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BUILDING LIME – SETTING THE STANDARD[*]

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Abstract

Carefully developed standards assist in the success of building products by assuring that they balance the needs of contractors, architects, owners and manufacturers. This paper provides an overview of standards related to building lime developed by organizations in the United States, Europe, Australia and Japan. The reasons for the requirements in these standards are discussed along the appropriate methods to measure the required properties. Differences and similarities between standards are explored. Based on this review, areas of current ASTM building lime standards that may be improved are discussed and suggestions are provided for future revisions.

Keywords

Lime, plasticity, building, masonry, hydraulic, standards

1 Introduction

Users appreciate products whose performance is predictable and consistent. Development of standard requirements, consistent with the needs of these users, assures the success of products in the field. Each type of user has unique requirements. For example, contractors in building construction are concerned with the ease of application of the product. This improves their

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productivity and enhances the quality of application. In contrast, owners are concerned with durability of the product after application. Products that have good workability may not be durable. A good standard will address the needs of both groups by providing minimum requirements for workability as well as requirements for durability. This paper reviews the standards for building lime products used in the United States as well as standards for Europe, Japan and Australia. Analyses of the key components of the standards are made to determine what characteristics are considered important by users and how they are tested.

2 ASTM – the American standards

Standard specifications in the United States, relative to building lime and its applications, are currently developed by ASTM International, originally known as the American Society for Testing and Materials. ASTM standards are developed through a consensus-based process in committees made up of user, producer and general interest members. Voting rights for committee members are assigned to maintain balance between each membership type.

Originally, lime standards were developed by ASTM Committee C1 (Cement, Lime and Clay), which was established in 1902. In 1912, Committee C7 was formed to focus only on lime and limestone standards.

2.1 U.S. building lime standards

Currently, five building lime standards are administered by ASTM Subcommittee C7.02 (Structural Lime). Standards exist for quicklime, finishing hydrated lime, mason's hydrated lime, hydraulic lime and lime putty.

2.1.1 Quicklime

ASTM C 5 (Standard Specification for Quicklime for Structural Purposes) was originally published in 1913. Quicklime, defined by this standard, can be slaked to produce a lime putty product that can be used in building applications. Guidance is provided for slaking and preparing lime putty in the appendix of this standard. Prior to 1900, slaking quicklime to produce lime putty at the jobsite was a common practice. This was one of the first specifications developed for the building construction industry. Today, this specification is rarely used because of the time required to produce lime putty and safety concerns due to the heat given off by the slaking reaction.

2.1.2 Hydrated lime

The original ASTM standard for hydrated building lime products was ASTM C 6-15 (Standard Specification for Hydrated Lime). This standard was tentatively adopted in 1913, with formal adoption in 1915. In the late 1930s and early 1940s, two developments led to the subdivision of ASTM C 6 into three separate hydrated lime standards. A study of plastering failures by the National Bureau of Standards (Wells 1927) indicated that delayed hydration of magnesium oxide in the finish coat could create "turtlebacks" and general separation of the finish and brown coats (Lovewell 1975). To address these concerns, pressure hydration systems were developed by Warner (1918) and Corson (1943). These hydration systems were capable of hydrating magnesium oxide and eliminating the "turtlebacks" problem. These developments resulted in the separation of hydrated building lime products based on their level of hydration and physical characteristics. In 1946, ASTM C 6 was divided into a new ASTM C 6 Standard Specification for Normal Finishing Lime (Type N) and a new standard ASTM C 206 (Standard Specification for Special Finish Lime) (Type S). In 1980, these standards were merged into ASTM C 206 (Standard Specification for Finishing Hydrated Lime). A third hydrated lime standard was developed in 1946, ASTM C 207 (Standard Specification for Hydrated Lime for Masonry Purposes).

ASTM C 206 defines the current standards for Finishing Hydrated lime. This standard is used to specify hydrated lime for interior and exterior plastering applications. Two types of hydrated lime products are defined in the scope of this specification. Type N, or Normal hydrated lime, must achieve a plasticity figure of 200 when soaked for a period of 24 hours. Type S, or Special hydrated lime, must have a plasticity value of at least 200 when tested within 30 minutes of mixing with water. Type S hydrated lime must have an unhydrated oxides concentration below 8%. Both Type N and Type S hydrated lime products must pass soundness and sizing tests.

ASTM C 207 defines standards for Hydrated Lime for Masonry purposes. Four types of hydrated lime are defined. Type N (Normal) Hydrated lime does not have a plasticity or unhydrated oxides requirement. Type S (Special) hydrated lime requires a plasticity of 200 or higher and the unhydrated oxides concentration must be below 8%. Two parameters required in ASTM C 270 (Standard Specification for Mortar for Unit Masonry) are also required for ASTM C 207-classified mason's limes. Air-entrainment additives can be added to either product to produce a Type NA or SA hydrated lime. Air content levels must be below 7% for a Type S or N hydrated lime and between 7 and 14% for a Type SA or NA product. Water retention levels must exceed 75% for Type N hydrated lime and 85% for Type S hydrated lime.

