higher than that in similar prisms constructed with mortar of other cementitious materials. At the University of Texas at Arlington, John Matthys (1988) showed that cement-lime blends of mortar Types N and S had significantly higher flexural bond strength than the same Types of masonry cement mortars. This study involved bond wrench testing of both brick (1988) and block (1989) assemblages. The Matthys studies also demonstrated that CL mortars have significantly higher diagonal tension (shear) strength than the same Types of masonry cement mortars.

Large studies performed on cement-lime mortar (Hedstrom et al 1991) and masonry cement mortars (Melander et al 1993) demonstrated significantly higher bond strengths for cement-lime mortars. This studies explored randomly selected masonry cement and portland cement-lime samples. Bond strength tests were performed on the selected samples at three different testing laboratories (University of Texas at Arlington, National Concrete Masonry Association and Construction Technology Laboratory) using test procedures detailed in UBC Standard 24-30 (1991). Thirty bond tests were performed on each mortar selected in order to obtain a 90% confidence level for test data. Results showed that cement-lime mortars had significantly higher bond strengths than the other products tested for both Type N and Type S mortar mixes.

Testing performed by the Brick Industry Association on assemblages made of bricks of low, medium and high rates of absorption also demonstrated that cement-lime mortars were able to provide excellent bond. (Borcheldt et al 1999) For masonry units having high rates of absorption, only cement-lime mortars performed well without pre-wetting the brick. The bond strength advantages of Type S hydrated lime and portland cement mortars have been well documented in building code requirements developed by the Masonry Standards Joint Committee (MSJC 2002). Cement-lime and mortar cement have significantly higher allowable flexural tension values for Allowable Stress Design and higher modulus of rupture values in out-of-plane bending in Strength Design. As an example of these differences, the current values of modulus of rupture for out-of-plane bending are shown in Table 4.

Table 4
ACI 530-02/ASCE 5-02/TMS 402-02
Modulus of Rupture for Out-of Plane Bending
Table 3.1.7.2.1

Direction of Flexural Tensile Stress and Masonry Type	**Mortar Types (psi)**			
	Cement-Lime or Mortar Cement		**Masonry Cement or air-entrained cement lime**	
	M or S	**N**	**M or S**	**N**
Normal to bed joints in running or stack bond:				
Solid units	100	75	60	38
Hollow units[a]				
Ungrouted	63	48	38	23
Fully grouted	170	145	103	73
Parallel to bed joints in running bond:				
Solid units	200	150	120	75
Hollow units				
Ungrouted and partially grouted	125	95	75	48
Fully grouted	200	150	120	75
In stack bond	0	0	0	0

a For partially grouted masonry, modulus of rupture values shall be determined on the basis of linear interpolation between hollow units that are fully grouted and ungrouted based on amount (%) of grouting.

3.2.2 Minimizes Water Penetration

Low air content, a fine particle size, high plasticity and good water-retention contribute to excellent extent of bond for cement-lime mortars. Good extent of bond eliminates easy migration paths for water penetration. Munro (1988) indicates that "*Ninety percent of the masonry problems I investigate are related to leaks, most of which occur through hairline cracks between mortar and brick.*" Good extent of bond helps to prevent these cracks, or bond-line separations, from forming.

Masonry built with cement-lime mortar mixtures have been shown to have less water permeance than those built with other cementitious mortar materials in tests of masonry assemblages in accordance with ASTM E 514. This test utilizes an environmental chamber attached to a masonry assemblage to study water penetration through the wall. Water flow rates and air pressure are maintained in the environmental chamber to simulate a 5-inch per hour rainfall in 62.4 mile-per-hour wind. A limewash

on the back face of the masonry assemblage makes it easy to identify leakage. Water penetrating through the assembly is collected and measured for comparisons.

