

## Mortar Analysis

### Part 1: Mortar-Making Materials

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#### Introduction

Almost every repair to historic masonry requires the use of mortar. The significance of selecting an appropriate mortar, whether for repointing or rebuilding, cannot be underestimated due to the structural and aesthetic roles that mortar plays in masonry construction. Physically inappropriate mortar can cause a repair to fail and can damage the original masonry. Visually inappropriate mortar alters the original intent of the building's designer by changing our perception of the design. For these reasons analysis of historic mortars is a topic of abiding interest to most preservation professionals.

The publication of Blaine Cliver's article "Tests for the Analysis of Mortar Samples" in the *APT Bulletin* in 1974 acknowledged the importance of mortar analysis when designing repairs to historic masonry structures.<sup>1</sup> The simple, accessible acid-digestion method presented in his article was an important step in the pursuit of a deeper and fuller understanding of the nature of historic mortar materials and how best to evaluate them (Fig. 1). However, in the subsequent 30 years there have been many developments in our understanding of historic mortar materials, in our appreciation of the interactions between masonry and mortars, and in the analytical methods applied to mortars and other cementitious material.

Accordingly, a series of three Practice Points has been developed to review the rationale for mortar analysis and to explore the current directions in the field. The intent is not to provide a comprehensive literature review of the subject but to present my view of the subject based on nearly 20 years of experience and practice. Because an understanding of the components of mortar and how they relate to one another is essential to evaluating mortar-analysis techniques, this first article reviews mortar-making materials; subsequent articles will cover analytical methods and buying mortar-analysis services.

#### Mortar Materials

Historically, a variety of materials were used to make mortars, but generally speaking mortar is composed of



**Fig. 1.** The apparatus for acid-digestion analysis is extremely simple, making the method highly accessible. All photographs by the author, unless otherwise noted.

an aggregate and a binder that are combined with water to form a coherent, plastic mass. The following discussion addresses these two primary ingredients as they are typically found in North American mortars; though the distinctive materials used in other localities are well worth reviewing, discussion of mortars from other countries is beyond the scope of the article.

**Aggregates.** Aggregate is volumetrically the most significant part of any mortar. Aggregate is generally considered to be inert in a mortar, in that it does not change during the process of mixing or curing and does not react with the other mortar ingredients.<sup>2</sup> The primary purpose of aggregate in a mortar is to limit shrinkage. Properly graded aggregate also improves workability, thereby permitting the addition of less water into a mortar mix than would otherwise be required.

Natural sand, the most commonly used aggregate in mortar, typically is either primarily quartz or primarily carbonate (Fig. 2). Quartz sands are the product of the breakdown of quartz-bearing rocks, such as granite, sandstone, schist, and gneiss. They are the typical beach and river sands, although most sands quarried for mortar are from ancient deposits, not modern beach and river environments. Carbonate sands typically come from marine environments and may include coral



**Fig. 2.**

A portion of the author's sand library. A sand library is only useful if it is kept up to date by frequent replenishment with currently available materials. Sand is a natural material and is therefore not homogeneous throughout a deposit. Half-pint tubs are used because a larger sample is more representative of a particular sand than a small sample. The sand is kept moist for use in preparing replication mixes.

sands. They are found and used most commonly in coastal areas.

Historically, local sources of sand would have been used for making mortar. Transporting sand has always been costly due to its weight and bulk, so most sands used in modern construction are also obtained locally. Much information can be gained about the source of a sand by careful examination of the size and shape of the grains and by carefully identifying the trace (non-quartz or non-carbonate) constituents. For example, abundant glauconite in sand suggests a marine source; well-rounded lithic (rock) grains indicate deposition from a river or stream (Figs. 3 through 5).

Some aggregates used in mortar are manufactured by crushing rock. The crushed rock is processed through a series of screens or sieves to provide aggregate of proper grading. Crushed shells have also been used as aggregate where locally abundant.

**Binders.** There are two principal types of binders. Non-hydraulic binders set through loss of water, or dehydration. Hydraulic binders use up water as they set; water is an essential part of the chemical reactions that produce a hardened material. Non-hydraulic binders used historically include clay and lime; historic hydraulic binders include gypsum, hydraulic lime, natural cement, and portland cement. The array of modern binders is even broader, including such materials as masonry cement and mortar cement.

**Non-hydraulic binders.** Clay is a soil material that becomes plastic and malleable when mixed with water, then hardens as it dries. Unlike other non-hydraulic mortar binders, there is no chemical reaction between the clay and the water; the change in the clay with the addition of water is purely physical. Unless the hard-

ened material is subsequently exposed to high heat (as happens with bricks and other ceramic materials), the addition of water will return the clay to a plastic state. Clay was used historically for mortars, especially in vernacular buildings in rural areas where lime may not have been readily available. Clay mortars were often used where the construction was not expected to be exposed to moisture, such as in chimneys below the roofline, and where it could be protected from moisture by broad roof overhangs. Mortars that are mixtures of clay and lime are extremely common in vernacular historic structures of the eighteenth and nineteenth centuries. I believe the clay in such mortars was used as an extender for the more expensive or less readily available lime.