2.1.3 Hydraulic lime

The ASTM C 141 Standard Specification for Hydraulic Hydrated Lime for Structural Purposes was first published in 1938. The standard contains requirements for chemical composition, setting, compressive strength, fineness and soundness. The standard currently has no requirements for workability. This standard is currently being revised.

2.1.4 Lime putty

Though lime putty has been used for thousands of years, ASTM C 1489 (Specification of Lime Putty for Structural Purposes) is the newest building lime standard. This standard was first published in 2001. Parameters specified for lime putty are similar to those in the quicklime and hydrated lime standards. Specifications unique to putty include the length of soak time required to produce the putty as well as the density of the slaked product. Adequate soak times are required to ensure high levels of hydration in the slaked product. The density of lime putty is required to be between 80 and 100 lbs./ft^3 to ensure that the putty can be proportioned by volume with performance similar to hydrated lime in building applications.

2.2 Chemical requirements

In general, the chemical requirements for building lime products reflect the need for lime products with high levels of calcium and magnesium oxides and low levels of carbonates. Test methods for determining the chemistry of lime products are detailed in ASTM C 25, which was originally published in 1919. The chemical requirements for building lime products can be seen in Table 1.

2.2.1 Calcium lime and magnesium lime

The quicklime standard (ASTM C 5) defines calcium lime as containing a minimum of 75% calcium oxide. Magnesium lime is defined as containing a minimum of 20% magnesium oxide, and the sum of the calcium and magnesium oxides must exceed 95% for both magnesium lime and calcium lime. The remaining chemical and physical standards are the same for both. Normally, the ASTM C 51 definition of lime type (high-calcium, magnesian or dolomitic) is used in place of these classifications.

2.2.2 Calcium and magnesium oxides

High levels of calcium and magnesium oxides (95% minimum), on a non-volatile basis, are required by all of the building lime standards, with the exception of hydraulic lime. High levels of oxides, along with low levels of carbonates, help to provide predictable performance of the lime products in terms of strength development and compatibility with other masonry materials. Hydraulic lime products are allowed to have lower levels of calcium and magnesium oxides (65-75%). These products have higher levels of silica and alumina compounds, which are needed along with lime and water, to produce a hydraulic setting reaction.

2.2.3 Silica and iron oxide

The quicklime standard (ASTM C 5) requires a 5% maximum level of silica, alumina and iron oxides. This is normally determined by an acid-insoluble residue test. Silica could act as inert filler or could add to the hydraulicity of the product. Iron oxide is detrimental to the color of the product and could potentially leach from the product. This requirement seems redundant for quicklime products, since they are already required to have 95% calcium and magnesium oxides.

2.2.4 Carbonates

Carbon dioxide in lime products can be obtained from two sources. Since lime products are produced from limestone, which contains calcium and magnesium carbonates, incomplete calcination will result in calcium carbonate in the finished product. This source of carbon dioxide acts mainly as a filler. The amount of carbon dioxide allowed in the product is restricted to 3% for quicklime and 5% for hydrated lime at the place of manufacture. More problematic is carbon dioxide from the air, which chemically reacts with hydroxides in hydrated lime products after they are produced but before they are used at the jobsite. Carbonation of lime products before use can decrease workability and the final strength of the lime-based plaster or mortar. Limits are placed on carbonates, in terms of carbon dioxide both at the plant and at the jobsite. Jobsite limits are less strict (7-10%) in comparison to plant requirements (3-5%). Hydraulic hydrated lime has a limitation of 8% carbon dioxide on an as-received basis.

2.2.5 Unhydrated oxides

The unhydrated oxides concentration is restricted (8% maximum) in Types S and SA hydrated lime products. This requirement mainly addresses concerns about failures related to delayed hydration of magnesium oxides (Wells, 1927). This requirement is most important for dolomitic hydrated lime products. High-calcium quicklime products hydrate readily at atmospheric pressure. Dolomitic quicklime, however, contains a calcium oxide portion that easily hydrates at atmospheric pressure and a magnesium oxide portion that requires high pressure levels or long periods of soaking to hydrate completely. This test ensures that the magnesium oxide portion of dolomitic hydrates is hydrated sufficiently to prevent delayed hydration concerns.

2.2.6 Silica

The current hydraulic lime standard has minimum and maximum requirements for silica (SiO_2). This requirement ensures that adequate silicates are available for the hydraulic lime to develop strength when mixed in water.

2.2.7 Iron and aluminum oxides

Hydraulic lime standards also require the measurement of iron and alumina oxides separate of the silica level. The maximum allowable concentration of iron and alumina oxides is 12%. Aluminates also contribute to strength through a reaction with water and calcium hydroxide.

2.3 Physical requirements

Physical requirements of hydrated lime include application properties, durability and soundness of the finished product. Most of the physical test methods are found in ASTM C 110 Standard Test Methods for Physical Testing of Quicklime, Hydrated Lime, and Limestone. Table 2 details the physical test requirements for building lime materials.

