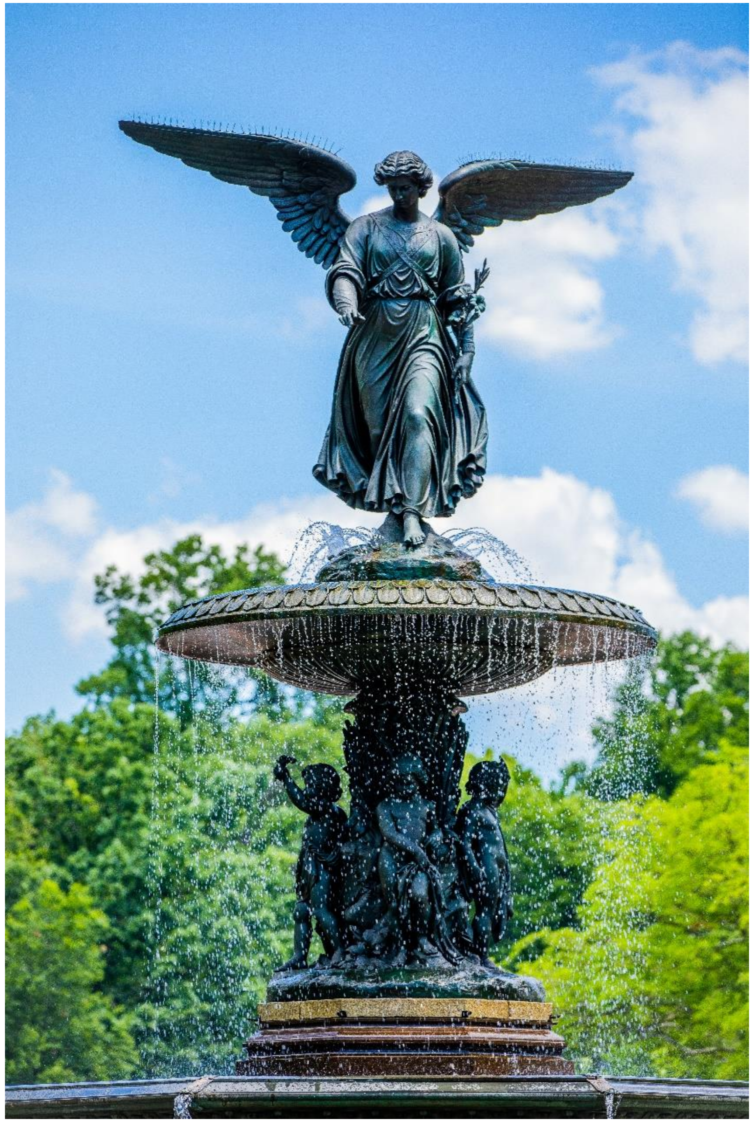
SPHC
Society for the Preservation of Historic Cements

SPHC7:

The 7th
American
Historic
Cements
Conference

June 12-13, 2023
Central Park, NYC



Masonry Mortars:

- Function & Properties
- History
- Chemistry
- Proportioning & Performance
- Esthetics & Matching
- Selection
- Best Practices

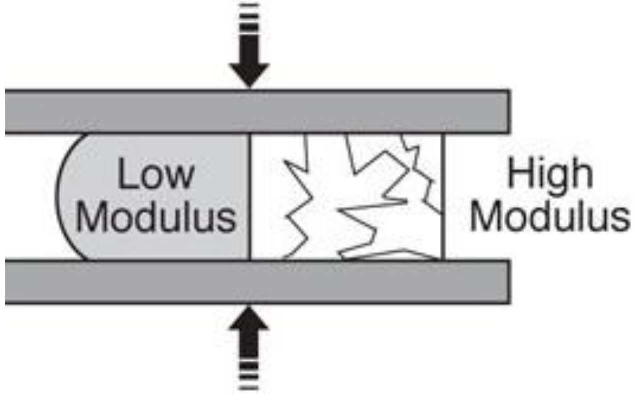
Michael P. Edison

What Is Mortar?

- Mortar is a workable paste which hardens to bind building blocks such as stones, bricks, and concrete masonry units, to fill and seal the irregular gaps between them, spread the weight of them evenly, and sometimes to add decorative colors or patterns to masonry walls.
- It generally consists of a Binder, Aggregates and optional additives

Mortar Functions

- During Construction:
  Keep Masonry Units Apart
- Thereafter:
  Keep Units Together
- Relieve Stresses Due to Unit Expansion & Contraction
    - Mortar Should Be Softer than Unit Masonry
    - Repointing Mortar Strength Should Be The Same Strength or Softer Than Original Mortar
- Mortar Should Be More Permeable than Masonry



Mortar Functions

- Functional Part of the Building Envelope
    - Mortar Should Not Leak
- Sacrificial, But Durable
- Mortar is Supposed to be SIMPLE
    - But There is Widespread Confusion

Functional Failure:

When Simple Goes Wrong..

- SUNY Buffalo North Campus Ellicott Center
- 27 Years Old, Leaking Since Built
- Over-sanded Mortar
- 100% Repointing of 1.5 Million Sq. Ft. = $32 Million

Key Mortar Properties

REF: ASTM C270
Appendix X1

FRESH

- WORKABILITY
  - Enhances Mason's Ability to Fill Joints
- WATER RETENTION
  - Gives Mason Time to Place Units & Overcome Suction
- TIME OF SETTING
  - Influences Working Time and Timing of Final Tooling/Finishing

HARDENED

- BOND STRENGTH
  - The Most Important Property
  - Extensibility/Creep
    - Lower Strength and Modulus Impart Better Flexibility
- COMPRESSIVE STENGTH
  - Lower Than Masonry Units
- APPEARANCE
  - Color, Texture, Profile
- DURABILITY
  - Materials, Process, Workmanship

6000 Years Ago

1000 Years Ago

200 Years Ago

Mortar History

HIGHER TEMPERATURE PROCESSING, STRONGER MORTARS

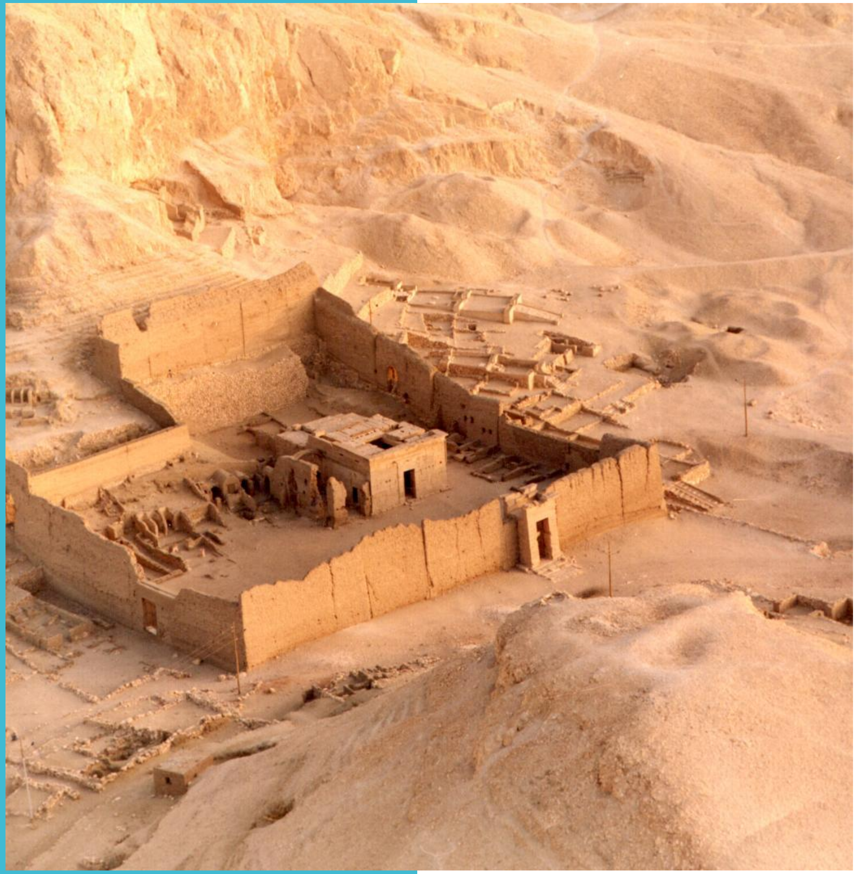
Ancient Mortars

Clay Cliffs on Martha's Vineyard

- Mud, Clay, Pitch, Asphalt
- 6000 Years Ago
- Ambient Temp or Low Heat

Adobe Wall Renewal

Ancient Mortars



- EGYPT:
  4500 years ago
- Gypsum mortar
  - 300° F

Ancient Mortars

- ROME:
  2000 years ago
- Lime (1700° F)
- "Roman Cement"
  - Lime & Pozzolan
    - Volcanic Ash (2700° F)
    - Ground-Up Tile or Pottery Fragments (2300° F)
- Should it be "Greek Cement"?

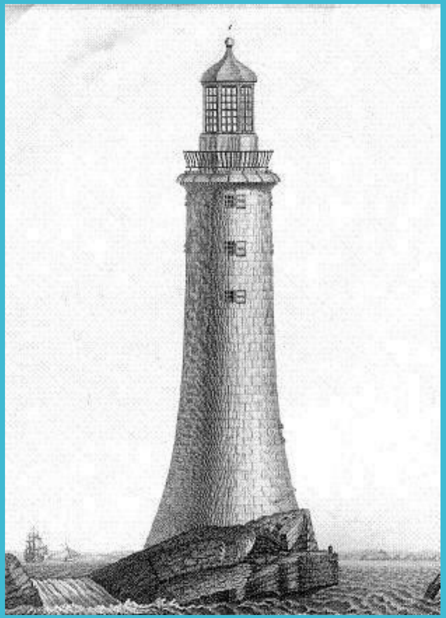
Definition:
HYDRAULIC CEMENT

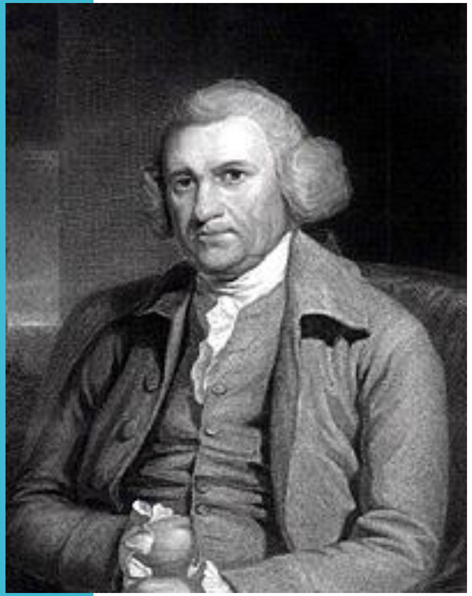
A cement that hardens by reaction with water (hydration) and cures underwater

Ancient Mortars

- "Dark Ages":
  800-1500 years ago
- Art of Roman Cement Lost
- Quality of Lime-Burning Deteriorates

Hydraulic Mortars





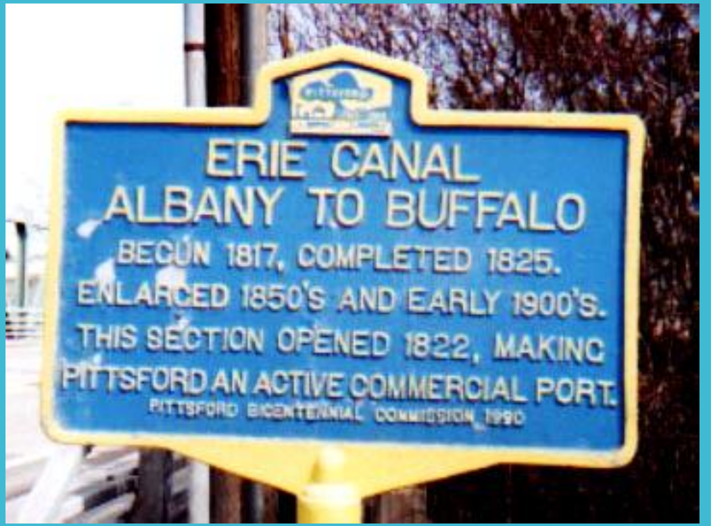
- John Smeaton
  - 1750's: Researched Lime from Various Sources
  - Discovered that Clay Impurities Made Lime Hydraulic
  - 1759: Eddystone Rock Lighthouse Built with Hydraulic Lime / Pozzolan Blend
  - Research Published After His Death in 1791

18th/19th Century British Hydraulic Mortars

Pontcysylte Aqueduct, Wales, Completed 1805

- 1796:
  Parker's Roman Cement Patented
- Natural Cement from Argillaceous Limestone Septaria
- Used in British Canal System
- Some Imported to USA

American Natural Rock Cement



Canvass White

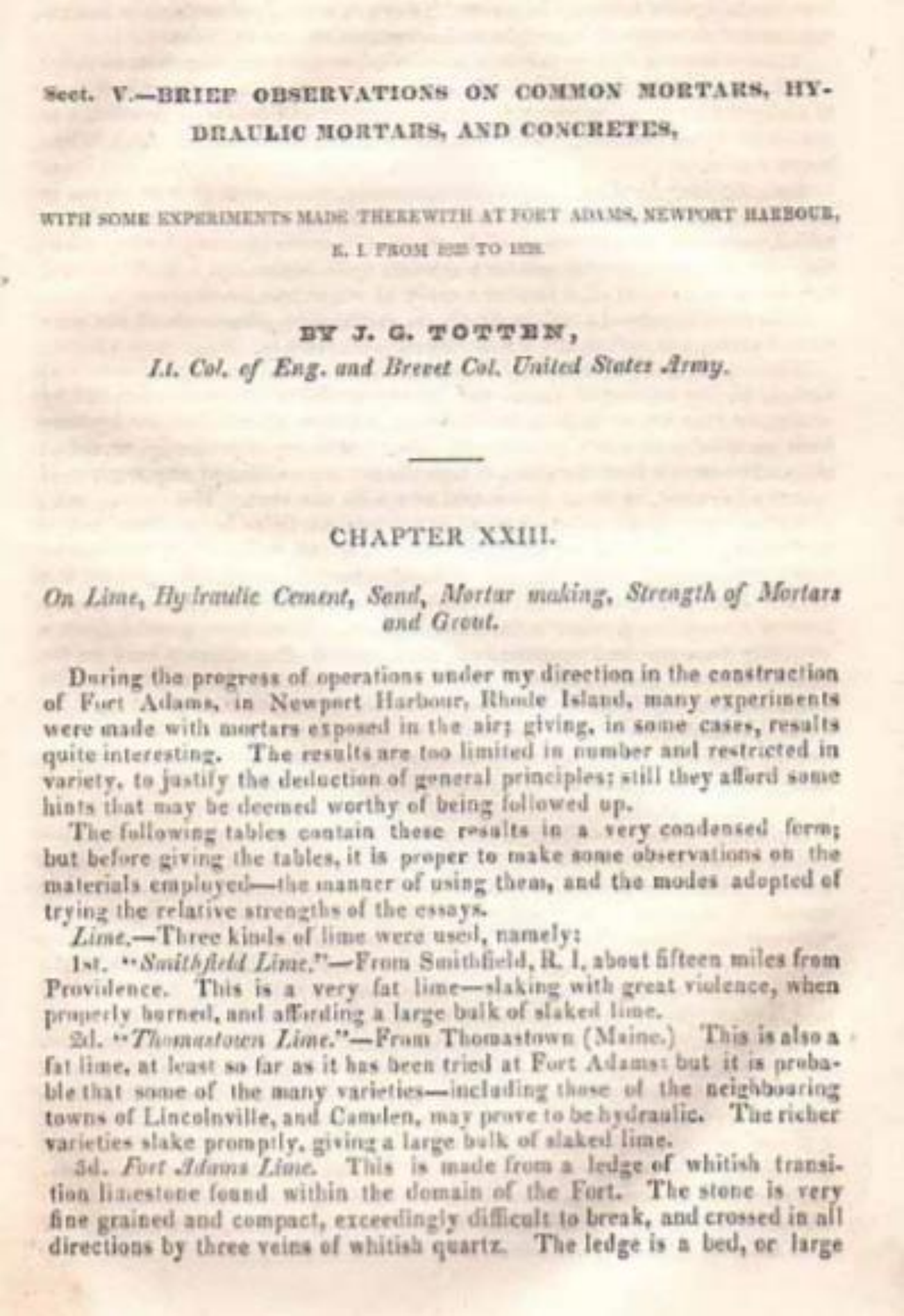
- Sent to England by the Builders of the Erie Canal to Learn Their Secrets
- Learned of Use of Roman (Natural) Cement by the British
- Recommended Use of Roman Cement for the Erie Canal
- Transatlantic Shipment of British Cement Deemed Impractical
- Found Rock to Produce Natural Cement in New York State
- Set Up His Brother in the Cement Business


CANAL ERA, 1825-1860
km 0 100 200
mi 0 100 200
Lake Superior
SOO CANALS
Lake Michigan
Lake Huron
Lake Ontario
Lake Erie
CUMBERLAND AND OXFORD
Portland
CHAMPLAIN
BLACK RIVER
Lowell
MIDDLESEX
Boston
Rome
Northampton
Worcester
OSWEGO
Albany
BLACKSTONE
Providence
Lockport
ERIE
CHENANGO
WELLAND CANAL
Buffalo
CHEMUNG
GENESEE VALLEY
NEW HAVEN AND NORTHAMPTON
DELAWARE AND HUDSON
Erie
MORRIS
Detroit
PENNSYLVANIA STATE CANAL SYSTEM
New York
OHIO AND PENNSYLVANIA
DELAWARE AND RARITAN
Toledo
Cleveland
Chicago
OHIO AND ERIE
SCHUYLKILL
ILLINOIS AND MICHIGAN
Pittsburgh
Philadelphia
WALHONDING AND MOHICAN
Ft. Wayne
Alleghany Portage R.R.
SUSQUEHANNA AND TIDEWATER
La Salle
SANDY AND BEAVER
CHESAPEAKE AND DELAWARE
MIAMI
WABASH AND ERIE
CHESAPEAKE AND OHIO
Cumberland
Columbus
MUSKINGUM
Washington
HOCKING
WHITE-WATER
Terre Haute
OHIO AND ERIE
Cincinnati
JAMES RIVER AND KANAWHA
Portsmouth
Richmond
Ohio
Buchanan
Norfolk
Louisville
OHIO FALLS
DISMAL SWAMP
ALBEMARLE AND CHESAPEAKE
Evansville

Historic American Mortars

By the dawn's early light

The Third System



Sect. V.—BRIEF OBSERVATIONS ON COMMON MORTARS, HYDRAULIC MORTARS, AND CONCRETES,

WITH SOME EXPERIMENTS MADE THEREWITH AT FORT ADAMS, NEWPORT HARBOUR, R. I. FROM [illegible] TO [illegible]

BY J. G. TOTTEN,
Lt. Col. of Eng. and Brevet Col. United States Army.