Lime is the most common historic non-hydraulic mortar binder. Although a chemical reaction occurs when water is added to lime, it is only through the loss of water that it can become a solid material again. Lime is a product of the heating (also called burning or calcining) of limestone, a type of rock made up of calcium carbonate ( $\text{CaCO}_3$ ). Shells that are made of calcium carbonate, such as oyster shells, have also been used to make lime, though the volume of shell lime produced in the U.S. pales in comparison with that derived from limestone (Fig. 6). Interestingly, oyster shells were used to manufacture lime into the twentieth century, though it is not clear if the lime produced was used for building purposes.<sup>3</sup>

The limestone is crushed and then heated to 1650–1830°F (900–1000°C) in a kiln.<sup>4</sup> The heating process drives off carbon dioxide, leaving behind calcium oxide, also known as quicklime:



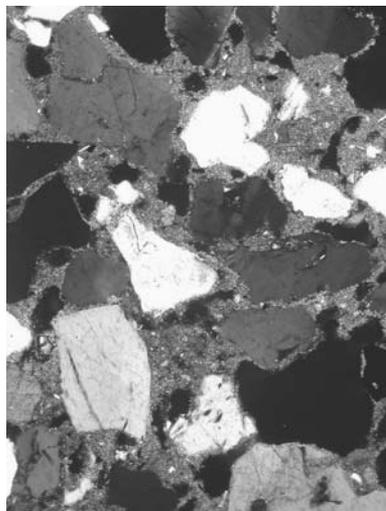
When water is added to hydrate the calcium oxide (a process called slaking), calcium hydroxide is

**Fig. 3. (left)**

Mortar sample with primarily quartz aggregate. The gray and white grains are quartz. The grains are angular. This photograph and the next two were taken through the microscope at 100x magnification. The mortar is ground to transparency and observed in transmitted light. The bright white grain at the top of the image is approximately 20  $\mu\text{m}$  across.

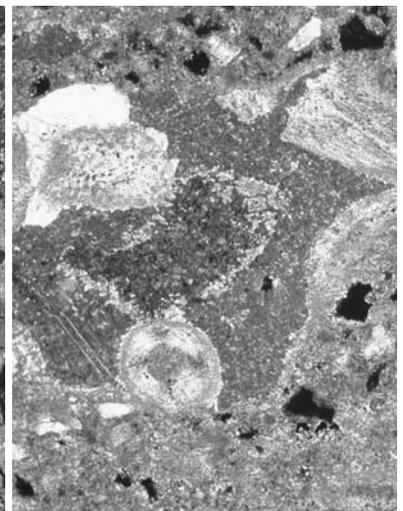
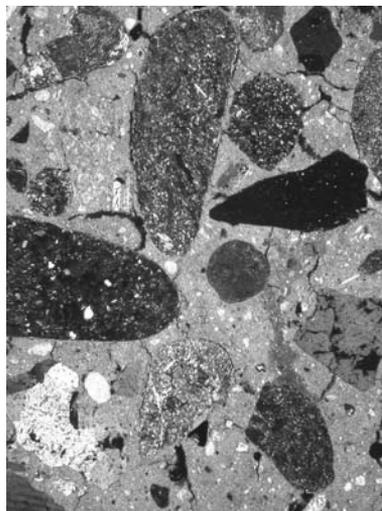
**Fig. 4. (middle)**

Mortar sample in which rounded rock fragments form a significant part of the aggregate. The circular grain at the center of this microscope image is approximately 15  $\mu\text{m}$  across.



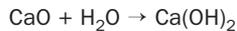
**Fig. 5. (right)**

Mortar sample with a crushed-limestone aggregate. The bright circular grain near the bottom of this microscope image is in a limestone fragment (medium gray grain) and is approximately 15  $\mu\text{m}$  across.

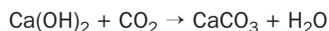




formed. The slaking process is an exothermic reaction, meaning that a great deal of heat is generated (Figs. 7 and 8):



If more water than is necessary is used to hydrate all of the calcium oxide, the product is a wet paste or lime putty. However, if just enough water is used to hydrate all the calcium oxide, a dry hydrate or powder can be produced. Bagged dry hydrate is the more familiar form in use today; water must be added to make a mortar from a dry hydrate. To make mortar, the lime is mixed with sand and (if necessary) water. As a lime mortar loses water, it gains carbon dioxide from the air and returns to its original form, calcium carbonate<sup>5</sup>:



Most limestones are not pure calcium carbonate. Some contain more or less calcium-magnesium carbonate, or dolomite. Because dolomite will calcine at a lower temperature than calcite, dolomitic limes slake more slowly. The effect of the magnesium content on the final quality of the lime is open to debate. Early twentieth-century data suggest that the initial tensile strength of dolomitic lime mortars is less than that of a high-calcium lime mortar but that over time the tensile strength of the dolomitic lime mortar will exceed that of a high-calcium lime mortar.<sup>6</sup>

**Hydraulic binders.** Some limestones contain clay (aluminum-silicates) and quartz (silicon dioxide). When these limestones are burned, some of the calcium combines with the aluminum and silicon to create calcium silicates, while the remainder forms lime. The calcium silicates are hydraulic: when combined with water they form a different solid material. As they take on water, these silicates become hydrated to form a gel, which is called the initial set. This gel then crystallizes to form a network of interlocking needles of hydrated calcium and aluminum silicates. The distinction between a hydraulic lime and a natural cement is that a hydraulic lime will slake when water is added; a natural cement will not. The curing of a hydraulic lime is a hybrid process of carbonation and gel formation.