In the 1970's, a group of masonry contractor-related organizations from Chicago sponsored a research study at H.H. Holmes Testing Laboratories, Inc. (Brown 1978) that demonstrated that cement-lime mortars were more resistant to water than other mortar compositions. The results of this study were replicated by a second study sponsored by three National Lime Association (NLA 1979) members. Data showed that mortars containing Type S hydrated lime performed better in the following ways:

- Reduced wall leakage
- Longer time for first dampness
- Longer time for first visible water to appear
- Lower percentage of damp area on the back of the panel

Water permeance tests were also performed along with bond strength analyses in the late 1980's by Matthys (1988). Results of these tests showed less water leakage for both brick and block assemblages when cement-lime mortars were used. In a study funded by NLA, PCA and BIA, testing performed on assemblages that included a high IRA brick showed similar results (Borchelt et al 1999). Finally, a study of assemblages constructed with lime replacement products (Schuller et al 1998) showed that assemblages containing cement-lime mortars performed significantly better than those containing lime-replacement products.

The Holmes (Brown 1979) study as well as a study sponsored by the Mortar Producer's Association (Thomas 1978) in Warwickshire, England demonstrated that walls containing cement-lime mortars have improved resistance to water penetration with age. Retests of the test panels six months after construction showed that the majority of panels containing cement-lime mortar had less water penetration. This may be attributed to the ability of lime to absorb carbon dioxide and convert back to limestone over time.

Each of these studies demonstrated that the combination of hydrated lime and cement provided a mortar product that enabled the masonry assembly to resist leakage. A summary of the data generated by each study can be found in the National Lime Association (2001) publication "Lime-Based Mortars Create Watertight Walls".

3.2.3 Durability

Masonry construction is a durable, low maintenance system. Use of a mortar that forms a permanent and complete bond between the masonry units is a primary contributor to masonry durability. The use of lime in mortars contributes to this durability in the several ways.

3.2.3.1 Freeze-Thaw Durability

The ability of mortar to withstand cycles of freezing and thawing is an important consideration in northern climates. Freeze-thaw durability is dependent on the ability of the mortar to:

1) resist water penetration;
2) prevent mortar saturation by permitting transmission of water vapour out of the mortar;
3) have an appropriate pore structure that will accommodate the hydraulic porepressures associated with pore fluid freezing.

Two types of laboratory tests exist for determining the freeze-thaw durability of masonry mortars. Omni-directional testing, which exposes a cube of mortar to freeze-thaw cycling on all six sides, has traditionally been used. More recently, unidirectional freeze-thaw test procedures have been used at

several testing laboratories as a more relevant test of field performance. Unidirectional tests measure the impact of freezing and thawing cycles on the face of a masonry assemblage containing the mortar to be tested and frost-resistant brick.

Unidirectional freeze-thaw tests have been run on cement-lime mortars at the Canadian National Research Council Laboratory in Ottawa, ON and the CERAM laboratory in Stoke-On-Trent, UK. Unidirectional freeze-thaw testing at the NRC Laboratory (Thomson et al 1998) focused on the performance of mortars for maintenance and restoration of buildings in the Parliamentary Precinct in Ottawa. Thirty-four mortar combinations were examined for compressive strength, bond strength and freeze-thaw durability. Masonry cements, Type N hydrated lime, Type S hydrated lime, hydraulic lime and lime putty were all examined. The three best-performing mix designs tested contained Type S hydrated lime. Of the three mix designs, two combined portland cement with lime (¾ : 1½ : 5½ and 1 : 3 : 9, cement : lime : sand). The third mixture was a blend of masonry cement and Type S lime (1½ : ½ : 6¼). This study concluded that there was no relationship between compressive strength and freeze-thaw durability. The study did show, however, that there appeared to be a relationship between freeze-thaw durability and bond strength.

The British CERAM laboratory has also tested the freeze-thaw durability of cement-lime mortars. In a study sponsored by the National Lime Association Building Lime Group (Tate et al 2002), prisms constructed with Type S cement-lime mortars were studied. Panels were constructed with frost-resistant brick and Type S cement-lime mortars that contained 5.2%, 8.0% and 11.5% air-entrainment. Each of the prisms tested met the British frost-resistant criteria of 100 freeze-thaw cycles without any visible damage. This study concluded that the ability of the mortar to resist water penetration was important in preventing damage during freeze-thaw cycles.