CHAPTER XXIII.

On Lime, Hydraulic Cement, Sand, Mortar making, Strength of Mortars and Grout.

During the progress of operations under my direction in the construction of Fort Adams, in Newport Harbour, Rhode Island, many experiments were made with mortars exposed in the air; giving, in some cases, results quite interesting. The results are too limited in number and restricted in variety, to justify the deduction of general principles; still they afford some hints that may be deemed worthy of being followed up.

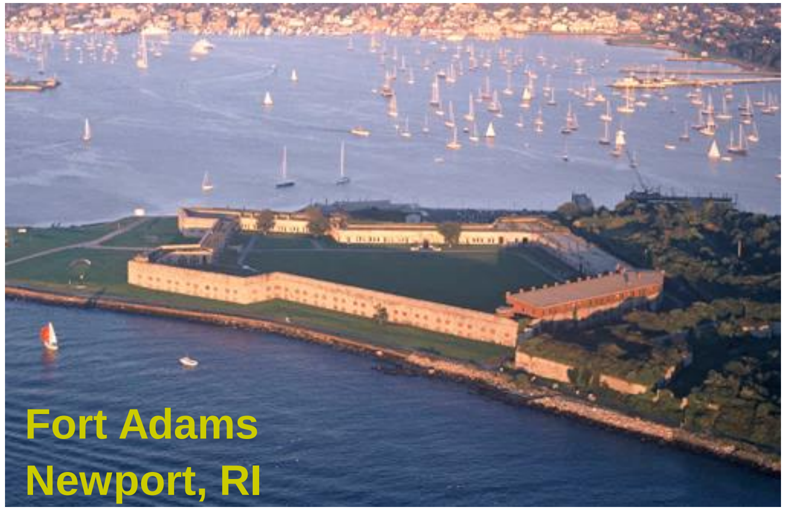
The following tables contain these results in a very condensed form; but before giving the tables, it is proper to make some observations on the materials employed—the manner of using them, and the modes adopted of trying the relative strengths of the essays.

Lime.—Three kinds of lime were used, namely:

1st. "*Smithfield Lime.*"—From Smithfield, R. I. about fifteen miles from Providence. This is a very fat lime—slaking with great violence, when properly burned, and affording a large bulk of slaked lime.

2d. "*Thomastown Lime.*"—From Thomastown (Maine.) This is also a fat lime, at least so far as it has been tried at Fort Adams: but it is probable that some of the many varieties—including those of the neighbouring towns of Lincolnville, and Camden, may prove to be hydraulic. The richer varieties slake promptly, giving a large bulk of slaked lime.

3d. *Fort Adams Lime.* This is made from a ledge of whitish transition limestone found within the domain of the Fort. The stone is very fine grained and compact, exceedingly difficult to break, and crossed in all directions by three veins of whitish quartz. The ledge is a bed, or large



Fort Adams
Newport, RI

Chief Engineer
Corps of Engineers
1838-1864

Table No. LXV.

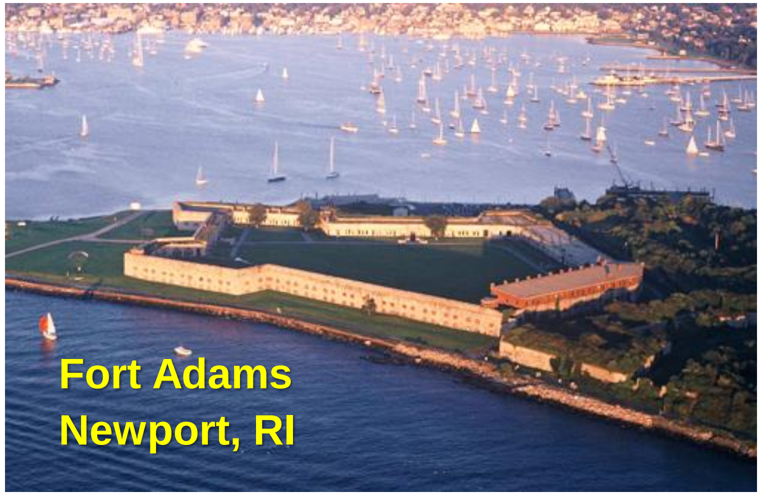
No.	Nature and Composition of the mortar.	Bricks wet or dry.	Tenacity.		Hardness.		Remarks.
			Number of series affording the mean.	Mean tenacity.	Number of series affording the mean.	Mean hardness.	
1	New York Hydraulic cement B, alone .	W	1	32.6			
2	do. do. do. A, alone . .	W	5	56.2	4	1053	
3	Roman cement (Parker's English) alone .	W	1	18.5	1	260	
4	do. (do.) alone	D	1	22.6	1	412	
5	Lime alone	W	1	10.5	1	98	
6	Hydraulic cement A in powder . 1 Sand No 3 .50	W	1	61.9	1	1055	
7	Cement A do. 1 Sand the same 1	W	6	40.3	5	993	
8	Cement A do. 1 Sand the same 1.50	W	5	33.1	4	918	
9	Cement A do. 1 Sand the same 1.30	D	2	30.4	1	765	
10	Hydraulic cement A in powder . 1 Sand No. 3 . 2	W	3	17.5	3	670	
11	Cement A do 1 Sand the same 3	W	3	19.8	2	367	
12	Cement A do. 1 Lime slaked to powder .50 Sand the same 1.50	W	2	29.6	3	573	
13	Cement A do. 1 Lime the same .50 Sand No. 2 2	W	4	20.1	3	609	
14	Cement A do. 1 Lime the same 1 Sand No. 2. 2	W	4	28.3	3	778	
15	Cement A do. 1 Lime the same 2 Sand No. 2 4	W	4	17.1	3	545	
16	Cement A do. 1 Lime the same 2 Sand No. 2 6	W	4	16.2	3	267	
17	Cement A do. 1 Lime in paste, .50 Sand No. 2 1.50	W	1	44.4	1	765	
18	Cement A 1 Lime in paste .50 Sand No. 2 1.50	D	1	54.7	1	915	
19	Cement B do. 1 Sand No. 3 1	W	2	18.9			
20	Cement B do. 1 Sand No. 2 1.50	W	1	23.4			
21	Cement B do. 1 Sand No. 2. 2	W	2	14.7			

30

Table No. LXV—Continued.

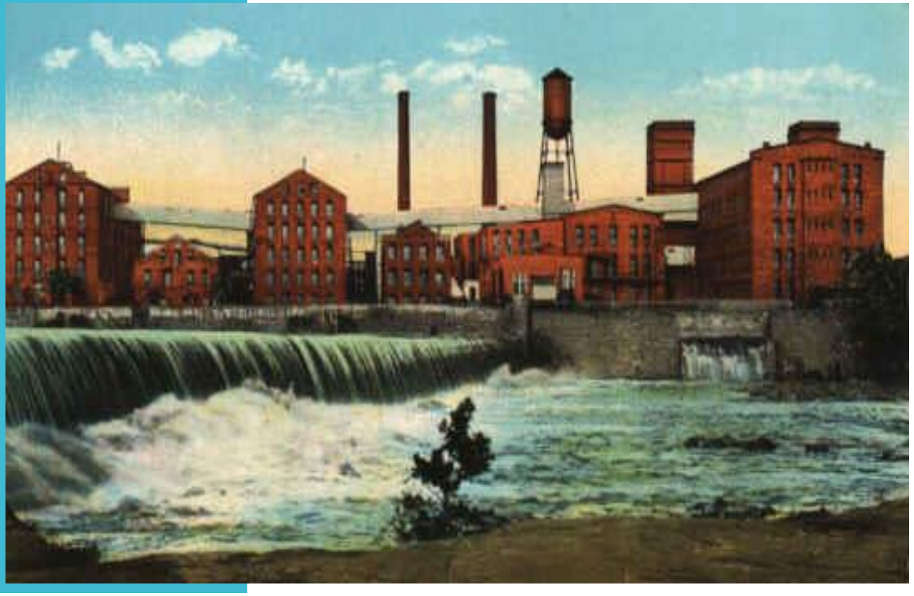
No.	Nature and Composition of the mortar.	Bricks wet or dry.	Tenacity.		Hardness.		Remarks.
			Number of series affording the mean.	Mean tenacity.	Number of series affording the mean.	Mean hardness.	
22	Cement B do. 1 Lime in powder slaked . .50 Sand No. 2 2	W	2	17.5			
23	Cement B do. 1 Lime the same 1 Sand No. 2 2	W	2	19.1			
24	Hydraulic cement B in powder 1 Lime slaked in powder 2 Sand No. 2 4	W	2	18.1			
25	Cement B 1 Lime the same 2 Sand No. 2 6	W	2	15.0			
26	Roman cement 1 Sand No. 2 .50	W	1	19.2	1	597	
27	Roman cement 1 Sand No. 2 1	W	1	16.8	1	309	
28	Roman cement 1 Sand No. 2 1.50	W	1	15.5	1	266	
29	Roman cement 1 Lime in paste 0.50 Sand No. 2 1.50	W	1	26.7	1	471	
30	Roman cement 1 Lime in paste 0.50 Sand No. 2 1.50	D	1	23.1	1	787	
31	Lime in powder 1 Sand No. 3 3.30	W	3	12.5	1	159	
32	Lime in powder 1 Sand No. 3 6	W	1	6.6	1	107	
33	Lime in paste 1 Sand No. 3 .50	W	1	14.3	1	208	
34	Lime in paste 1 Sand No. 3 1.50	W	3	15.4	2	275	
35	Lime in paste 1 Sand No. 3 3	W	4	12.8	2	146	Made with a hoe.
36	Lime in paste 1 Sand No. 3 2.50 a 3	W	6	14.3	5	202	Made in mortar mill.
37	Lime in paste 1 Sand No. 3 2.50 a 3	D	3	14.9	4	234	do. do.
38	Lime in paste 1 Sand No. 1 2.50 a 3	W	1	13.7	1	217	do. do.
39	Lime in paste 1 Sand No. 1 2.50 a 3	D	1	16.2	1	206	do. do.
40	Lime in paste 1 Sand No. 1 2	W	1	35.8	1	242	Lime different.
41	Lime in paste 1 Sand No. 1 2	D	1	25.6	1	231	

19th Century Historic American Mortars



Fort Adams
Newport, RI

- Military Construction of 51 "Third System" Seacoast Forts
- Industrial Revolution
- Railroad-Building



B & O Railroad

C & O Canal

Where Was Natural Cement Produced in the 19th Century?

- **TOP US SITES**:
    1. Rosendale, NY
    2. Louisville, KY
    3. Western/Central NY
    4. Pennsylvania
    5. Illinois
    6. Wisconsin
    7. Potomac River

- USA, 1890's:
    - >70 Sites
    - >17 States
- Canada
    - Limited Historical Data
    - At Least 2 Sites in Ontario & Quebec

"Rosendale" Became Synonymous with American Natural Cement
Rosendale Natural Cement Products® is a Registered Trademark of Edison Coatings, Inc.

Natural Cement in the 20th Century

- Most Sites Close by 1910
- Top Remaining Sites:
  - Louisville, KY*
  - Rosendale, NY
  - Fort Scott, KS
- All Closed in the 1970's

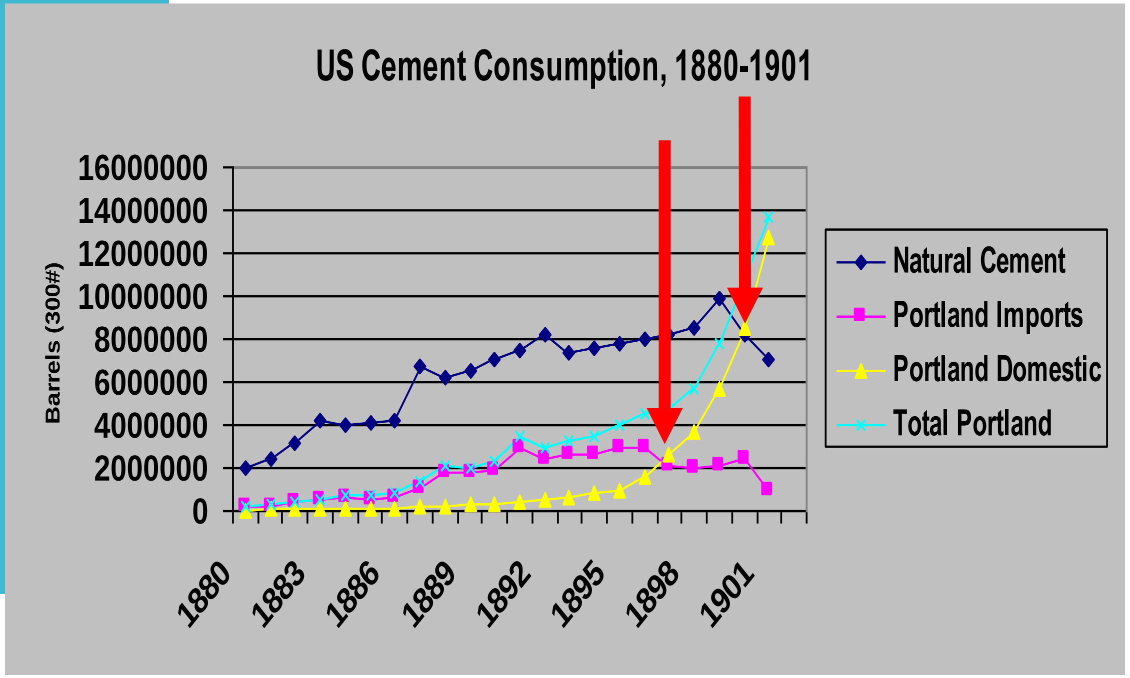
Quarry Near Louisville, KY

Rosendale, NY

Quarry in Fort Scott, KS

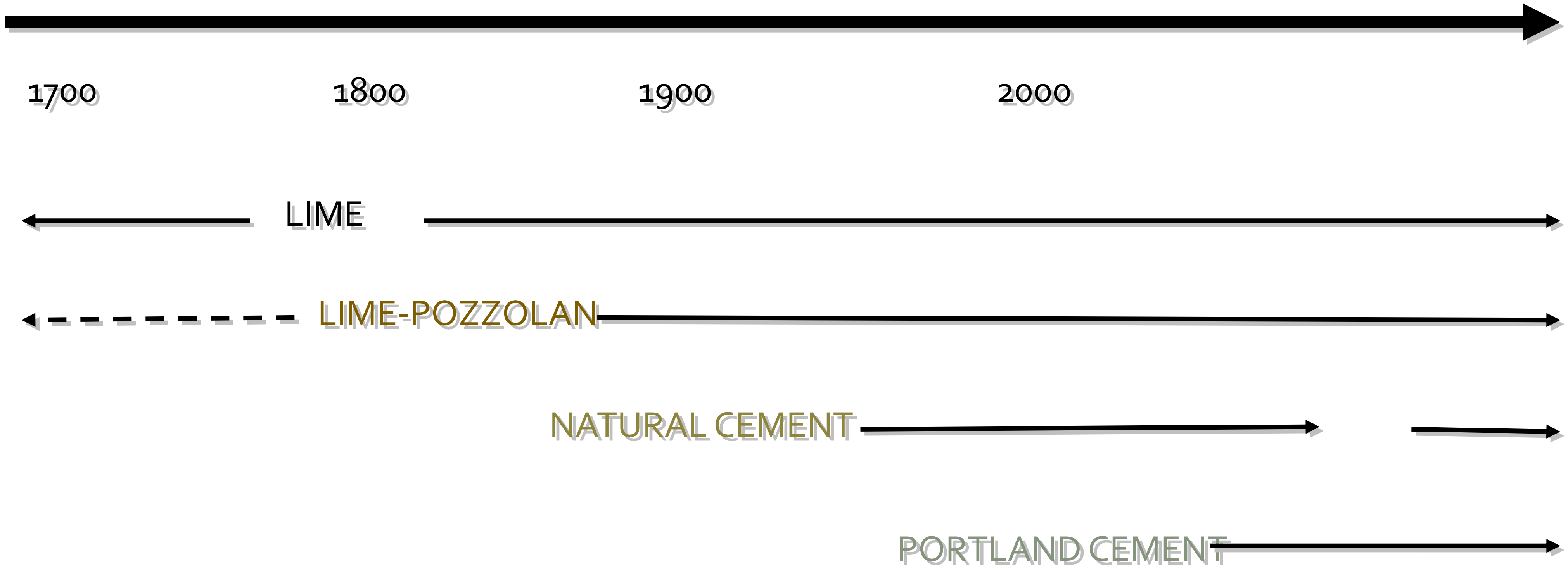
Portland Cement


Coplay Cement Co. Kilns, 1875


US Cement Consumption, 1880-1901

- First Imports: 1868
- US Domestic Production Begins 1872-1875
  - Coplay Cement Co., Lehigh Valley, PA
  - Production Rates are Low Until 1897
  - Imports Exceed Domestic Production Until 1897
  - Portland Overtakes Natural Cement 1900
- Early Cements Low-Fired, Coarse Grind