2.3.1 Emley plasticity

In the plastic (wet) state, workability of the mortar or plaster product is, perhaps, the most important concern of the applicator. One method of quantifying workability is by determining the plasticity of lime. Warren Emley defined plasticity as having two properties (Emley 1920).

1. Plasticity increases as the ability of the material to retain water against the suction of the application surface increases.
2. Plasticity increases as the work required to spread the material decreases.

The test procedure starts with the production of lime putty with a standard consistency, as measured by the Vicat apparatus. The upper surface of the putty is placed against a metal plate that simulates the trowel of a plasterer or mason. The lower surface of the putty is placed against an absorptive plate, which simulates the basecoat plaster or masonry unit to which the putty would be applied in the field. The force exerted on the metal plate is measured when rotating the putty in contact with both the absorptive and metal plates.

Though most building lime products must meet a minimum level of plasticity (200), there are no plasticity requirements for hydraulic lime or Type N mason's lime. The soak period allowed before samples are tested differs for each product. Quicklime, prepared by the Appendix of ASTM C 5, must be slaked and aged according to the manufacturer's direction. Type N Finish lime must be soaked between 16 and 24 hours. With both of these products, long soak periods are required to assure that the resulting putty is hydrated prior to use. Type S hydrated limes in ASTM C 206 and ASTM C 207, as well as lime putty in ASTM C 1489, must be tested for plasticity within 30 minutes of mixing the putty.

2.3.2 Residue

Residue testing requirements for quicklime (ASTM C 5) are different than those for hydrated lime. Quicklime residue is typically measured with the slaking rate test of ASTM C 110, with a wet sieve analysis. Lime putty and hydrated lime (75-μm sieve analysis) samples also require wet screening. Hydrated lime samples are also tested by dry sieve analysis on a 600-μm sieve. Residue is especially important in thin-coat plaster work. Hard particles, coarser than a 600-μm sieve, make finishing the plaster to a smooth surface difficult. Residue can also contribute to the potential for popping and pitting of plaster (Boynton, 1980). Hydrated lime that passes the 600-μm sieve analysis (0.5% max) is not required to meet the soundness tests in ASTM C 207.

2.3.3 Popping and pitting

Pops and pits are surface imperfections that can be caused by a number of sources, including the expansion caused by hydration of unhydrated oxides or reaction with contaminants in lime-based mortars and plasters. The effect of this potential defect is most evident in smooth-coat plasterwork. Two methods can be used to test for pops and pits. With the first method, a thin, smooth lime-gauging coat, the thickness of the finish coat in plaster, is spread on a glass or hydrocal plate. This sample is then put into a steam chamber for at least 5 hours. The types of imperfections are then recorded. Alternatively, the pitting potential can be determined from examining a pressed tablet subjected to 125 to 150 psi in an autoclave for a period of 2 hours. The quicklime, lime putty and finishing lime standards all require popping and pitting testing. The mason's lime standard only requires this test if the residue on a 30 mesh sieve exceeds 0.5%.

Table 1: United States Building Lime – Chemical Standards

Product Types	Quicklime		Hydraulic Lime	Finish Lime		Masons Lime				Lime Putty
	Calcium Lime	Magnesium Lime		Type N	Type S	Type N	Type NA	Type S	Type SA	
Calcium Oxide, min., %	75									
Magnesium Oxide, min, %		20								
Calcium and magnesium oxide, min, %	95	95	65 - 75	95	95	95	95	95	95	92
Silica, alumina, and oxide of iron, max, %	5	5								
Carbon dioxide, max,%										
If sample is taken at place of manufacture	3	3		5	5	5	5	5	5	5
If sample is taken at any other place	10	10	8	7	7	7	7	7	7	7
Unhydrated Oxides (as-received basis), %					8			8	8	
Silica (SiO_2 calculated to nonvolatile basis) %			16 -26							
Iron and aluminum oxides (nonvolatile basis) %			12							

Table 2: United States Building Lime – Physical Standards

Product	Quicklime (C 5)		Hydraulic Lime (C 141)	Finish Lime (C 206)		Masons Lime (C 207)				Lime Putty (C 1489)
Types	Calcium Lime	Magnesium Lime		Type N	Type S	Type N	Type NA	Type S	Type SA	
Plasticity - Soaked for 30 min or less					200			200	200	200
- Soaked for a min. of 24 hours	200	200		200						
Residue										
Residue retained on 600-µm (30 mesh) sieve, max, %	15	15	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Residue retained on 75-µm (200 mesh) sieve, max, %			10	15	15					
Popping and Pitting	None	None		None	None	None	None	None	None	None
Water Retention						75	75	85	85	
Air Content (%) – Minimum								0	7	
- Maximum								7	14	
Bulk Density (lbs/ft3) – Minimum										80
- Maximum										100
Time of Setting-Gillmore method-Initial Set (min.) (hours)			2							
-Final Set (max.)(hours)			24							
Soundness (max.) %			1							
Compressive Strength - 7 day (min.) psi			250							
- 28 day (min) psi			500							

2.3.4 Water retention

Water retention is critical in developing workability of mortars that are applied over an absorptive base. In masonry construction, retention of water also ensures that adequate water is available for hydration of the cement in the mortar mixture. The water retention of hydrated lime is determined by an apparatus originally developed by Rogers (Rogers et. al., 1934). The apparatus has recently been modified to replace the mercury manometer, used to control the amount of vacuum, with a vacuum gauge. A mortar containing lime and sand is tested. The mortar is mixed to a standard consistency and the flow is measured on a flow table. The sample is then placed in a perforated dish and exposed to vacuum for 60 seconds. The flow after suction is then measured and recorded. The change in flow is recorded as the percentage of water retention.