3.2.3.2 Elasticity

Voss (1960) found that high lime content mortars were slow-hardening and remained elastic or flexible. Lime, therefore, enhanced the ability of the assemblage to accommodate stresses caused by building movement and cyclical changes without excessive cracking. An example of the flexibility of lime-based mortars is its use in the construction of tall industrial masonry chimneys. Industrial masonry chimneys are known to sway significantly during periods of high wind. Builders of these structures typically use mortars with high lime content. Boynton (1980) indicates that a typical formulation used for these structures is one part (by volume) cement to two parts hydrated lime to five parts sand.

3.2.3.3 Autogenous Healing

When hairline cracks develop in the mortar, the combination of hydrated lime, moisture and carbon dioxide from the air can help to seal the crack by the formation of limestone (calcium carbonate). The crystals formed by this process help to plug the hairline cracks. This process is called autogenous healing (Voss 1960).

3.2.3.4 Proven Performance

Evidence of the use of lime in masonry applications dates back to 500 BC. Portland cement was not manufactured in the United States until 1871. Prior to this time, lime was used as the primary ingredient of all mortars. The durability of these structures serves as testimony to the lasting durability of lime mortars. Conner (1948) published an empirical study of 100 buildings with a wide range of mortar types, all of which were owned by the New Jersey Bell Telephone Company. The buildings varied from 6 to 23 years old. One of the four factors he found to be present in water-tight construction was the use of a lime-cement mortar of a 1:1:5 or 1:1:6 mix design.

3.2.4 Compressive Strength

ASTM C 270 allows mortars to be specified by proportion or property guidelines. Cement-lime mortars mixed under the proportion specification generally have enough compressive strength to meet the strength of the next highest mortar class of the ASTM C 270 property specification. For example, a Type N cement-lime mortar mixed by the proportion specification will normally have enough compressive strength to meet the Type S mortar property specification. Specifying CL blends by proportion provides a margin of safety concerning compressive strength. If high compressive strengths are undesirable, the lime content can be increased and the property specifications used. In either event, cement-lime mortar compressive strength levels are adjustable and predictable.

Hydrated lime improves the strength of the mortar by several mechanisms:

- **Carbonation -** Hydrated lime reacts with carbon dioxide in the atmosphere to form limestone. This provides the mechanism for autogenous healing as well as long-term strength development of the mortar.
- **Cementitious reactions -** Pozzolonic reactions can occur between hydrated lime and silica compounds in the mortar mix.
- **pH -** Hydrated lime helps to maintain high pH levels in the mortar mix. This makes siliceous materials more soluble and reactive.

Normally, compressive strength of mortar is measured by crushing two-inch cubes of mortar. Though a significant difference in compressive strength is seen in cube tests, research shows that the addition of lime can have very little impact on the compressive strength of piers. Davey (1937) of the British Building Research Station found that there was little change in the compressive strength of brick piers with a substitution of up to 50% lime (by volume) for cement, despite drops in mortar cube strength. Staley (1939) also studied the difference between mortar cube strengths and masonry pier strength. He found that the range between the lowest and highest strength of mortar cubes (1000% difference) and masonry piers (30-50% difference) were significantly different. Pier strengths, in general, exceeded the strength of mortar cubes.

3.2.5 Vapour Permeability

Vapour permeability is a key consideration for masonry applications. Walls that cannot “breath” trap moisture, which could cause problems with mold on interior finishes or freeze-thaw damage to the masonry. Research in this area has been limited. Studies have shown, however, that the vapour permeability of mortar increases with increasing lime content (Jacob et al 1989). More work is needed to provide better definition in this area.

4 Conclusions

What is the most important property of cement-lime mortar? The answer to this question depends upon who asks the question and their application. For the contractor, workability may be the most important characteristic. For the architect or engineer, bond strength may be more important. For the owner, the durability of the structure is important. For restoration applications, low strength and high levels of vapour transmission may be needed. In geographic areas with seismic concerns, a Type S cement-lime mortar with high bond strength may be required by code.

Research and field performance have shown that cement-lime mortars are high quality systems that are flexible enough to meet a wide range of needs.

- Mortars made with cement-lime mortars can have excellent workability with low levels of air entrainment.
- The water-retentive property of lime optimizes cement hydration and is beneficial for use on highly-absorptive masonry units.