North American Binder History



1700

1800

1900

2000

LIME

LIME-POZZOLAN

NATURAL CEMENT

PORTLAND CEMENT

Air Lime

Water Lime

Portland/Lime

Binder Chemistry

AIR LIME, WATER LIME, POZZOLANS, CARBONATION, HYDRATION

Lime

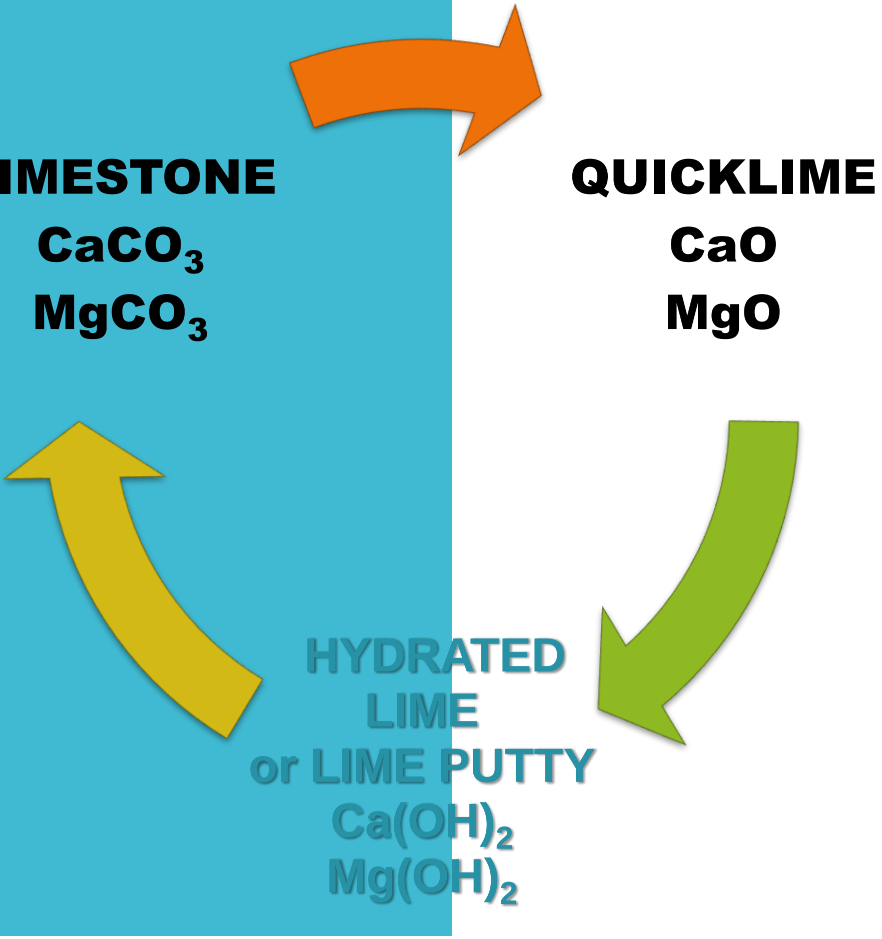
- Quicklime
  Hydrated Lime
  Lime Putty
- "Air Lime"
- Non-Hydraulic Lime

ASTM C5
ASTM C207
ASTM C1489

New York Botanic Gardens Stone Mill
Built 1840, Lime-Sand Mortar
Repointed 2008, Lime-Sand Mortar

The Lime Cycle

900-1000°C



LIMESTONE

$CaCO_3$

$MgCO_3$

QUICKLIME

CaO

MgO

HYDRATED LIME or LIME PUTTY

$Ca(OH)_2$

$Mg(OH)_2$

Step 1: Calcination

LIMESTONE

$CaCO_3$

$MgCO_3$

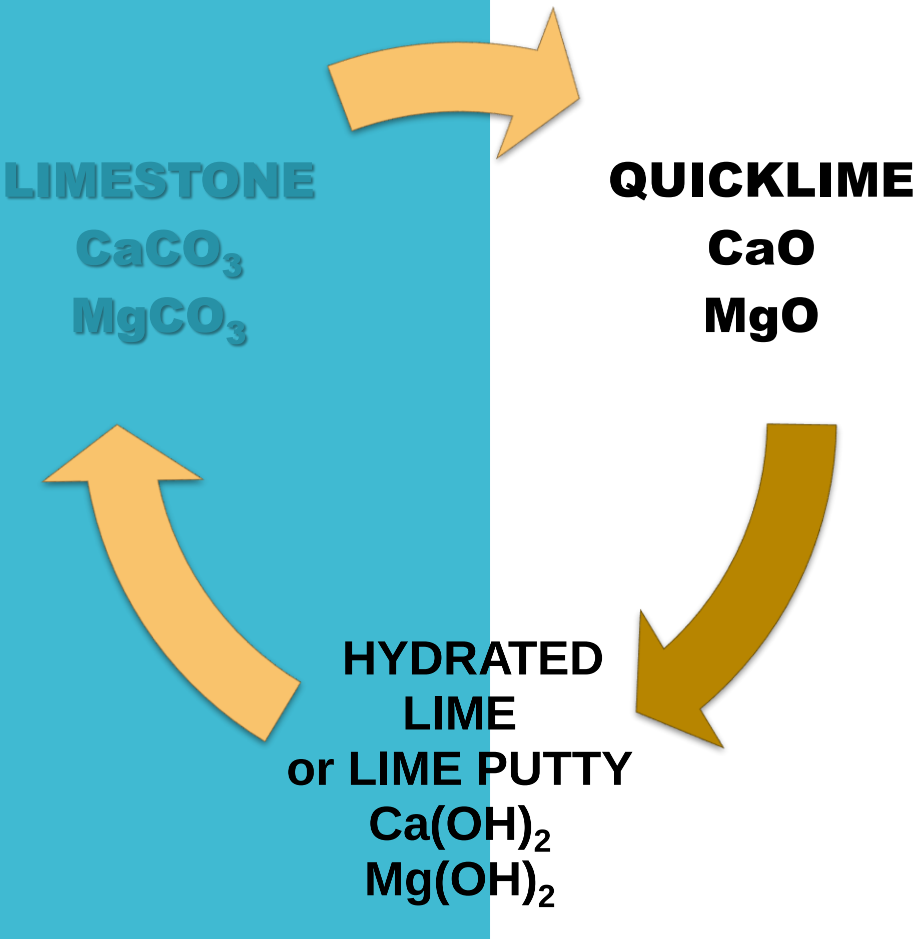
$$\xrightarrow[-CO_2]{+HEAT}$$

QUICKLIME

CaO

MgO

The Lime Cycle



LIMESTONE
$CaCO_3$
$MgCO_3$

QUICKLIME
CaO
MgO

HYDRATED LIME or LIME PUTTY
$Ca(OH)_2$
$Mg(OH)_2$

Step 2: Hydration

QUICKLIME
CaO
MgO

$$\xrightarrow[+H_2O]{-HEAT}$$

HYDRATED LIME or LIME PUTTY
$Ca(OH)_2$
$Mg(OH)_2$

ASTM C5

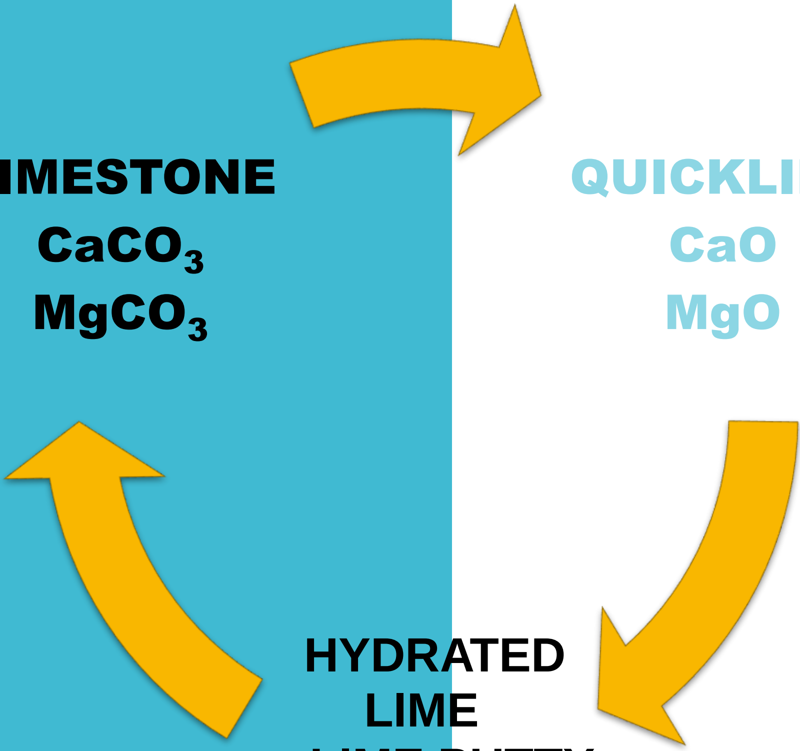
ASTM C207

ASTM C1489

Quicklime Slaking Demonstrations

SLAKING BY SPRINKLING,
SLAKING BY DROWNING,
SLAKING BY "HOT-MIXING"

The Lime Cycle



LIMESTONE
$CaCO_3$
$MgCO_3$

QUICKLIME
CaO
MgO

HYDRATED LIME
or LIME PUTTY
$Ca(OH)_2$
$Mg(OH)_2$

Step 3: Carbonation

HYDRATED LIME
or LIME PUTTY
$Ca(OH)_2$
$Mg(OH)_2$

$\xrightarrow[+CO_2]{}$

LIMESTONE
$CaCO_3$
$MgCO_3$

AGING:
Putty vs. Hydrate
Hi-Cal vs. Dolomitic

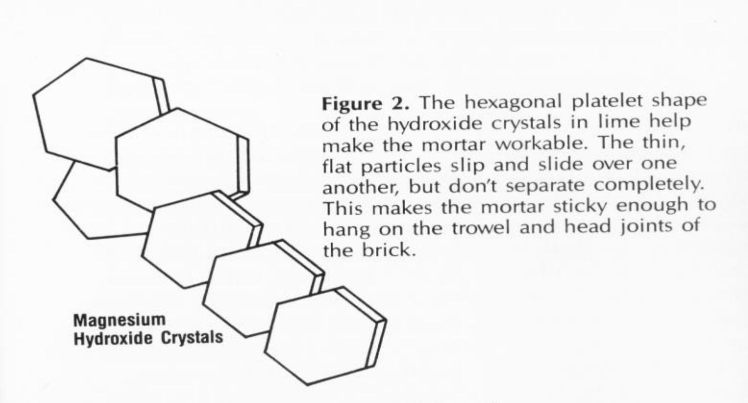


Figure 2. The hexagonal platelet shape of the hydroxide crystals in lime help make the mortar workable. The thin, flat particles slip and slide over one another, but don't separate completely. This makes the mortar sticky enough to hang on the trowel and head joints of the brick.

- Getty Institute Study:
  - Hi-Calcium Lime Develops Hexagonal Platelet Microstructure in 4 Months
- National Lime Association:
  - Magnesium Hydroxide Has Hexagonal Microstructure
- Workability:
  - Water Retention
  - Plasticity
  - "Feel"

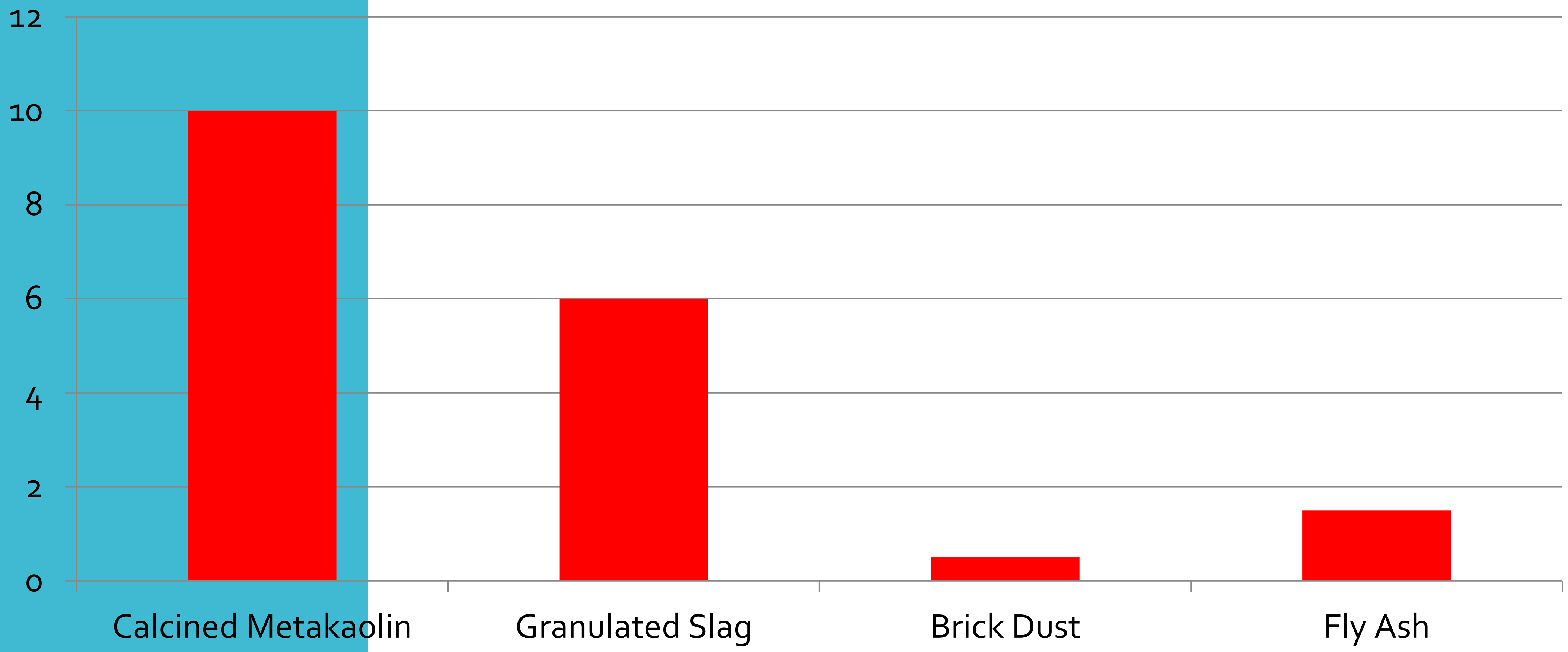
Pozzolans

Siliceous or aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in **the presence of moisture**, chemically react with calcium hydroxide $Ca(OH)_2$ to form compounds possessing hydraulic cementitious properties

Simply Stated: Materials that react with lime to impart cement-like properties

- Natural (Volcanic ash, volcanic tuff, pumicite)
- Artificial (fly ash, silica-fume, granulated blast furnace slag)