2.3.5 Air content

ASTM C 270 places limitations on the amount of air-entrainment that is allowable in mortars. Lime products can contribute to the air-entrainment levels of mortars. To be classified as Type S, the air content of the cement-lime mortar must be below 7%. For lime-sand mortars with Type SA lime, the air contents range from 7 to 14%. The traditional method for determining the air content of lime-based mortars has been measuring the weight of 400 ml of mortar. The air content can be calculated knowing this weight and the density and weight of the mortar materials. Since the density of mortar materials can be difficult to determine accurately, a pressure pail technique is currently being explored as a more accurate representation of air-entrainment levels. The addition of air-entrainment additives can be beneficial for workability, board life and freeze-thaw durability of building lime applications. However, excessive air-entrainment can be detrimental to bond strength of mortars (Fishburn 1961). Air-entrainment additives can also be detrimental to the application of smooth plaster finishes. Air-entrainment additives are not allowed in Type S hydrated lime products. In Type SA hydrated lime, air contents are restricted to 14% maximum by ASTM C 207 to minimize bond strength impact.

2.3.5 Lime putty soak period

The lime putty standard requires that putties be soaked for a period of time prior to use in the field to assure that quicklime has adequately reacted. The required amount of soak time is dependent on the chemistry and reactivity of the lime product used to make the putty. Putties made from quicklime should be soaked for a minimum of two weeks. Lime putty made from Type N hydrated lime requires soaking for at least 16 hours. Lime putty made with Type S hydrated lime can be soaked for less than 30 minutes before use.

2.3.6 Lime putty bulk density

The bulk density of lime putty is important to ensure consistency when batching mortar formulations according to the proportion specifications of ASTM C 270. The bulk density range of 80 to 100 lbs/ft^3 is required to provide a range of density similar to that seen in the field with bagged hydrated lime.

2.3.7 Hydraulic lime Gillmore set

The amount of working time before set occurs is an important component of hydraulic lime. If the set time is too short, the mortar could harden before it can be used, which increases waste. If the set time is too long, delays in construction could result because the masonry units are “floating”. The current expected range for set to occur is from 2 to 24 hours.

2.3.8 Soundness

The soundness requirements of hydraulic lime are currently measured by making bars containing 75% hydraulic lime and 25% cement by weight. These bars are cured for 7 days and then tested for expansion by autoclaving. One percent expansion is allowed when comparing the original length to the length of the bar at an age of two days. Popping and pitting are not currently examined in this standard.

2.3.9 Compressive strength

The strength level of a mortar containing one part of hydraulic lime and three parts of Ottawa sand by weight must be a minimum of 250 psi at 7 days and a minimum of 500 psi at 28 days. This compressive strength measurement is not the same as that required in ASTM C 270, where proportions by volume of cement and lime serve as the basis. A mix of one-part non-hydraulic hydrated lime to three-parts sand by volume contains 14.3% hydrated lime by weight. The hydraulic lime mixes, proportioned by weight, contain 25.0% hydraulic lime.

3 Building lime standards of other countries

The requirements of the European, Japanese and Australian Standards were reviewed and compared to similar ASTM requirements.

3.1 European Standard EN 459

The European Committee for Standardization was formed in 1961 to promote harmonization of the technical standards in Europe. At the present time, twenty-eight countries participate in this process as members.

Building Lime Standards are developed by Technical Committee CEN/TC 51 “Cement and building limes”. The building lime standard, EN 459, which was issued in 2002, has three parts: EN 459-1 contains definitions, specifications and conformity criteria; EN 459-2 covers test methods; and EN 459-3 details conformity evaluation.

Analysis of the chemical and physical requirements of EN 459-1 follows.