- Cement-lime mortars have high levels of flexural bond strength.
- CL mortars resist penetration of liquid water through the wall.
- Mortars made with cement and lime have been proven to be durable in the laboratory as well as in the field.
- Strength levels of cement-lime mortars can be varied by adjusting the ratio of cement to lime.
- Each ingredient of a cement-lime mortar has its own standard, which requires chemical and physical properties that are desirable for mortar.

What is the most important property of cement-lime mortars? Perhaps the most important property of cement-lime mortar is its versatility in meeting the needs of a wide range of masonry applications.

References

American Society for Testing and Materials, C 110, Methods of Physical Testing of Quicklime, Hydrated Lime, and Limestone, Philadelphia, PA.

American Society for Testing and Materials, C144, Standard Specification for Aggregate for Masonry Mortar, Philadelphia, PA.

American Society for Testing and Materials, C150, Standard Specification for Portland Cement, Philadelphia, PA.

American Society for Testing and Materials, C207, Standard Specification for Hydrated Lime for Masonry Purposes, Philadelphia, PA.

American Society for Testing and Materials C270, Standard Specification for Mortar for Unit Masonry, Philadelphia, PA.

American Society for Testing and Materials, C595, Standard Specification for Blended Hydraulic Cements, Philadelphia, PA

American Society for Testing and Materials C1157, Standard Specification for Hydraulic Cement, Philadelphia, PA.American Society for Testing and Materials C1489, Standard Specification of Lime Putty for Structural Purposes, Philadelphia, PA

Borchelt, G.J., Melander, J.M. and Nelson, R. L., June 1999, "Bond Strength of and Water Penetration of High IRA Brick and Mortar," 8th North American Masonry Conference, University of Texas at Austin, Austin, TX.

Boynton, R.S. 1980, Chemistry and Technology of Lime and Limestone, Second Edition, John Wiley & Sons, Inc.,

Boynton, R.S. & Gutschick, K.A., September 1964, "Strength Considerations in Mortar and Masonry," Masonry Mortar Technical Notes #2, National Lime Association, Arlington, VA

Brick Industry Association, June 2003, "Mortars for Brick Masonry", Technical Notes on Brick Construction #8

Brown, R. H, August 1978, "Effect of Mortar On Water Permeance of Masonry," Proceedings of the North American Masonry Conference (NAMC), University of Colorado, Boulder, Colorado.

Brown, R.H. and Robinson, G., Dec. 1986, "Inadequacy of Property Specification In ASTM C-270", ASTM

Brown, R. H., and Sarder, Ashok, , November 1987, "Flexural Strength of Brick Masonry Using Bond Wrench", Brick Institute of America Research Report No. 20.

Connor, C.C., 1948, "Factors in the Resistance of Brick Masonry Walls to Moisture Penetration", Proc. ASTM

Copeland, R.E. and Saxer, E., Nov. 1964, "Tests of the Structural Bond of Masonry Mortars to Concrete Block", Proceedings of the American Concrete Institute, ACI Detroit, Mich., Vol. 61, pp 1411-1451.

Davey, N., 1937, "Strength of Brickwork in Relation to that of Brick and Mortar," British Building Research Station, Proc., International Association for Testing Materials, London.

Fishburn, C., Nov. 20, 1961, Effect of Mortar Properties on Strength of Masonry, NBS Monograph 36, National Bureau of Standards, Washington, D.C.

Godbey, R.J. and Thomson, M.L., 2002, "Emley Plasticity Testing: First Steps to a Precision and Bias Statement," Masonry: Opportunities for the 21st Century, ASTM STP 1432, D. Throop and R.E. Klingner, Eds., ASTM International, West Conshohocken, PA.

Grimm, Clayford T., "Effect of Mortar Air Content on Strength of Masonry, Unpublished Report.

Grimm, C.T., Sept. 1988,, "The Most Important Property of Masonry and 20 Ways to Improve It", The Magazine of Masonry Construction, pp 254-5.

Gutschick, K. and Walker, D., July 1988, Why Use Lime-Cement Mortar?, The Magazine of Masonry Construction, pp. 441-455.