Pozzolanic Reactivity



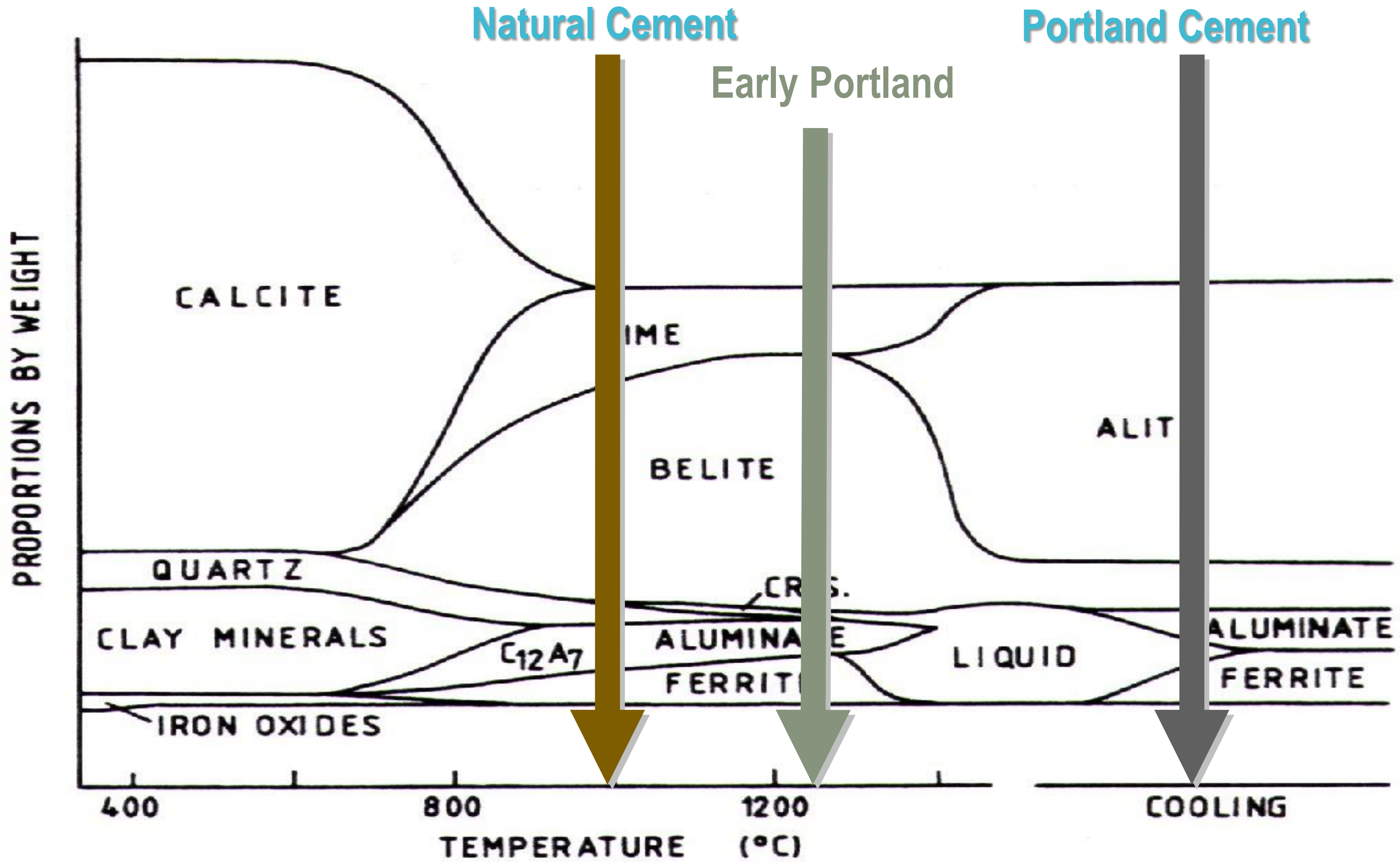
Natural Cement

ASTM C10

vs.

Portland Cement

ASTM C150



Natural Hydraulic Lime (NHL)

- Made from Impure Limestone Without Modifications or Additions
- 3 Strengths:
  - 2.0 Mpa
  - 3.5 Mpa
  - 5.0 Mpa
- Never Intentionally Manufactured in the United States
- Imported for Limestone & Marble Non-Staining White Mortars

100 Centre Street, NYC
Built & Repointed with
Natural Hydraulic Lime

America's Historic View of Natural Hydraulic Lime

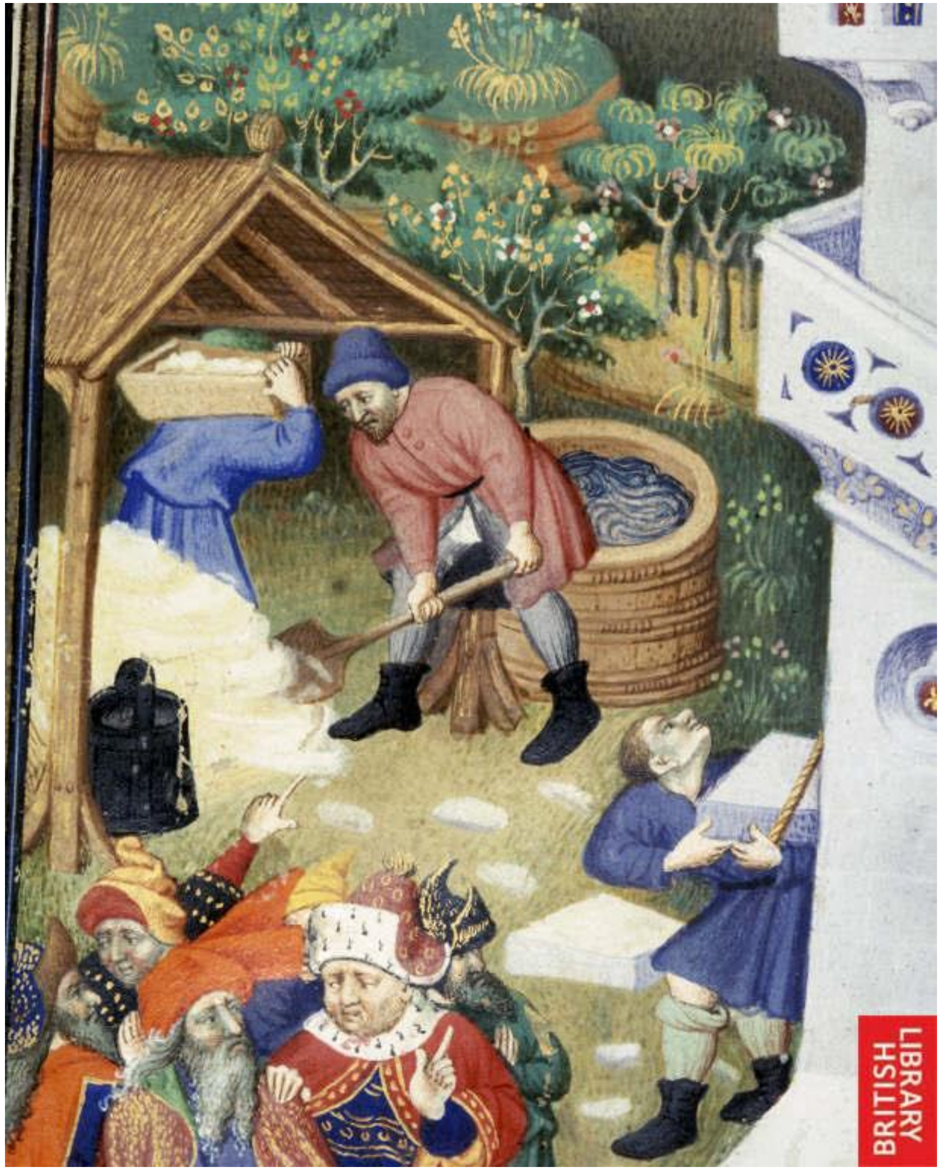
"The hydraulic limes are usually, compared to portland or good natural cements, only feebly hydraulic. This fact, taken in connection with the abundance of materials suitable for the manufacture of natural cements, has prevented the introduction of hydraulic lime manufacture into the United States, though in Europe the industry is of considerable importance. ***No hydraulic lime is at present made in this country*****."**

-Edwin C. Eckel,
"Cements, Limes & Plasters", 9th Edition, 1928

Mortar Proportioning

How Do We Properly Set Binder: Sand Ratio?

- Binder Should Be Just Sufficient to Fill Voids in Sand
- Excess Binder Increases Shrinkage
- Inadequate Binder Leads to High Porosity, Potential Leakage
- For Well-Graded Sand, 2¼-3 :1



Void Ratio Demonstration

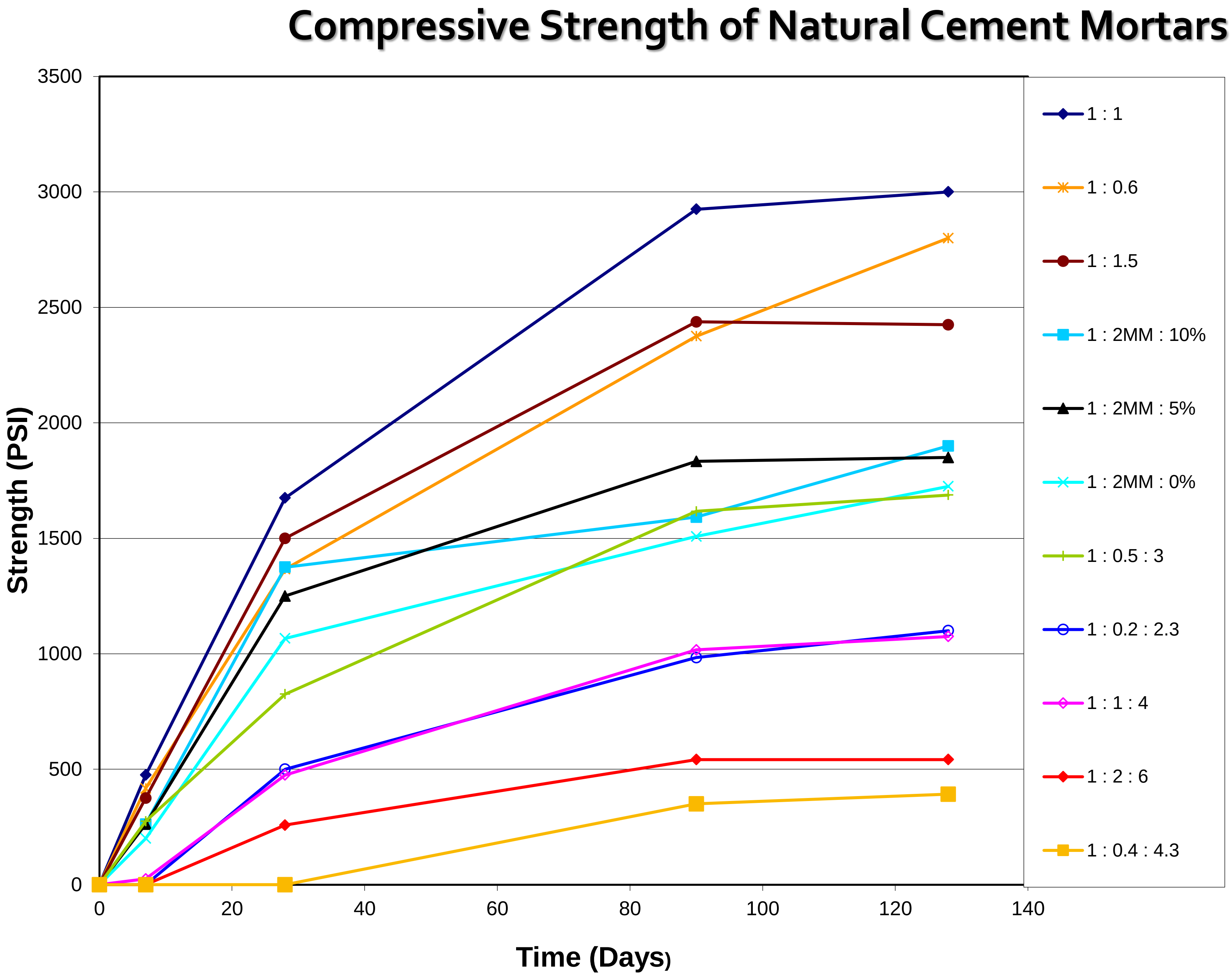
DETERMINING OPTIMUM BINDER:SAND RATIO

Historic Mortar Proportions

- NHL
  - 1:2½ is Optimal
- Lime
  - 1:2 - 1:4
- Roman Cement
  - "Straight" - 1:2
- Natural Cement
  - 1:½ - 1:3.7
  - May or May Not Include Lime

ROMAN CEMENT REPOINTING AT PALAU GUELL, BARCELONA

With Natural Cement One Binder Can Produce Any Strength Desired by Adjusting Aggregate Ratio and/or Lime Addition Levels



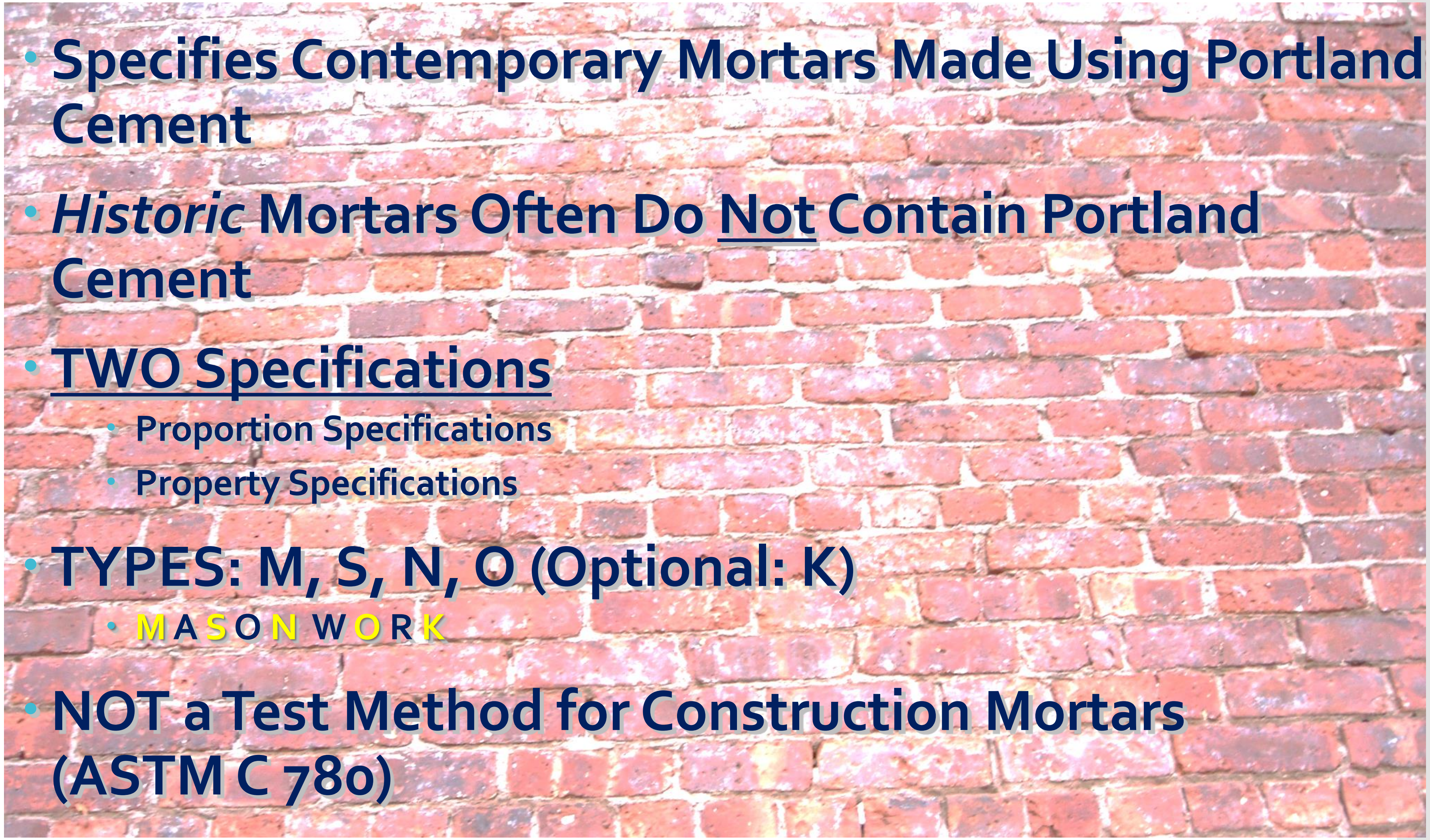
Modern Mortars

ASTM C270

- Binder
  - Portland Cement
    - ASTM C150
  - w/ Lime
    - ASTM C207
  - Masonry Cement
    - ASTM C91
  - Mortar Cement
    - ASTM C1329
- Sand
  - ASTM C144
- Optional Additives
  - Time of Setting, Workability, Water Repellent
    - ASTM C1384
  - Color
    - ASTM C979

ASTM C 270

Specification for Mortar for Unit Masonry



- **Specifies Contemporary Mortars Made Using Portland Cement**
- ***Historic* Mortars Often Do Not Contain Portland Cement**
- **TWO Specifications**
  - **Proportion Specifications**
  - **Property Specifications**
- **TYPES: M, S, N, O (Optional: K)**
  - **MASON WORK**
- **NOT a Test Method for Construction Mortars (ASTM C 780)**