3.1.2 EN 459 chemical requirements

The chemical requirements of EN 459-1 are seen in Table 3. Key points include:

- Four types of lime products are defined: calcium lime (CL), dolomitic lime (DL), hydraulic lime (HL) and natural hydraulic lime (NHL).
- For hydrated lime, lime putty and hydraulic limes, the calcium and magnesium oxide values are based on the product after subtraction of free moisture and chemically-combined water.
- Calcium lime (CL) has three different levels of calcium/magnesium oxide concentrations, ranging from 70 to 90%. Carbon dioxide levels can range up to 12%.
- Two levels of dolomitic lime (DL) are defined, based on magnesium oxide content. DL 85 is required to have over 85% calcium and magnesium oxides, with over 30% magnesium oxide. DL 80 is required to have only 80% calcium and magnesium oxides, with over 5% magnesium oxide. (ASTM requires 95% calcium and magnesium oxides with a minimum level of 20% magnesium oxides.)
- Hydraulic lime (HL) consists of lime, silicates and aluminates produced by mixing suitable materials to produce a product with hydraulic properties. There are three different grades based on strength levels. The minimum amount of available lime in these products ranges from 3 to 8%.
- Natural hydraulic lime (NHL) is produced by the burning and hydrating of argillaceous or siliceous limestone. Similar to hydraulic lime, NHL is divided into three different grades according to strength. The minimum amount of available lime in these products varies from 3 to 15%.
- Calcium and dolomitic limes have maximum levels of SO_3 of 2%. Hydraulic and natural hydraulic lime products are allowed up to 3% SO_3, although up to 7% is permissible if soundness is demonstrated. The presence of SO_3 and carbonates in mortar can cause

deterioration due to the formation of Thaumasite. The presence of SO_3 can also create delayed ettringite formation (DEF), which can also be problematic in the field (Dunster et. al. 2003). (The ASTM building lime standards do not specify limits for SO_3 at the present time.)

- Each product can contain additives in small quantities to enhance its properties. The amount and type of additive must be declared if the quantity exceeds 0.1% of the product weight.

Table 3: European Building Lime – Chemical Standards

Type Of Building Lime	CaO + MgO	MgO	CO_2	SO_3	Available Lime
CL 90	≥ 90	≤ 5[b]	≤ 4	≤ 2	
CL 80	≥ 80	≤ 5[b]	≤ 7	≤ 2	
CL 70	≥ 70	≤ 5	≤ 12	≤ 2	
DL 85	≥ 85	≥ 30	≤ 7	≤ 2	
DL 80	≥ 80	≥ 5	≤ 7	≤ 2	
HL 2				≤ 3[a]	≥ 8
HL 3.5				≤ 3[a]	≥ 6
HL 5				≤ 3[a]	≥ 3
NHL 2				≤ 3[a]	≥ 15
NHL 3.5				≤ 3[a]	≥ 9
NHL 5				≤ 3[a]	≥ 3

[a] Sulfate content of more than 3% and up to 7% is permissible, if soundness is demonstrated at 28 days of water curing using a test given in EN 196-2.

b. Magnesium Oxide content up to 7% is permissible if a soundness test

3.1.3 EN 459-1 physical standards

The physical standards for EN 459-1 are seen in Table 4. The following items in this table should be noted:

- Fineness is measured using the equivalent of an ASTM E 11 (Standard Specification for Wire Cloth and Sieves for Testing Purposes) 75 mesh (0.2 mm approximately) and 170 mesh (0.09 mm) sieves. The maximum allowable residue for calcium and dolomitic limes are much lower than those for hydraulic and natural hydraulic lime products. Lime putty products have no fineness standard.
- Free water content between 45% and 70% is allowed for lime putty. All other types of products are allowed a maximum free moisture content of 2%. (ASTM has no free moisture requirements.)

Table 4: European Building Lime – Physical Standards

Type Of Building Lime	Fineness (max % residue by mass)		Free Water Content (max. %)	Soundness			Mortar Tests					Setting Times	
				For building lime other than lime putty and hydrated dolomitic limes		For lime putty and hydrated dolomitic limes	Penetration (mm)	7 Day Compressive Strength	28 Day Compressive Strength		Air Content Max. (%)	Initial Set Min. (hrs)	Final Set Max. (hrs)
	0.09 mm	0.2 mm		Reference Method 5.3.2.1 (max %)	Alternative Method 5.3.2.2 (max %)			Minimum (MpA)	Min. (MpA)	Max. (MpA)			
CL 90	7	2	2	2	20	Pass	>10 and <50				12		
CL 80	7	2	2	2	20	Pass	>10 and <50				12		
CL 70	7	2	2	2	20	Pass	>10 and <50				12		
DL 85	7	2	2			Pass	>10 and <50				12		
DL 80	7	2	2			Pass	>10 and <50				12		
HL 2	15	5	2	2	20		>10 and <50		2.0	7.0	20	1	
HL 3.5	15	5	2	2	20		>10 and <50		3.5	10.0	20	1	15
HL 5	15	5	2	2	20		>10 and <50	2.0	5.0	15.0	20	1	15
NHL 2	15	5	2	2	20		>10 and <50		2.0	7.0	20	1	
NHL 3.5	15	5	2	2	20		>10 and <50		3.5	10.0	20	1	15
NHL 5	15	5	2	2	20		>10 and <50	2.0	5.0	15.0	20	1	15