Hedin, R, 1962, "Plasticity of Lime Mortars", National Lime Association, Victor J. Azbe Award

Hedstrom, E.G., Tarhini, K.M., Thomas, R.D., Dubovoy, V.S., Klingner, R.E., and Cook, R.A., February 1990, "Flexural Bond Strength of Concrete Masonry Prisms using Portland Cement and Hydrated Lime Mortars," TMS Journal, Vol. 9, No. 2.

Jacob, J. and Weiss, N.R., 1989, "Laboratory Measurement of Water Vapor Transmission Rates of Masonry Mortars and Paints," APT Bulletin, Vol. XXI, No. ¾, pp 62-70.

Levin, E., Clarke, W and Wells, L, February 20, 1956, "Plasticity and Water Retentivity of Hydrated Limes for Structural Purposes", United States Department of Commerce, Building Materials and Structures Report 146, p. 9.

Masonry Standards Joint Committee (MSJC), 2002, Building Code Requirements for Masonry Structures (ACI 530-02/ASCE 5-02/TMS 402-02)

Matthys, J.H., August, 1988, "Conventional Masonry Mortar Investigation," Report for the National Lime Association, Arlington, VA.

Matthys, J.H., January 1989, "Conventional Masonry Mortar Investigation On Concrete Block," Report for the National Lime Association, Arlington, VA.

Melander, J.M.; Gosh, S.K.; Dubovoy, V.S.; Hedstrom, E.G.; and Klingner, R.E., 1993, "Flexural Bond Strength of Concrete Masonry Prisms Using Masonry Cement Mortars," Masonry: Design and Construction, Problems and Repair, ASTM STP 1180, J.M Melander and L.R. Laursdorf, Eds., American Society for Testing and Materials, Philadelphia, PA

Munro, C, April 1988, "How to Specify Mortar", The Magazine of Masonry Construction, p 26.

National Lime Association (NLA), February 1979, "Effect of Mortar Composition On Wall Leakage," Masonry Mortar Technical Notes #5, Arlington, VA.

National Lime Association Building Lime Group, May 2001, "Lime-Based Mortars Create Watertight Walls," (http://www.lime.org/Walls.pdf)

Palmer, L.A. and Parsons, D.A., May 1934, "A Study of the Properties of Mortars and Bricks and Their Relation to Bond", National Bureau of Standards Journal of Research, Vol. 12, (Research Paper No. 683)

Redmond, T.B., 1962, "Lime and Pre-Cast Concrete Products", National Lime Association Proceedings.

Ritchie, T. and Davison, J.I., March-April 1964, "Cement-Lime Mortars", Building Research, March-April 1964.

Schuller, M.P., van der Hoeven, R.S.K, and Thomson, M.L., 1998, "Comparative investigation of Plastic Properties and Water Permeance of Cement-Lime Mortars and Cement-Lime Replacement Mortars," *Water Problems in Building Exterior Walls, STP 1352*, Jon M. Boyd, Ed., American Society for Testing and Materials.

Staley, H., 1939, "Volume Changes in Mortars and Strength Characteristics of Brick Masonry," Proc. National Lime Association.

Tate, M.J. and Thomson, M.L., 2002, "Effect of Air Entrainment on Freeze Thaw Durability of Type S Cement-Lime Masonry Mortars", 9th Canadian Masonry Symposium

Thomas, K., July 1978, "Journal of Institute Building"

Thomson, M., Suter, G., and Fontaine, L., 1998, *Frost Durability Testing of Stone Masonry Mortars: Restoring the Canadian Parliament Buildings*, APT Bulletin, Vol. XXIX, No. 2, pp 42-49.
Thomson, M.L., 1999, “Plasticity, Water Retention, Soundness and Sand Carrying Capacity: What a Mortar Needs”, Historic Mortars: Characteristics and Tests, PRO 12, RILEM Publications S.A.R.L., Edited by P. Bartos, C. Groot and J.J. Hughes.
Uniform Building Code Standard No. 24-30, 1991, (Standard Test Method for Flexural Bond Strength of Mortar Cement), International Conference of Building Officials, Whittier, CA.
Wallace, Mark A., February 1991, “How Mortar Is Chosen”, Masonry Construction Magazine, P. 50.
Voss, W.C., 1960, ”Exterior Masonry Construction,” NLA Bulletin 324, Second Edition, P. 27.