Proportion Specifications

ASTM c270

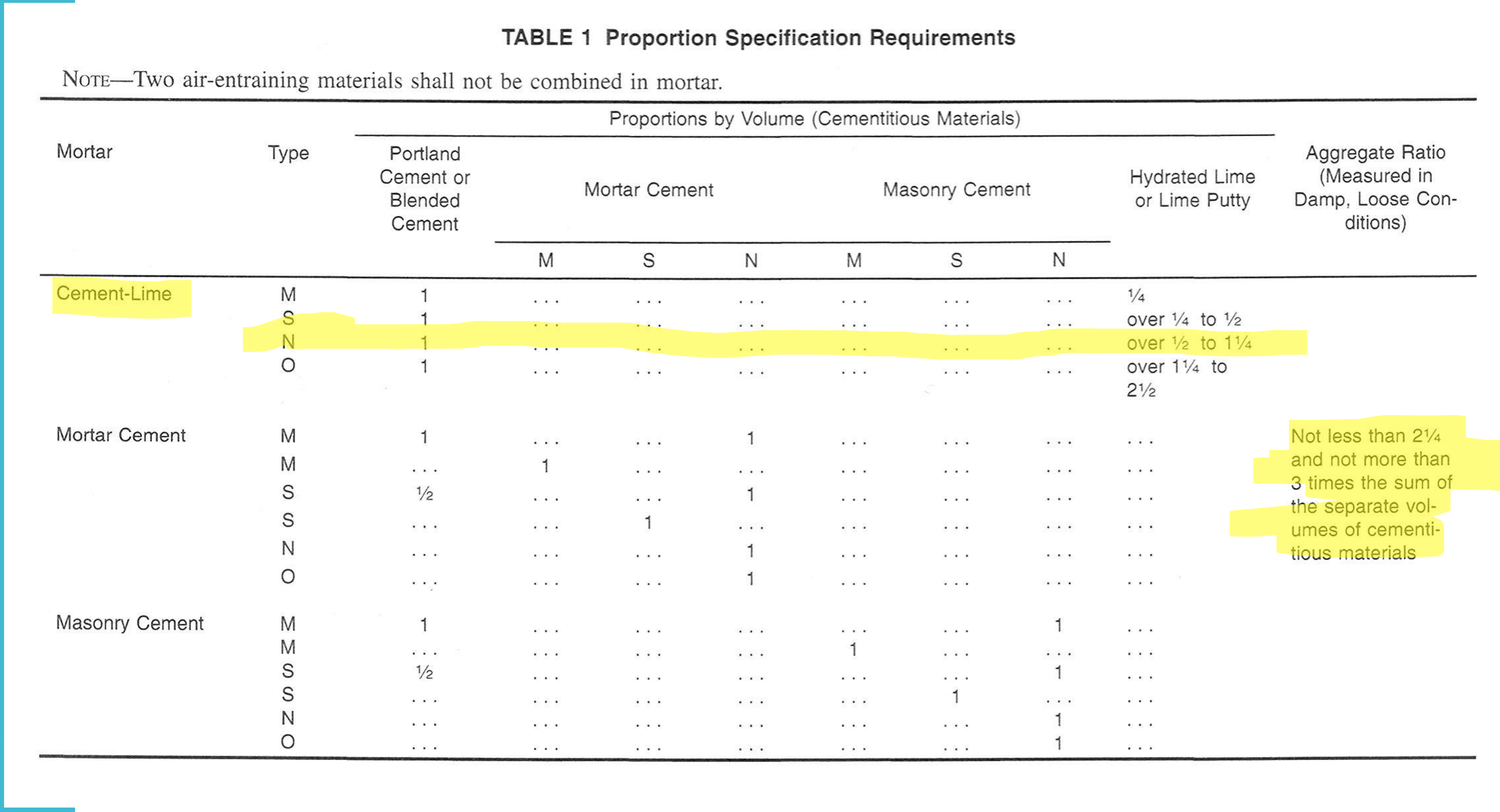
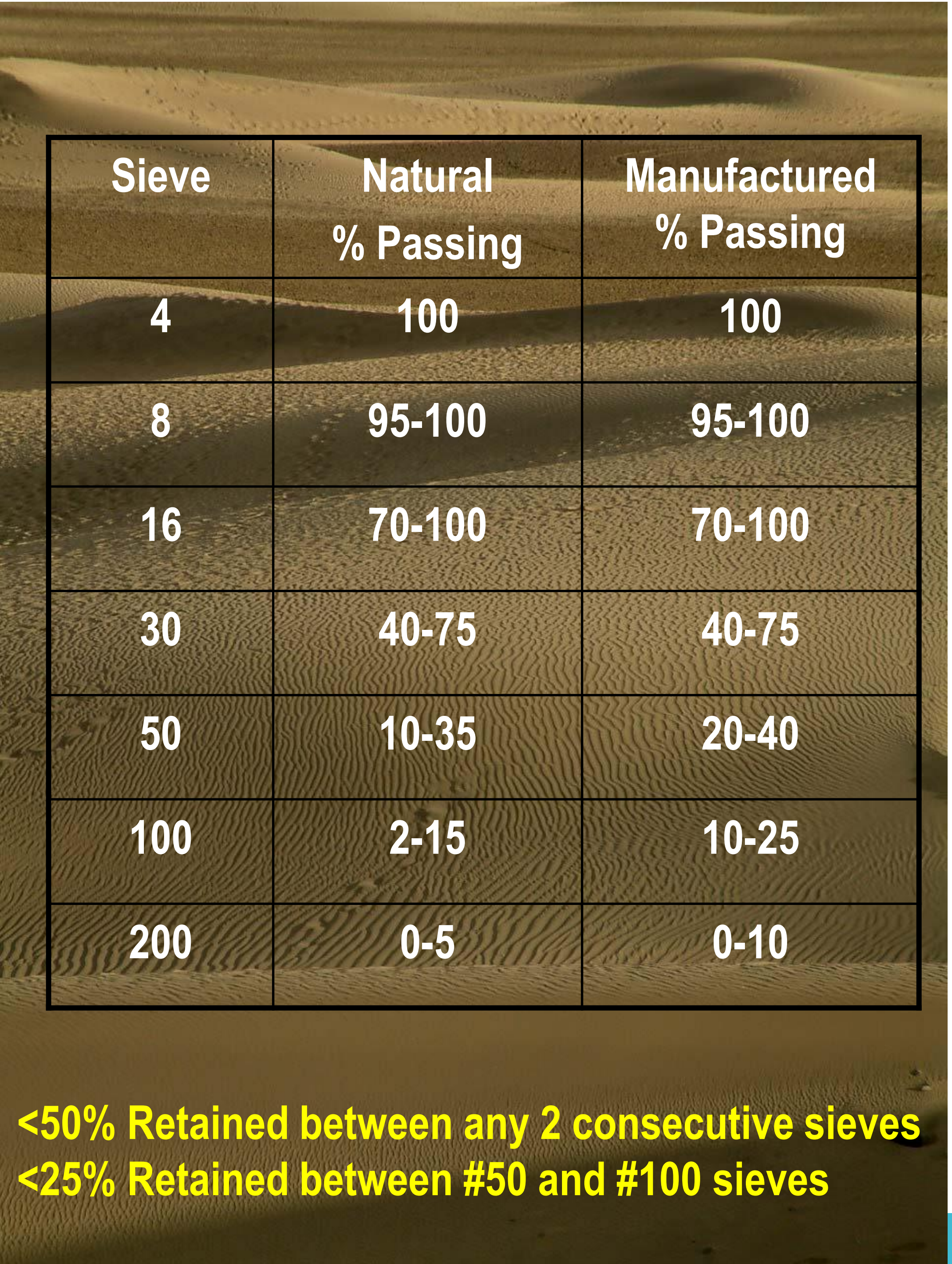


TABLE 1 Proportion Specification Requirements

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

Mortar	Type	Proportions by Volume (Cementitious Materials)								Aggregate Ratio (Measured in Damp, Loose Conditions)
		Portland Cement or Blended Cement	Mortar Cement			Masonry Cement			Hydrated Lime or Lime Putty	
			M	S	N	M	S	N		
Cement-Lime	M	1	. . .	. . .	. . .	. . .	. . .	. . .	¼	Not less than 2¼ 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 1¼	
	O	1	. . .	. . .	. . .	. . .	. . .	. . .	over 1¼ to 2½	
Mortar Cement	M	1	. . .	. . .	1	. . .	. . .	. . .	. . .	
	M	. . .	1	. . .	. . .	. . .	. . .	. . .	. . .	
	S	½	. . .	. . .	1	. . .	. . .	. . .	. . .	
	S	. . .	. . .	1	. . .	. . .	. . .	. . .	. . .	
	N	. . .	. . .	. . .	1	. . .	. . .	. . .	. . .	
	O	. . .	. . .	. . .	1	. . .	. . .	. . .	. . .	
Masonry Cement	M	1	. . .	. . .	. . .	. . .	. . .	1	. . .	
	M	. . .	. . .	. . .	. . .	1	. . .	. . .	. . .	
	S	½	. . .	. . .	. . .	. . .	. . .	1	. . .	
	S	. . .	. . .	. . .	. . .	. . .	1	. . .	. . .	
	N	. . .	. . .	. . .	. . .	. . .	. . .	1	. . .	
	O	. . .	. . .	. . .	. . .	. . .	. . .	1	. . .	



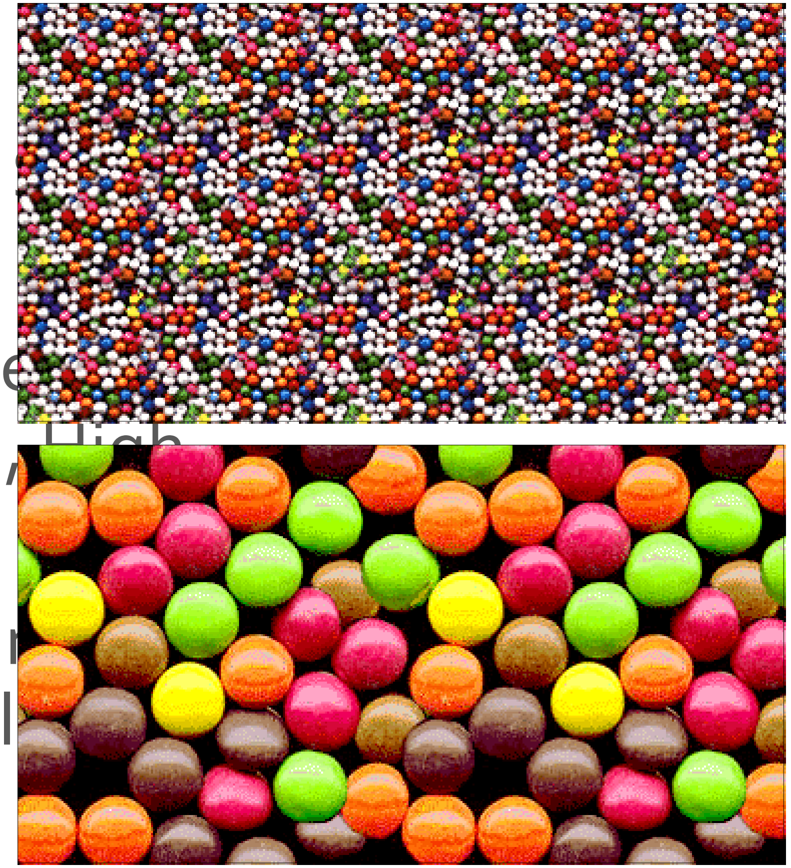
Sieve	Natural % Passing	Manufactured % Passing
4	100	100
8	95-100	95-100
16	70-100	70-100
30	40-75	40-75
50	10-35	20-40
100	2-15	10-25
200	0-5	0-10

<50% Retained between any 2 consecutive sieves
<25% Retained between #50 and #100 sieves

SAND

ASTM C144

- Particle Size,
  & Density
- Too Many Fine
  Low Strength, High
  Shrinkage
- Inadequate Fi
  Poor Workabil



Sand Bulking Demonstration

DRY VS. DAMP, LOOSE CONDITION

Pre-Packaged Mortars Are Proportioned by Weight

Density Differences in Materials

Converting Volumes to Weights

Natural Cement	Lime	C144 Sand	Lime Putty	Portland Cement
67.5 lb/ft^3	40 lb/ft^3	80 lb/ft^3	97.5 lb/ft^3	80 lb/ft^3

Property Specifications
ASTM C270

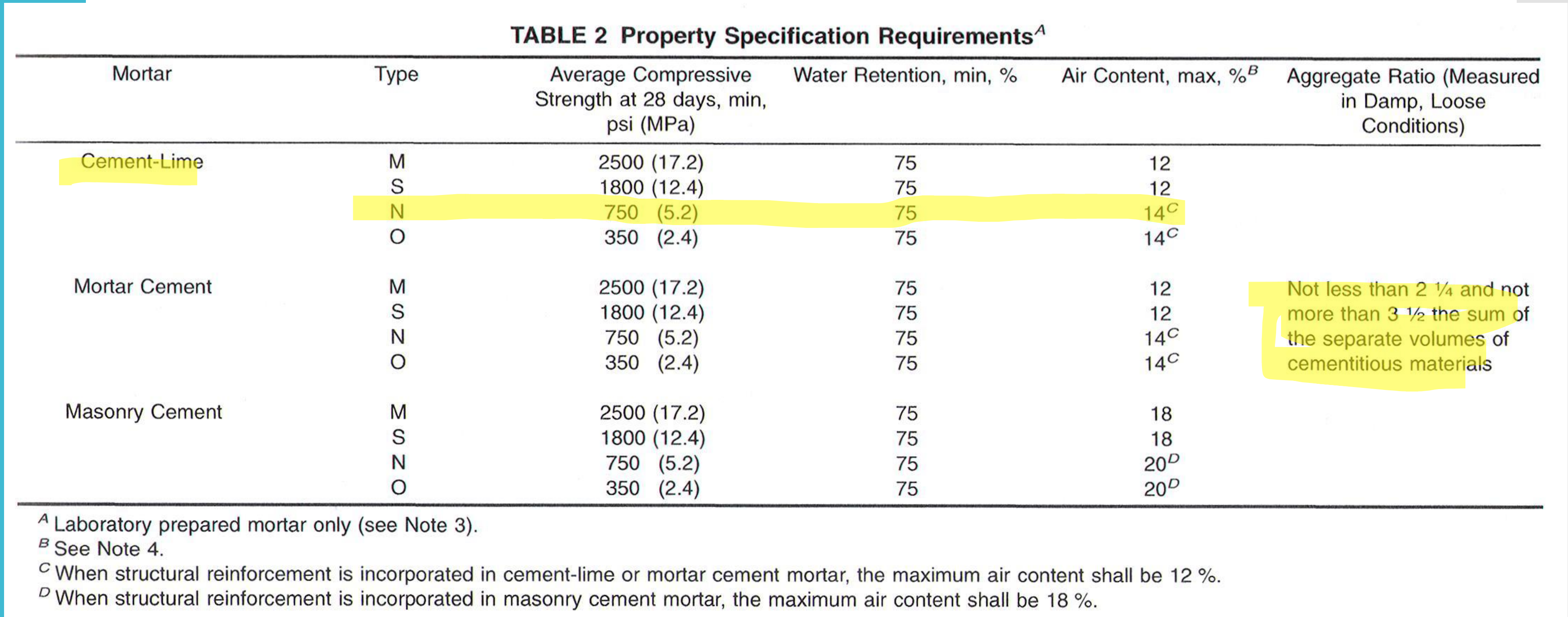


TABLE 2 Property Specification Requirements[A]

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	
	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	Not less than 2 ¼ and not more than 3 ½ 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]	
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]	

[A] Laboratory prepared mortar only (see Note 3).