- Four different soundness test methods are available in EN 459-2 Section 5.3.
  - For high-calcium hydrated lime and all types of hydraulic limes, two methods can be used. The first method involves the creation of a pressed disc with a lime sample. The sample is made from 25 grams of lime and 2.5 to 5 g of water. The specimen is then placed in a steam cabinet for 90 minutes and the change in diameter is measured. For the second method, the sample is made with 75 grams of hydraulic lime and 20 ml of water. The sample is cured in a mold for 48 hours prior to testing at 90% relative humidity and 20 ^{o}C. The difference between two indicator points is measured before and after being conditioned for 180 minutes in a steam cabinet.
  - For hydraulic lime samples with a SO_3 content of more than 3% but less than 7%, a cold water test is used. Two cakes are made on glass plates that are 10 mm thick and 50 to 70 mm in diameter. The cakes are allowed to harden for 24 hours and then placed in water at 18 ^{o}C to 21 ^{o}C for an additional 27 days. The cakes are observed over this period for splits and other signs of deterioration.
  - For quicklime, lime putty and dolomitic products, cakes are made by pouring pastes of lime upon absorbent plates. The cake size is 50 to 70 mm with 10 mm thickness. After 5 minutes, the cakes are transferred to a hot cabinet at 105 $\pm$ 5 ^{o}C for 4 hours. The cakes are then examined for signs of expansion cracks.
  - For hydrated calcium lime, calcium lime putty and hydrated dolomitic lime with grains larger than 0.2 mm, a lime putty is prepared and soaked for two hours. The putty is mixed with Plaster of Paris and spread into three flat patties in a ring mold. The resulting samples are dried at 40 ^{o}C for not less than 12 hours. They are then placed in a steam chamber for 3 hours. After steam conditioning, the patties are examined for disintegration, popping or pitting.
- A penetration test is used as an indirect measurement of consistency and workability of lime.
- Air content measurements are performed by a pressure method. Air content levels for standard mortars made with calcium and dolomitic limes can be up to 12%. For hydraulic and natural hydraulic lime products, up to 20% air content is allowable. (The maximum air content allowed in ASTM building lime standards is 14%.)
- For both HL and NHL products, hydraulic set must occur no sooner than one hour and no longer than 15 hours (the limits do not apply to HL2 and NHL2 hydraulic limes). (The ASTM limits are no sooner than 2 hours and no longer than 24 hours in ASTM C 141).

3.2 Japanese building lime standards

Japanese standards are developed by the Japanese Industrial Standards Committee (JISC). A consensus-based process is used with balanced committees containing producers, users and general interest voters. There are currently two Japanese Industrial Standards (Plastering Lime - JIS A6902 and Dolomite Plaster – JIS A6903) related to building lime.

3.2.1 Chemical requirements

The chemical requirements for the Japanese Industrial Standards (JIS) for building limes are seen in Table 5. The test procedures for these chemical requirements can be found in JIS R9011.

Table 5: Japanese Building Lime – Chemical Standards

Type	Classification	Calcium Oxide (min. %)	Magnesium Oxide (min. %)	CaO + MgO (min %)	Carbon Dioxide (max. %)
Plastering Lime	For Overcoating			65	15
Plastering Lime	For Undercoating			50	20
Dolomite Plastering Lime	For Overcoating	42	20		15
Dolomite Plastering Lime	For Undercoating	37	15.		20

Key items of note include:

- The basis for the specification of calcium and magnesium oxides in this standard is different than the basis in the ASTM and European Standards. Chemically-combined water and carbon dioxide are part of the basis used for the calculation of oxides.
- Two types of plastering lime are defined. Plaster lime has no requirements for calcium or magnesium oxides. Dolomite plastering lime does have distinct minimum levels required.
- For both plastering lime and dolomite plastering lime, less chemical purity is required for the undercoating.
- Allowable carbon dioxide levels for the undercoat (20% max.) is higher than that permitted in the overcoat (15% max).

3.2.2 JIS physical requirements

Table 6 summarizes the physical requirements in the Japanese Industrial Standards for Plastering Limes.

Table 6: Japanese Building Lime - Physical Testing Standards

Type	Classification	Fineness residue Maximum %		Consistency Coefficient (15 °C) Minimum (Newton-seconds)	Hardness Coefficient		Stability Test
		Nominal 590 μm	Nominal 88 μm		One Week Min.	Four Weeks Min.	
Plastering Lime	Overcoating	1	15	7	2.0	2.0	Compliance
Plastering Lime	Undercoating	2	20	5	1.5	1.5	Compliance
Dolomite Plastering Lime	Overcoating	1	15	20	2.3	2.3	Compliance
Dolomite Plastering Lime	Undercoating	2	15	15	2.1	2.1	Compliance

Key items noted include the following:

- Both sieves used for fineness residue are close to the ones used in the ASTM standards. The undercoating lime is allowed to be coarser than that for overcoating.
- The consistency coefficient is determined through use of a Stormer viscometer. A putty is prepared using a modified Vicat apparatus to determine the standard consistency. The putty is rotated 10 times at a load of 3.9227 N and the time is measured. The time in seconds is multiplied by a factor of 0.4 and a temperature correction factor to obtain the consistency coefficient. The viscosity measurement provides an indication of workability of the lime.
- The hardness coefficient is determined with a Martens-type scratching hardness meter. The samples are created by spreading a lime (140 g) and sand (700 g) undercoat (5 mm thick) over a glass plate. The undercoat is cured at room conditions for at least 24 hours and examined for cracks. If there are no cracks, a thin overcoat of lime putty is then applied and polished. The polished samples are then cured at room conditions for a period of one to four weeks and tested with a 3 mm ball. The amount of force used to push the ball into the sample increases from the one-week cure (1.9613 N) to the four-week cure (3.9227 N). The width of the flaw created by the ball is used to determine the hardness coefficient. The Japanese standard is the only one to use this type of test. It is an interesting way to predict the rate of carbonation (or curing) of a lime product. (There is no equivalent to this test in ASTM standards.)