Natural cements and portland cements were introduced in the mid- to late-nineteenth century. Natural cements predominated in the mid- to late-nineteenth century, while portland cements came into use late in the nineteenth century. Natural and portland cements are composed primarily of calcium silicates. As implied by their name, natural cements are made from rocks that contain just the right proportions of calcium, aluminum, and silica to yield a purely hydraulic material

when burned at the correct temperature. Portland and other “manufactured” cements are produced from mixtures of natural materials proportioned to provide the correct composition upon heating.

Gypsum is a distinct type of hydraulic binder. Although gypsum will set under water, it is not resistant to the action of water once set, as are hydraulic lime and cement. In the United States, gypsum has been identified in historic mortars, but it is most common as an additive in portland cement rather than as a mortar binder and therefore will not be discussed further here.<sup>7</sup>

### Additives and Admixtures

Though available modern admixtures for mortars abound, little study has been given to additions of materials to historic mortars to modify their properties. The most obvious additives and admixtures to historic mortars are those that leave behind evidence of their addition. Aesthetic additions to mortars, intended to modify their appearance, were quite common historically. Pigment is the most obvious of these, with the height of pigment use in the Victorian era; red and black mortars are commonly found in buildings of this period. Mica flake and crushed anthracite coal were also sometimes added, both of which give the mortar a characteristic color and sparkle.

Materials were also added to change the physical properties of mortar. Iron filings were added to improve strength; animal hair has been noted in some mortars, though it may have been an accidental inclusion. Sometimes aggregate materials that are known to be reactive with the mortar binder were added to improve the properties of the cured mortar. Materials such as fly ash and brick dust (or crushed brick or tile) have historically been added to mortars to improve their hardness by reaction between silica and lime over time to produce calcium silicates; these materials are called pozzolans. Chlorides (including salt) to retard freezing have a long record of use, persisting into the modern day.

Other types of additives that have been documented in the historic record include such organic materials as blood, egg whites, and fruit juices.<sup>8</sup> Such additives were used to improve the properties of a mortar before or after set such as workability and durability. Being organic, most admixtures of this type would be expected to disappear from the mortar relatively rapidly, leaving no detectable traces.

**Fig. 6.** (left) Pile of oyster shells ready for burning. The presence of oyster-shell fragments in a mortar can be indicative of a shell lime. Oyster shells were used to manufacture lime into the twentieth century. Photograph courtesy of Jeffrey Price, Virginia Lime Works.

**Fig. 7.** (middle) Field slaking of lime. Photograph courtesy of Jeffrey Price, Virginia Lime Works.

**Fig. 8.** (right) Lime “boiling” as it slakes. The mist above the lime is actually steam. Photograph courtesy of Jeffrey Price, Virginia Lime Works.

## Conclusions

Though the basic combination of binder and aggregate to create a mortar is generally well understood, materials used for making mortar have changed through time with changes in technology and transportation systems. Understanding the history of technology of mortar-making materials is critical to mortar analysis, just as understanding current materials technology is critical to development of suitable replacement mortars.

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## Notes

1. E. Blaine Cliver, "Tests for the Analysis of Mortar Samples," *APT Bulletin* 6, no. 1 (1974): 68–73.
2. Of course, reactions between the binder and certain types of aggregate (alkali-aggregate reactions) can occur in mortars just as they do in concrete.
3. Edwin C. Eckel, *Cements, Limes, and Plasters: Their Materials, Manufacture, and Properties*, 2nd ed. (New York: John Wiley and Sons, 1922), 95–96.
4. Detailed discussions of historic lime-burning technology can be found in many other sources, including Eckel. One point worth noting is that the fuel used to heat the lime was often mixed with the raw materials; traces of unburnt fuel can be found in the aggregate of many mortars.
5. This series of chemical reactions is often referred to as the "lime cycle."
6. Eckel, 124–125.
7. George Wheeler, Director of Conservation for the Historic Preservation Program, Columbia University, personal communication to the author, Nov. 2007.
8. Lauren-Brook Sickels, "Organics vs. Synthetics: Their Use as Additives in Mortars," in *Symposium on Mortars, Cements and Grouts Used in the Conservation of Historic Buildings*, ICCROM, Rome, 3-6 November 1981 (1982), 25–52.

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