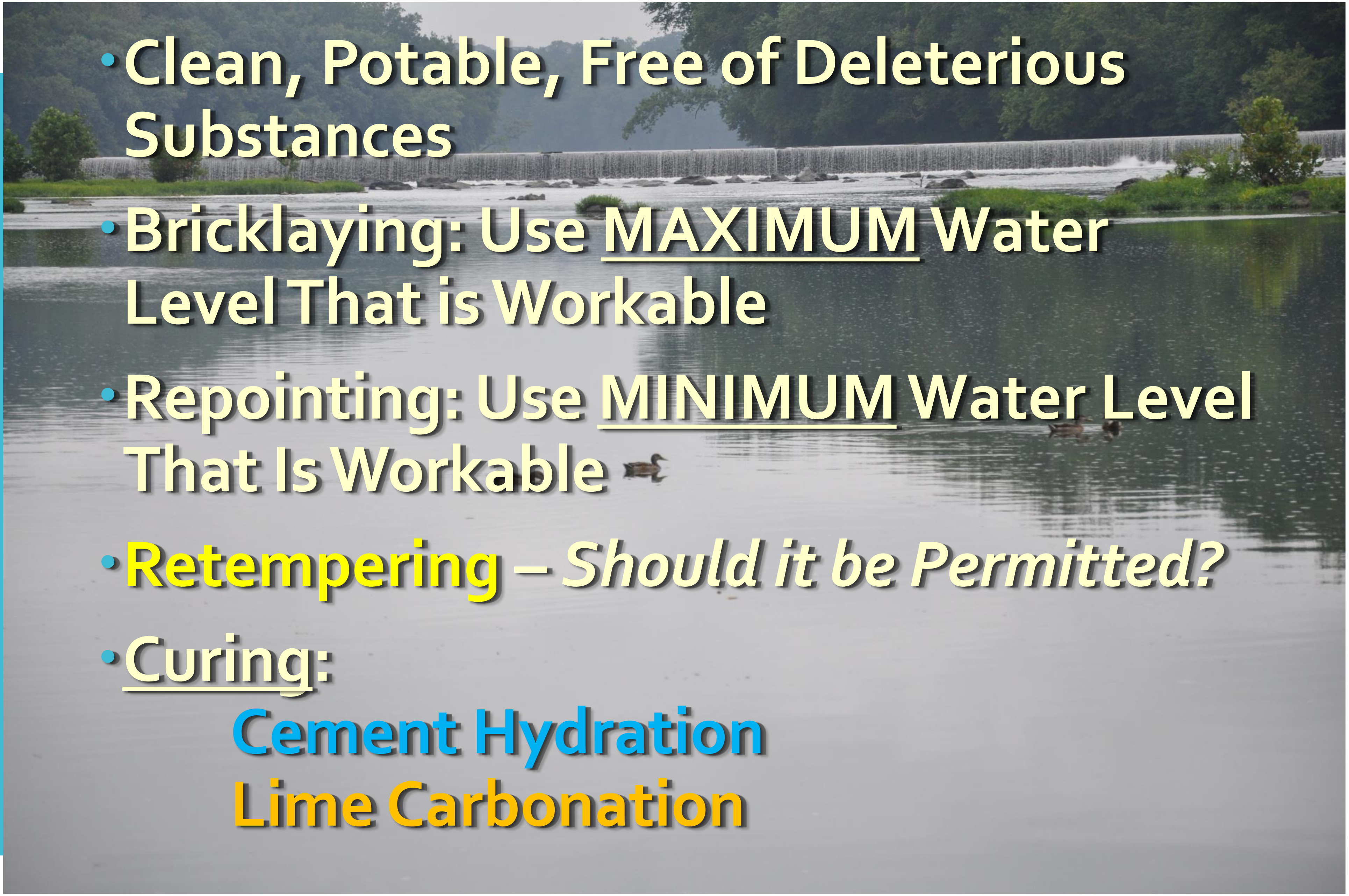
[B] See Note 4.

[C] When structural reinforcement is incorporated in cement-lime or mortar cement mortar, the maximum air content shall be 12 %.

[D] When structural reinforcement is incorporated in masonry cement mortar, the maximum air content shall be 18 %.

What is the Maximum Strength For TYPE N Mortar?

WATER

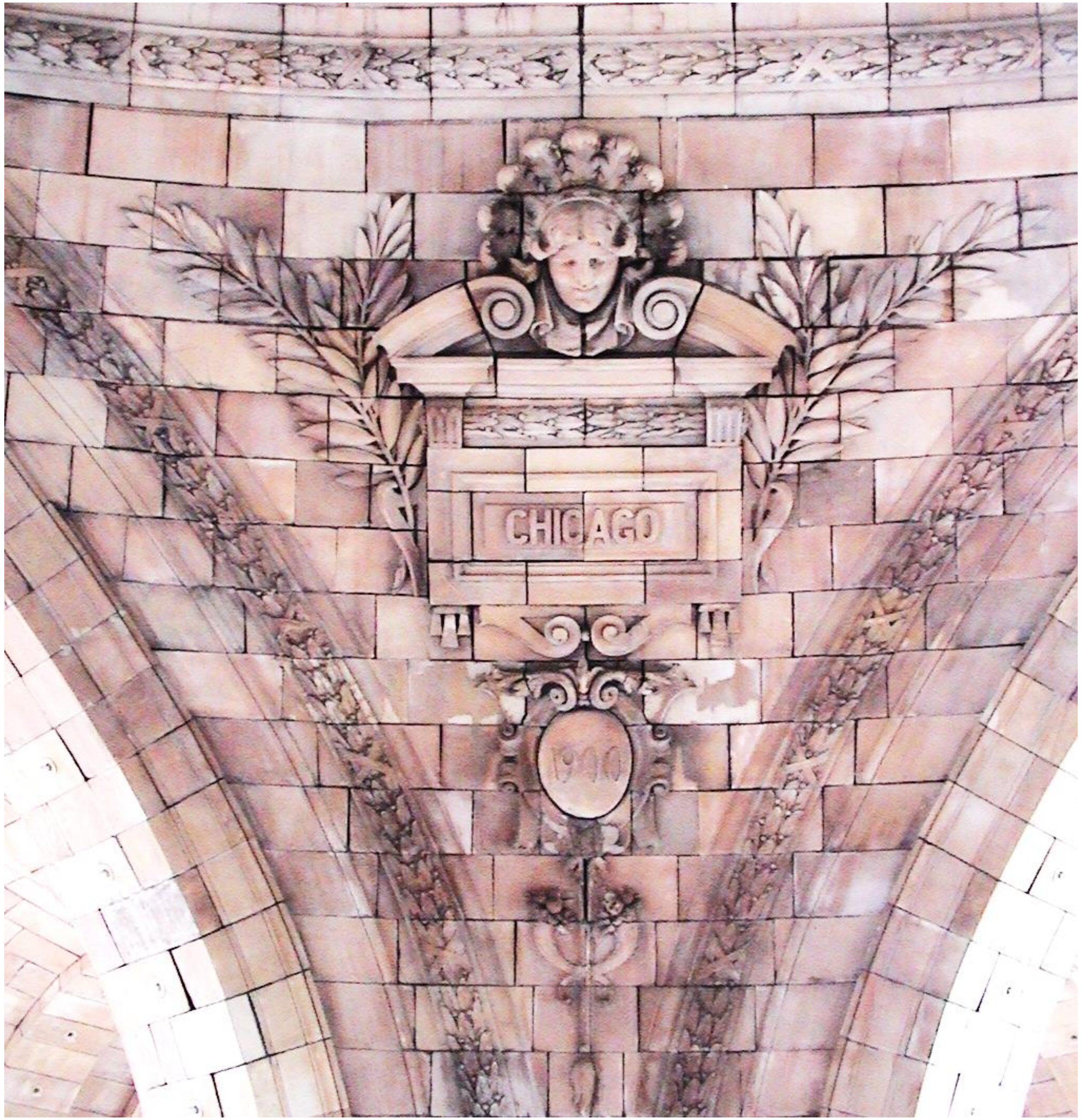


- Clean, Potable, Free of Deleterious Substances
- Bricklaying: Use MAXIMUM Water Level That is Workable
- Repointing: Use MINIMUM Water Level That Is Workable
- Retempering – *Should it be Permitted?*
- Curing:
  - Cement Hydration
  - Lime Carbonation

Curing

ASTM C1713

- Standard for Historic Mortars
- Expands the Range of Specifiable Performance Properties
- Applies to a Wide Range of Hydraulic and Non-Hydraulic Binders
- Property Approximation
- Acceptance Based On History of use



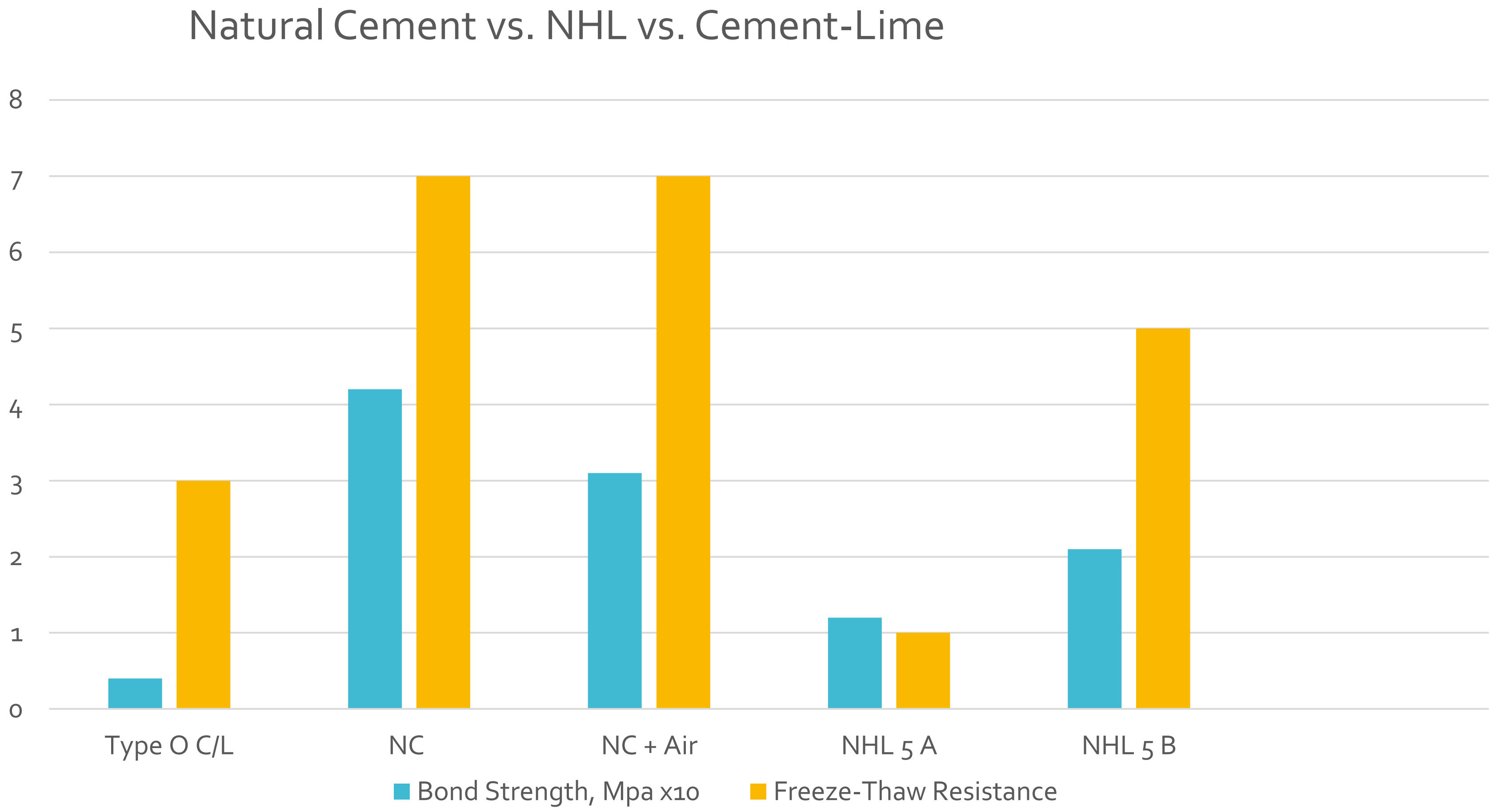
Nominal Mortar Cure Times

SPOT REPOINTING WITH LIME PUTTY MORTAR AT SMITHSONIAN CASTLE

- Portland-Lime
  - 28 days
- NHL
  - 60 days
- Lime
  - 2 Years
- Natural Cement
  - 30-90 days
- All Continue to Cure Over Time

Performance Profiles

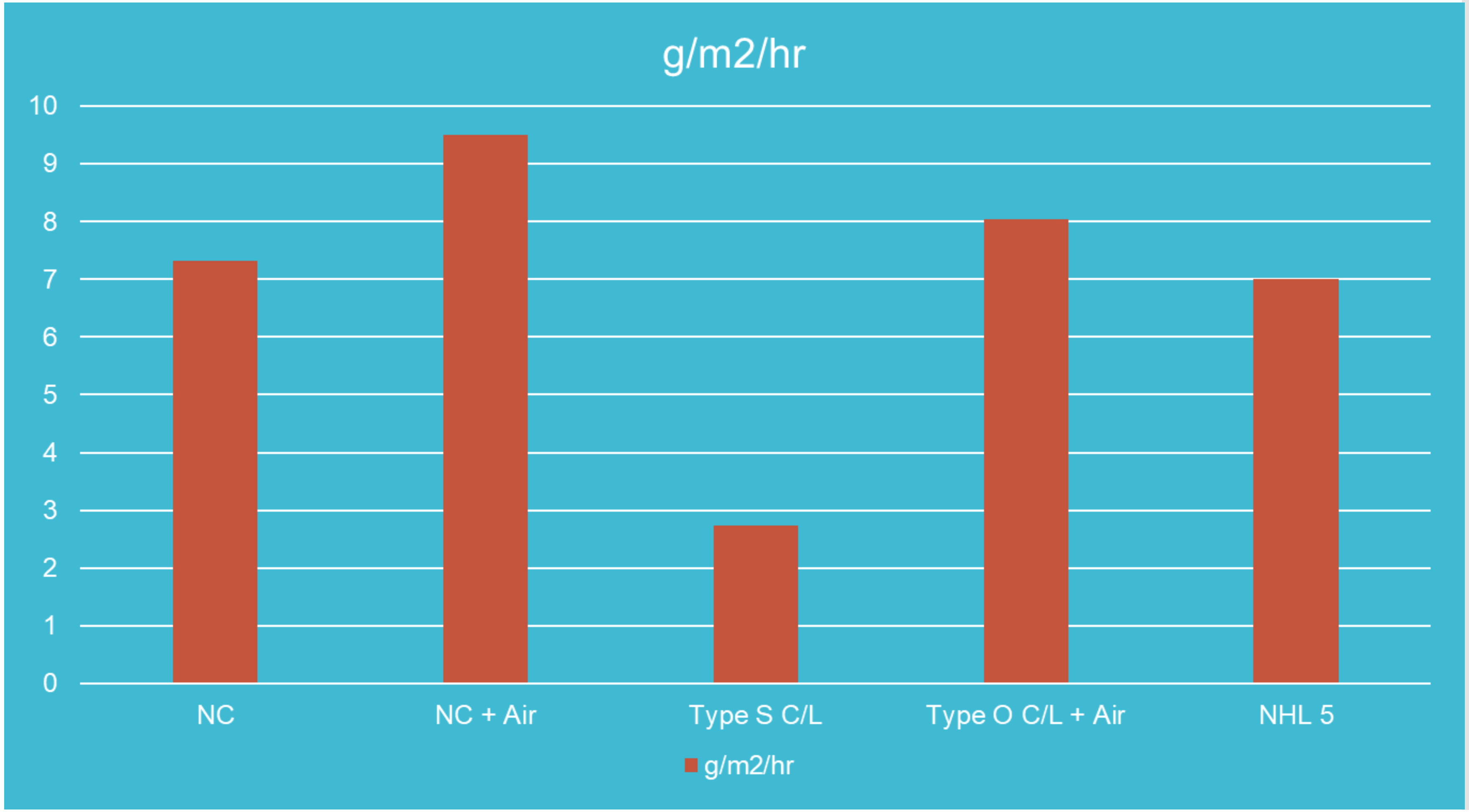
- Bond Strength
- Freeze-Thaw Resistance



Data Source: NRC Center Block Test Program 2013, Ohio Sandstone Substrate

Performance Profiles

Vapor Transmission



Color Matching Mortar

1. Replicate Original Binder
2. Match Original Sand
3. Add Minimum Required Pigments
4. Tool to Match Existing Texture and Profile

NATURAL CEMENT REPOINTING
PEMAQUID POINT LIGHTHOUSE
BRISTOL, ME

Replication Of Binder And Sand Produced A Pigment-free Match

Binder Color

Sand Color

Pigments & Saturation

- Non-Linear Relationship Between Pigment Concentration and Color Intensity
- Color Reaches Saturation Point
- Pigment Level Also Limited by Performance Concerns
    - 10% of Binder for Iron Oxide
    - 2% of Binder for Carbon Black

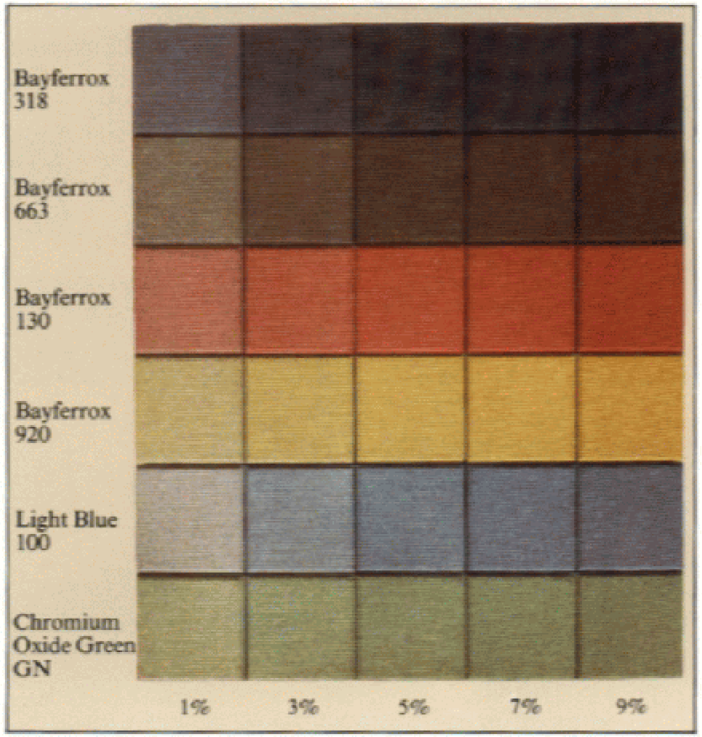


Fig. 3.
Concrete samples showing the increase in color intensity of various Bayferrox iron oxide and other inorganic color pigments proportional to increases of pigment quantities.