- The stability test samples are prepared in a manner similar to that for the hardness test. The samples, however, are not polished. The samples are cured for five days at room conditions then placed in a steam cabinet for five hours. After steam conditioning, the sample is examined for cracks or other imperfections. (This is similar to the soundness tests in the ASTM and EN standards.)

3.3 Australian building lime standards

The Australian standard for building lime products is AS 1672.1-1997 Limes and Limestone Part 1: Limes for Building. Australian Building Lime standards are developed by Committee BD/27, Lime. Both the chemical and physical requirements of this standard were examined.

3.3.1 AS 1672.1 Chemical requirements

The chemical requirements for Australian Building lime products can be seen in Table 7. Key items noted include:

- Four types of lime are defined. Finishing lime is hydrated lime prepared for use in a finishing coat, plaster or render.
- The basis of calculation for each product includes chemically-combined water and carbon dioxide. There is no distinction between high-calcium and dolomitic products.
- Carbon dioxide requirements are similar to those in ASTM standards.

Table 7: Australian Building Lime – Chemical Standards

Parameter	Quicklime	Hydrated lime	Finishing Lime	Lime putty and lime slurry (dry solids basis)
Available lime (calculated as calcium oxide)	≥60%			
Available lime (calculated as calcium hydroxide)		≥65%	≥65%	≥65%
Carbon Dioxide (at works)	≤5%	≤4%	≤4%	≤4%

3.3.2 AS 1672.1 Physical requirements

The physical standards for Australian Building Lime are seen in Table 8. Key items noted include the following:

- There are three different soundness tests. The pat test mimics plaster applications by combining lime and Plaster of Paris into patties that are autoclaved and examined for pops, pits and cracks. The Le Chatelier method examines cement-lime mortar soundness by comparing expansion of a cement-lime mortar to one that contains only cement. These samples are conditioned in a steam cabinet. The autoclave soundness test also involves a comparison of the expansion of cement-lime mortars to one that contains only cement when cured in an autoclave.
- The residue allowed on a 600 μm sieve (No. 25 ASTM equivalent) varies from up to 20% for quicklime to less than 5% for finishing hydrate.
- Free moisture levels must be less than 2.5% for hydrated lime. Lime putty can contain up to 62% free moisture.

3. Discussion

The building lime standards that were reviewed have many similarities as well as some significant differences. The following items were noted during review of the standards.

- **Chemistry** – In general, a broader range of quality, as measured by the percentage of calcium and magnesium oxides, is allowed in the European, Japanese and Australian standards than in the ASTM standards. European and Japanese standards allow for different grades of lime quality. Both of these standards allowed significant amounts of carbon dioxide. Japanese standards allow up to 20% carbon dioxide. Higher calcium carbonate levels in the finished product improve the energy-efficiency of lime production and reduce carbon dioxide emissions. In the United States, the ASTM C 1 (cement) committee recently voted to allow up to 5% calcium carbonate to be included in cement. This is a provision that lime producers in the United States should consider as well. Research, however, is needed to define the impact of carbonate content on the other performance characteristics of lime. The European standards also allow for additives in small concentrations. The United States standards only allow for the addition of air-entrainment agents at levels defined by the Type SA requirements of ASTM C 207. Only the ASTM standards contain a requirement for unhydrated oxides. The unhydrated oxides concentration of dolomitic products is particularly important, since this parameter can contribute to unsoundness of the finished surface.

Table 8: Australian Building Lime – Physical Standards

Property	Quicklime	Hydrated Lime	Lime Slurry	Finishing lime	Lime Putty
Soundness - Pat Test				Free from pops, pits or expansion cracks	Free from pops, pits or expansion cracks
Soundness - Le Chatelier Test		Expansion average for three specimens ≤10 mm			
Soundness - Autoclave Test				Expansion ≤1%	Expansion ≤1%
Residue on Slaking	≤20% residue on 600 µm sieve				
Fineness - Wet Sieving (expressed on dry basis)		≤5% residue on 600 µm sieve	≤5% residue on 600 µm sieve	≤5% residue on 600 µm sieve and all passing the 1.18 mm sieve	≤5% residue on 600 µm sieve and all passing the 1.18 mm sieve
Free Moisture		≤2.5%		≤2.5%	62%

- **Workability** – From the applicator's perspective, workability is a key quality consideration for the mortar or plaster product. Australian standards do not appear to directly address workability of the plaster lime. The European standards appear to address workability indirectly through a penetration test. The Japanese standards utilize a viscosity test to measure workability. Current ASTM standards utilize both the Emley plasticity test procedure and water-retention test to predict workability of mortars. When developing the Emley plasticity test, viscosity tests were examined (Emley 1920). Though viscosity tests will provide information on the workability of lime putty on a nonabsorptive surface, this view is limited since water-retention is important when the lime is used on an absorptive surface.

- **Soundness** – Soundness tests are required in all of the standards. There are a number of different approaches to soundness testing even within individual standards. The European Standards have four different soundness tests. The Australian standards have three. The United States has two and Japan has one. Test samples in all methods are either cured in a steam cabinet or autoclave. After curing, soundness is measured by observing imperfections and cracks on the surface of specimens, or by measuring the change in dimensions of the test sample. For example, the ASTM standards measure only the imperfections called pops or pits in the sample and not expansion. Expansion potential for Type S hydrated lime is limited by the unhydrated oxides and chemical purity requirements. Type N hydrated lime, however, can have high levels of unhydrated oxides. Type N products have shown expansive potential (Clifton et. al.. 1975). Type N products cannot be used in masonry applications unless it can be proven that they are acceptable for use, yet expansion does not have to be measured. Research could not be found that examines the reasons for curing test samples in the steam cabinet or autoclave. Further study is needed in this area to determine the science behind soundness testing.
- **Air Content** – Air content of mortars containing hydrated lime has been shown to be an important factor in the development of bond strength in mortars. Only the U.S. and European Standards measure air content of lime products. The European standards, however, indicate that air content levels can be as high as 20% in a standard hydraulic lime mortar. This level of air content has been shown to be detrimental to bond strength in masonry cement mortars (Grimm).
- **Particle Size –** The United States, Japanese and Australian standards restrict the amount of particles retained on a 590-600 µm (25-30 mesh) sieve in building lime products. The allowed percentage of residue ranges from 0.5% in ASTM to 5% in the Australian Standard. The European Standard measures residue on a 0.2 mm sieve (70 mesh). In the European Standard, calcium and dolomite limes are required to have no more than 2% residue on a 0.2 mm sieve. Hydraulic lime products are allowed up to 5% residue. The American, European and Australian standards also require testing on a finer screen.
- **Free Moisture –** The European and Australian standards both place restrictions on the free moisture level of lime. Currently, ASTM building lime standards have no free moisture requirements. Excessive free moisture can make transporting bulk lime in material handling systems difficult as well as accelerate the carbonation reaction. Despite no ASTM standard limitation, production process limitations normally restrict free moisture levels below those required in Europe and Australia.
- **Hydraulic Lime Standards –** Hydraulic lime standards were found in both ASTM and European building lime standards. In hydraulic lime standards ASTM C 141 and EN 459-1, the chemical requirements differ considerably. The European standard allows for much lower percentages of available lime. The ASTM standard has only one range for compressive strength while the European standard has three. Creating more than one level of strength for hydraulic lime products in the ASTM standard is currently being considered. The strength requirements, however, should be similar to those in the ASTM C 270 property standards to be consistent with current mortar specifications. At the present time, there is no requirement for workability in the ASTM standard. This will also be proposed in modifications to the standard. The chemistry requirements also require modification to provide more versatility in

the current ASTM standard. Consideration should also be given in these standards to regulating the presence of soluble salts.

- **Hardness Testing** – Japan is the only country that requires hardness testing of building limes. There is little research concerning the difference, if any, in the development of hardness between building lime products. This is another area that should be examined more closely.
- **Compressive Strength** – The reasons for differences between the measurement of hydraulic lime strength in the EN and ASTM standards in mortars proportioned by weight needs to be examined. Currently, most mortar formulations are based on volume proportions.

4 Conclusions

Strengths and weaknesses of four sets of building lime standards were examined. Though there are many similarities between the standards, there are also many differences. Exploration to determine best practices is required. Examining current ASTM building lime standards in light of these best practices is necessary. In particular, the following items should be examined:

- The ASTM Standard (C 141) for hydraulic lime is in need of revisions. Several strength categories, as well as workability requirements in the form of minimum plasticity levels, should be explored.
- The reason for and application of varying levels of calcium carbonate in the Japanese and European standards is interesting and should be explored further.
- The correlation of Emley plasticity to the Japanese viscosity test and field performance should be explored.
- The reason for the considerable number of different soundness testing procedures is unclear and requires further examination.
- The possible inclusion of a free moisture limit for hydrated and hydraulic lime in ASTM standards should be examined.
- The reason for SO_3 requirements in the European standard and its limits should be explored further.
- The reason for proportioning standard hydraulic lime mortars by different concentrations relative to ASTM C 270 should be studied.

Lime specifiers and users come to the United States from all over the world. Though many of the tests are similar, there are differences that we need to understand. Understanding the requirements of global building lime specifications and their associated rationales will help to serve the needs of applicators, architects and owners in the United States more effectively.

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