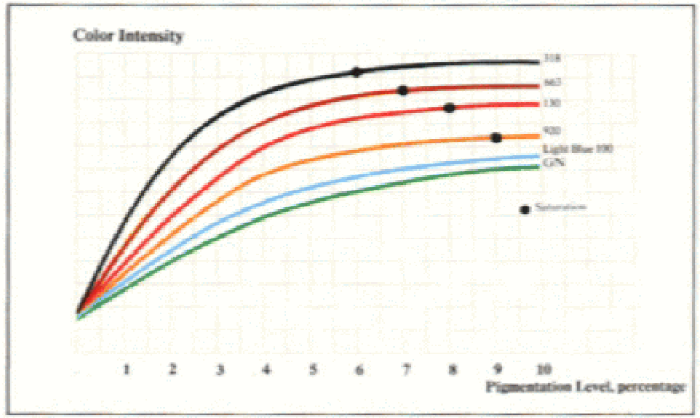


Fig. 4.
Color intensity curves of concrete specimens shown in figure 3.

Water-Cement Ratio

- Color Significantly Affected by Water Addition Level
- Performance Impact
- Repointing vs. Bricklaying Water Levels Impact Color & Strength

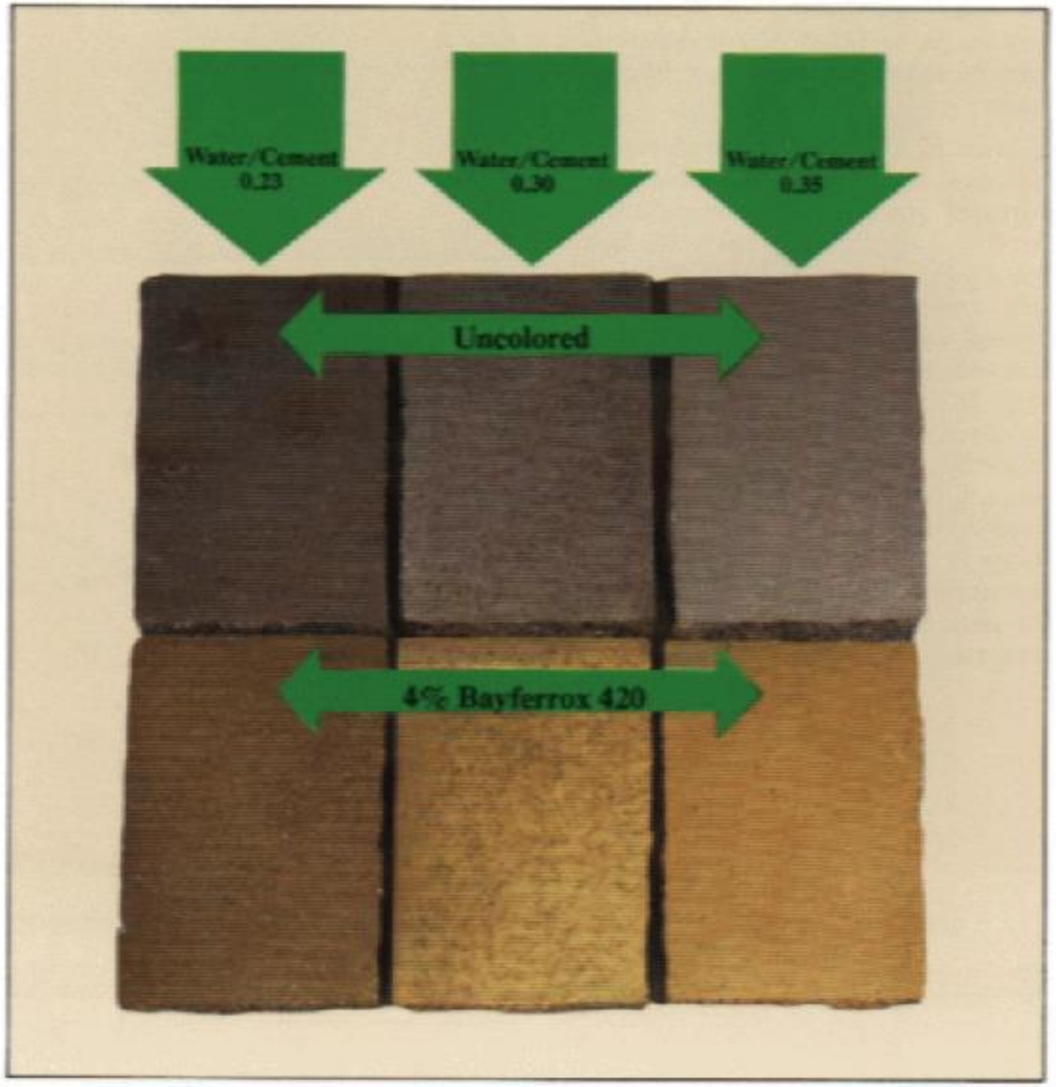


Fig. 7.
Pigmented and nonpigmented concrete specimens showing the effect of the water-to-cement ratio on lightness.

7

PLACEMENT & FINISHING

- Placement in “Lifts”
    - At Least 2
    - Thumbprint Hard Between Lifts
- Proper Compaction to Eliminate Voids & Establish Edge Bond
- Final Finishing After Final Lift is Thumbprint Hard
    - Properly Compacted Mortar Does Not Have to Be Smooth to Be Weather-Resistant

Plastic Shrinkage

- Most Shrinkage Occurs Before Set
- Quick Set Time for NC Eliminates Most Shrinkage
  - Allows Deep Applications to Proceed Continuously
  - Avoids Waiting for Thumb-Print Hardness

How Do We Decide What To Use?

REPLICATE, REVISE OR REPLACE?

Repointing Mortar Mock-ups at AMNH, 2007

HISTORIC CEMENTS: Should We Use Original Materials?

- **AUTHENTICITY:** Historically Correct, Repair/Replacement "In-Kind"
- **PRESERVATION:** Technologies and Methods Unique to a Particular Period
- **PRACTICAL:** Durability, Compatibility, Sustainability

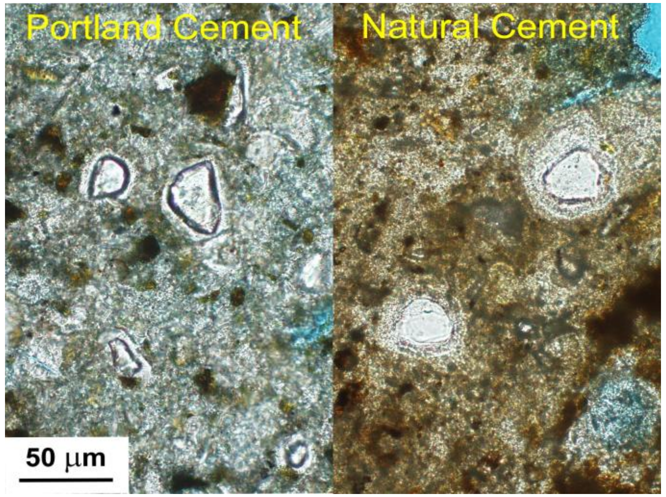
A PROPOSED DECISION TREE

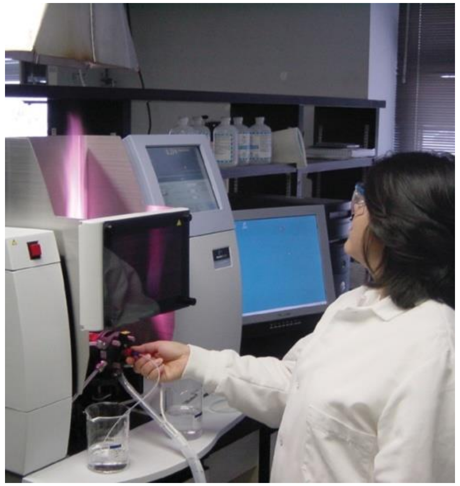
REPLICATE, REVISE OR REPLACE?

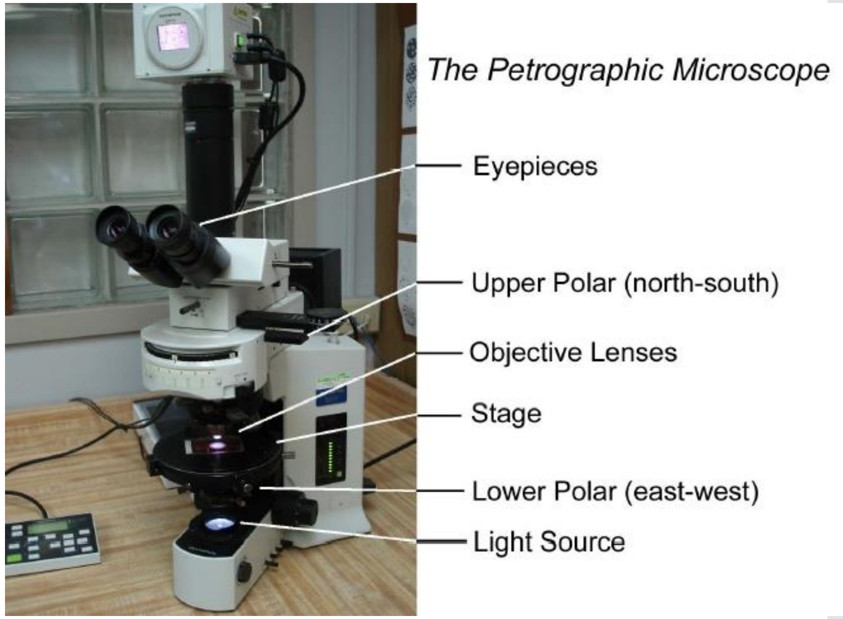
STEP1: ANALYZE ORIGINAL

- Independent Laboratory
- ASTM C1324/C856
- Petrographer Trained In Historic Materials
- Sufficient Detail To Permit Peer Review

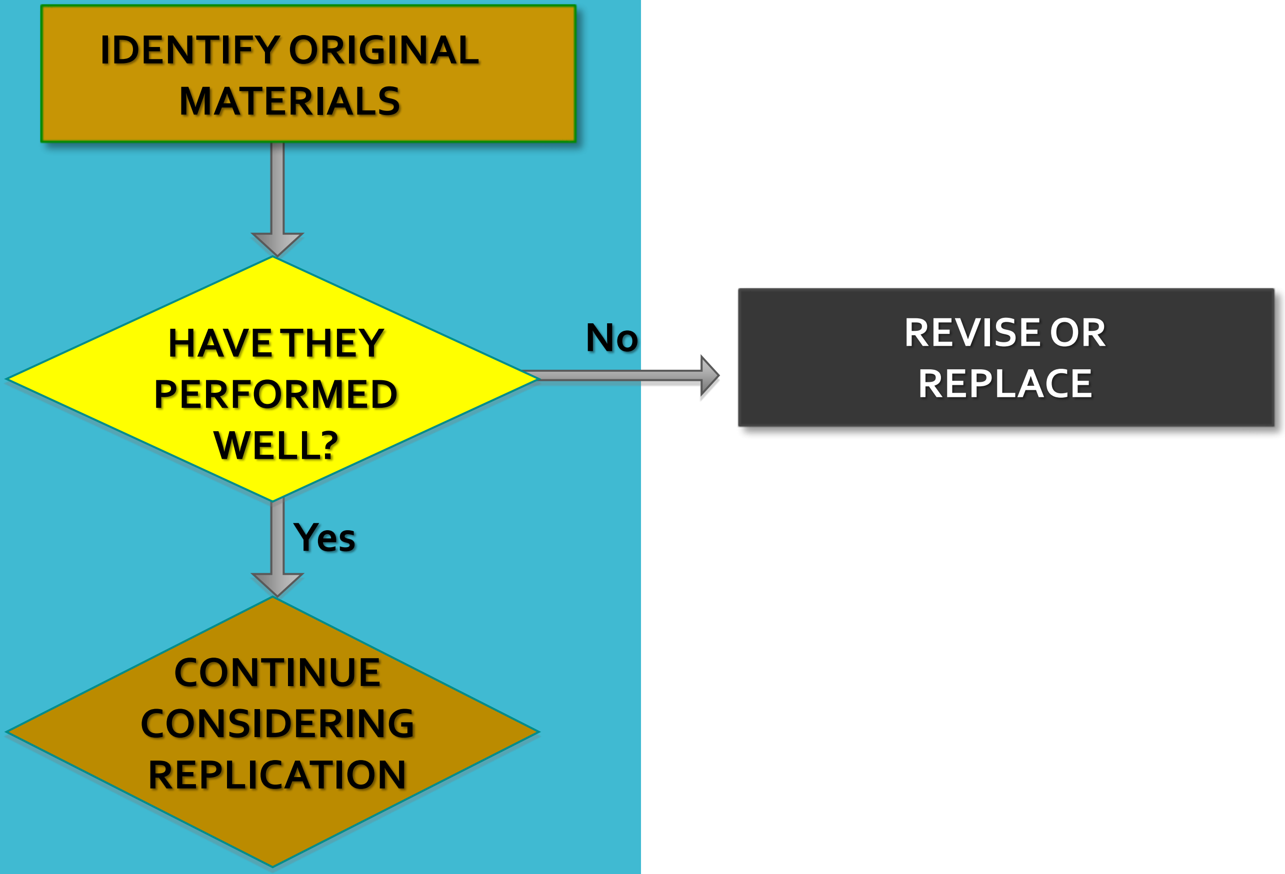
- Chemical Analysis
- Microscopy
- XRD
- SEM







2: EVALUATE PERFORMANCE



IDENTIFY ORIGINAL MATERIALS

HAVE THEY PERFORMED WELL?

No

REVISE OR REPLACE

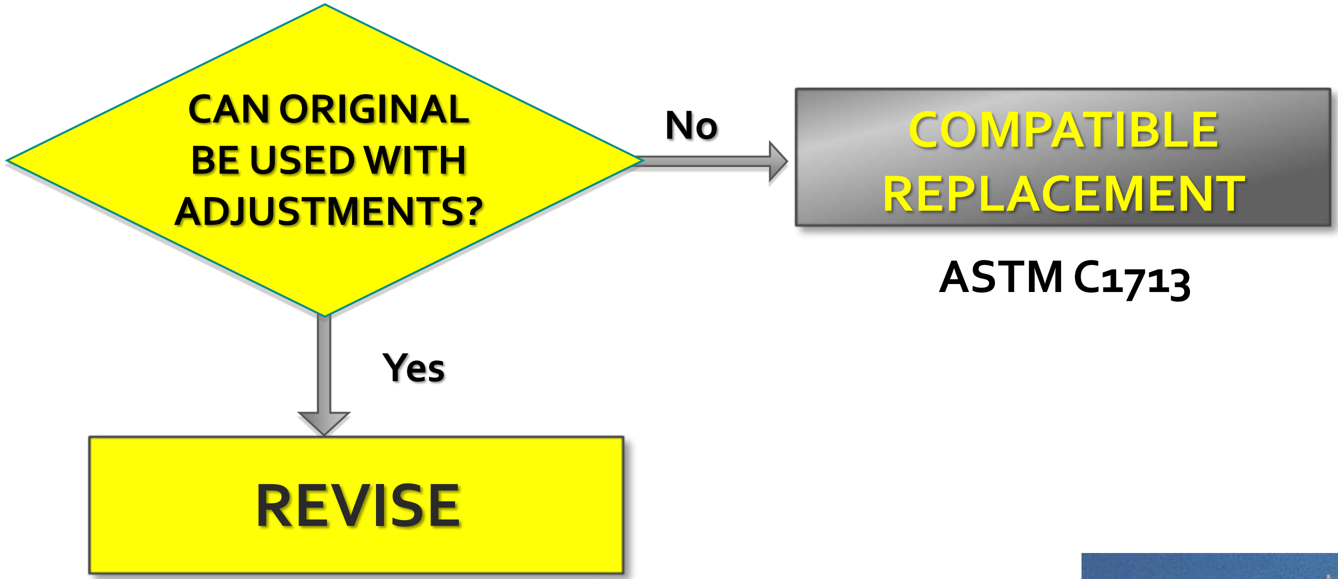
Yes

CONTINUE CONSIDERING REPLICATION

KEY WEST CUSTOMS HOUSE, 1910

- 22% RED PIGMENT
- SAND TOO FINE
- MORTAR TURNED TO DUST
- "DON'T REPLICATE A MISTAKE"

REVISE OR REPLACE?



CAN ORIGINAL BE USED WITH ADJUSTMENTS?

No

COMPATIBLE REPLACEMENT

ASTM C1713

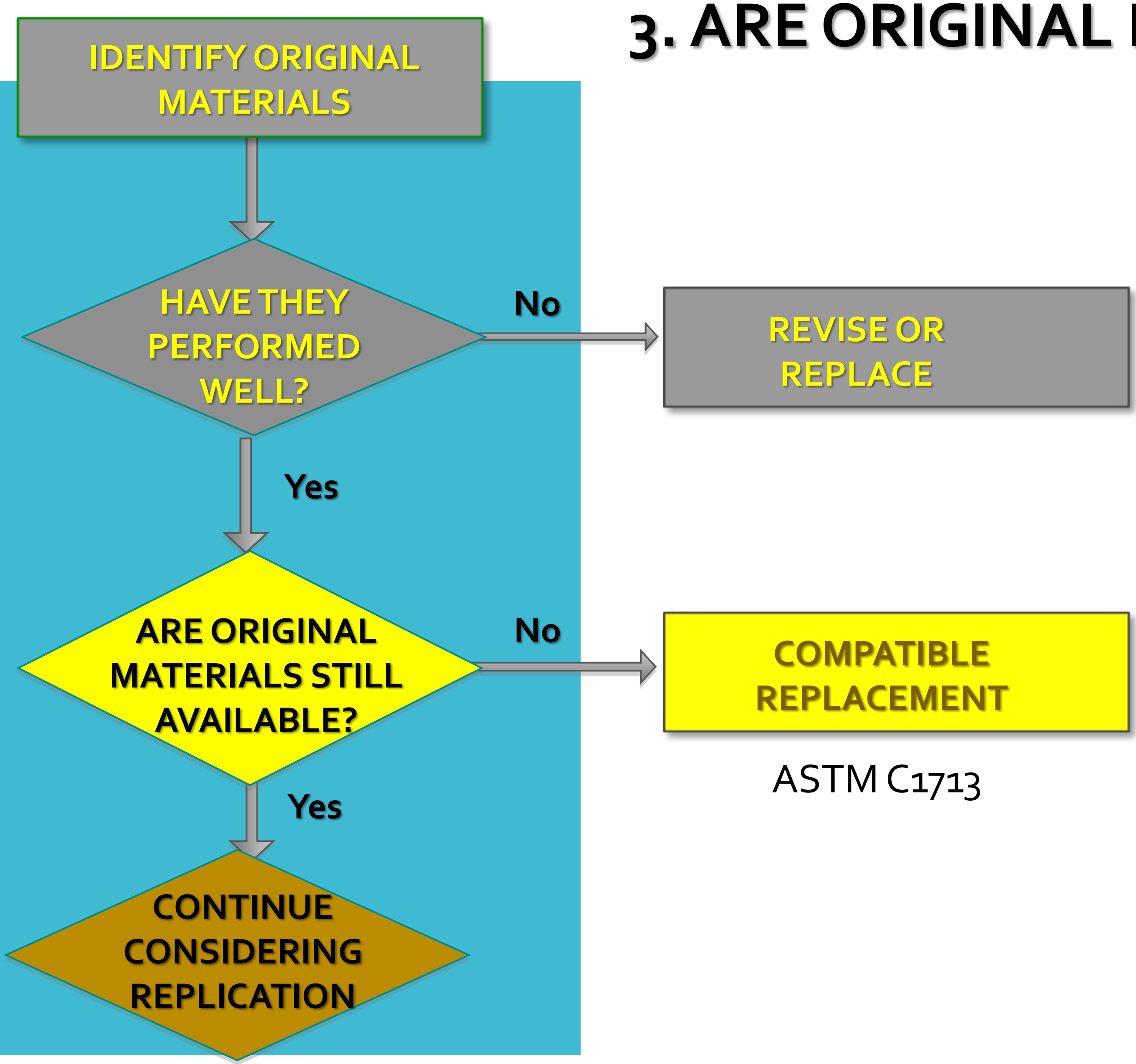
Yes

REVISE

KEY WEST CUSTOMS HOUSE, 1910

- Revised Mix design to Proper TYPE O
- Red Pigment Limited To 10% Of Binder Weight
- Sand Replaced With Astm C144 Sand
- Corrected To Type O By Proportions, Astm C270
- "Didn't Replicate A Mistake"

3. ARE ORIGINAL MATERIALS STILL AVAILABLE?



IDENTIFY ORIGINAL MATERIALS

HAVE THEY PERFORMED WELL?

No

REVISE OR REPLACE

Yes

ARE ORIGINAL MATERIALS STILL AVAILABLE?

No

COMPATIBLE REPLACEMENT

ASTM C1713

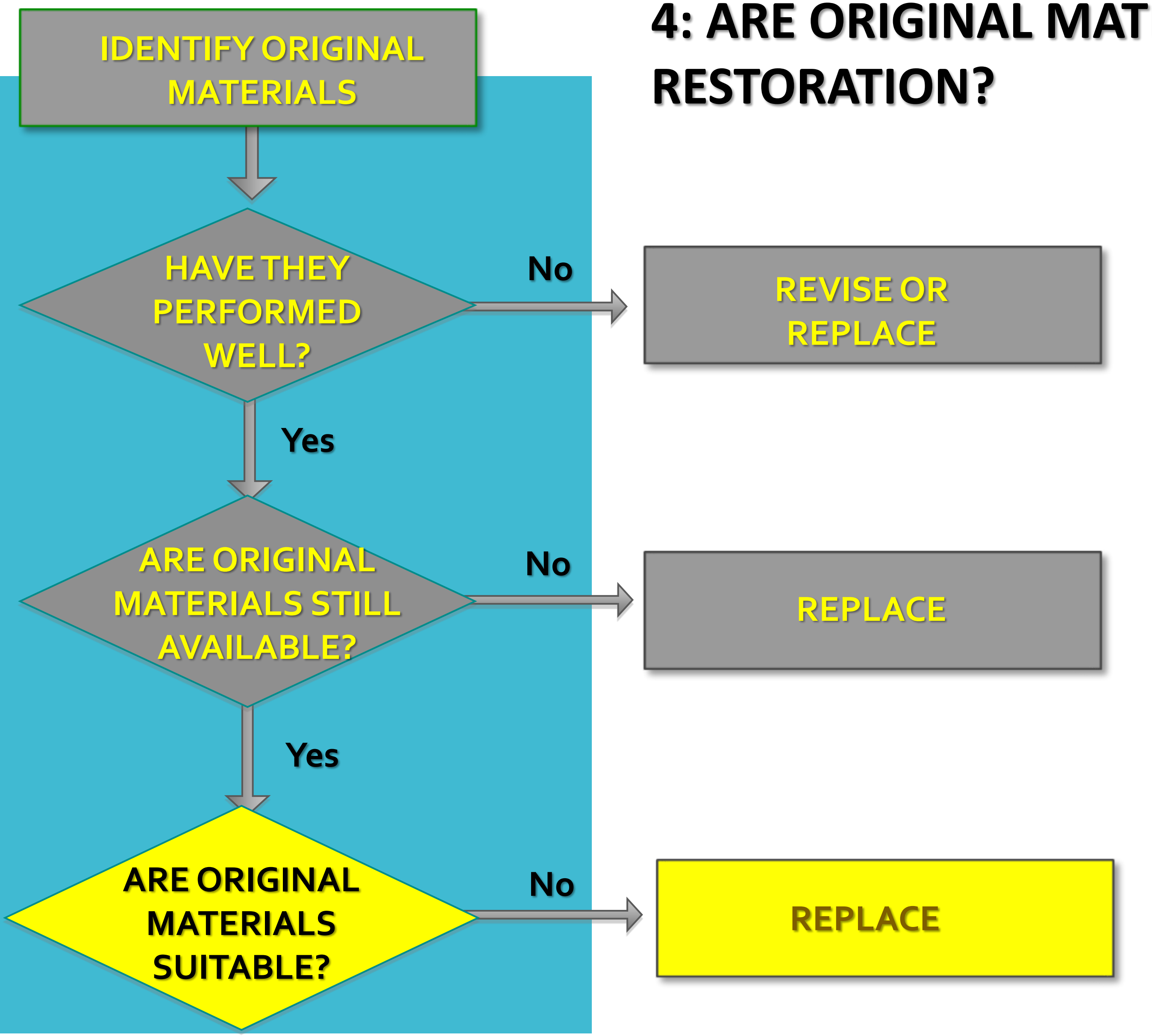
Yes

CONTINUE CONSIDERING REPLICATION

FORT POINT,
SAN FRANCISCO

Prior to 2004 Original Natural Cement Was Unavailable

4: ARE ORIGINAL MATERIALS SUITABLE FOR USE IN RESTORATION?



IDENTIFY ORIGINAL MATERIALS

HAVE THEY PERFORMED WELL?

No → REVISE OR REPLACE

Yes

ARE ORIGINAL MATERIALS STILL AVAILABLE?

No → REPLACE

Yes

ARE ORIGINAL MATERIALS SUITABLE?

No → REPLACE

LONDONTOWNE PUBLIK HOUSE
Annapolis, MD

2006

LONDONTOWNE PUBLIK HOUSE

Annapolis, MD

Built 1758-1764

- Originally Constructed with Lime Mortar
- After 250 Years' Groundwater Exposure:
  Salt-Contaminated
- Lime Unsuitable for Salt-Contaminated Masonry
- Replaced with Natural Cement

BROOKLYN NAVY YARD BUILDING 20

- Built Early 1900's
- Portland Cement Mortar
- Contemporary Cement Is Harder

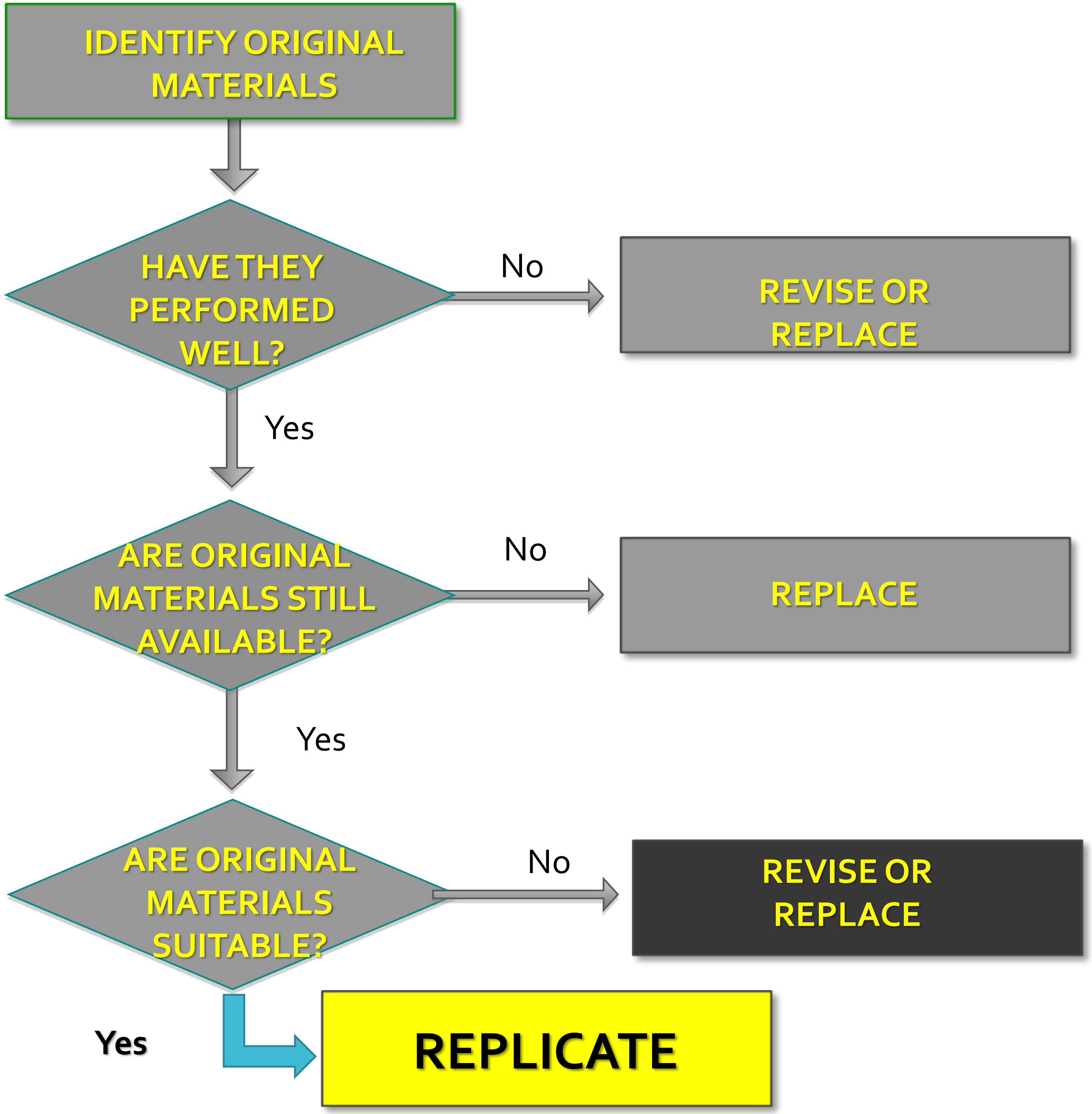
Repointed 2014
NHL 3.5 Mortar

BROOKLYN NAVY YARD BUILDING 128

- Built in 3 Phases
- 2 Portland Cement Mortars
- 1 Natural Cement Mortar

Repointed 2012
3 Distinct, Different Custom Mortars

5. If You Made It This Far, OK to Replicate



IDENTIFY ORIGINAL MATERIALS

HAVE THEY PERFORMED WELL?

No

REVISE OR REPLACE

Yes

ARE ORIGINAL MATERIALS STILL AVAILABLE?

No

REPLACE

Yes

ARE ORIGINAL MATERIALS SUITABLE?

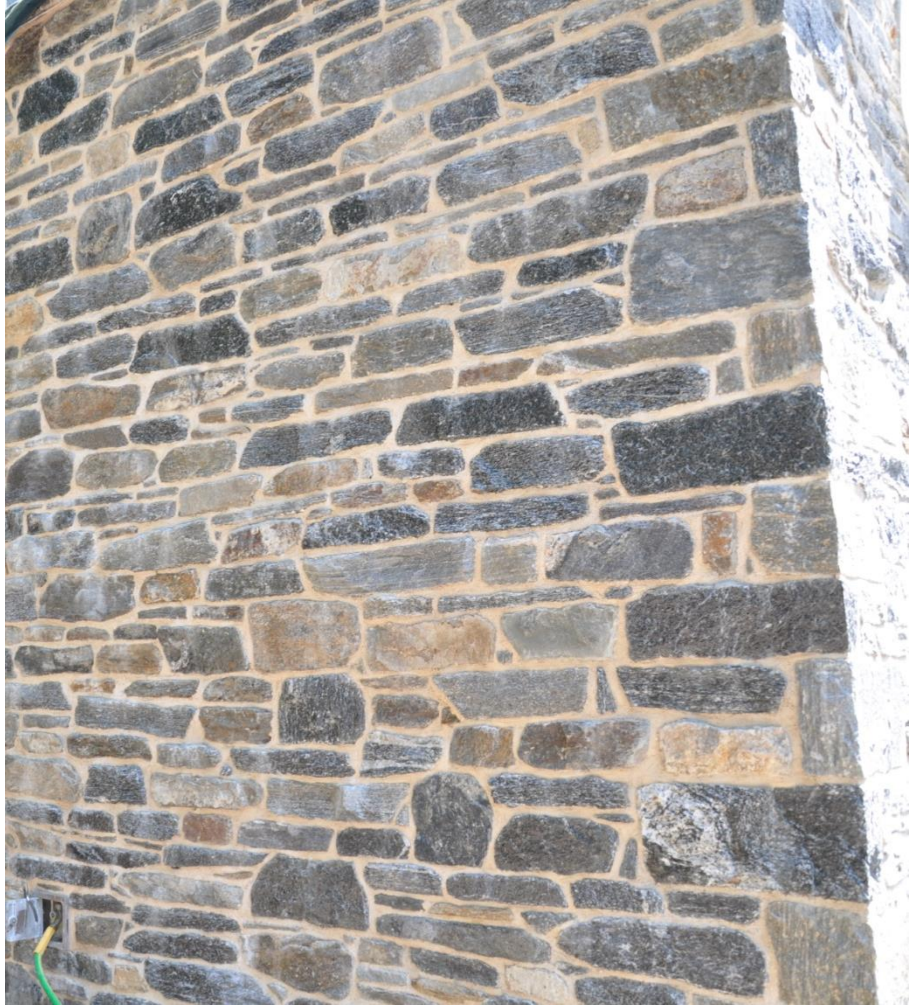
No

REVISE OR REPLACE

Yes

REPLICATE

In-Kind Restorations Are Special



NYBG STONE MILL

Built 1840, Lime-sand Mortar

Restored 2008, Lime-sand Mortar

FORT JEFFERSON
Dry Tortugas, Florida

Built 1860’s-1870’s
Natural Cement Mortar

Restoration Began 2006
Natural Cement Mortar

Courtesy National Park Service

AMERICAN MUSEUM OF NATURAL HISTORY

Built: 1890'S, Natural Cement Mortar

Repointed 2007-8, Natural Cement Mortar

In-Kind Repointing Projects in NYC

NATURAL CEMENT AT STATUE OF LIBERTY PEDESTAL, HIGHBRIDGE, BROOKLYN BRIDGE

Library of Congress
Washington, DC

QUESTIONS?