

Lime and Cement Technology: Transition from Traditional to Standardized Treatment Methods

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(ABSTRACT)

During the late eighteenth and throughout the nineteenth century masonry technology underwent a major transition, whereby, the production process increasingly absorbed techniques traditionally carried out by craftsmen. This transition also involved an increasing shift from lime technology to cement technology¹. This influenced traditional work methods involving lime mortars as well as creating new methods for preparation of cement. Development of cement assisted the expansion of vital infrastructure such as roads, bridges, dams, sewers, and high-rise structures. In order to facilitate high-rise construction with cement, masonry units such as commercially produced brick were developed with similar strength and compression characteristics as cement.

¹ Terminology and definitions for masonry materials have shifted throughout the course of their development and application. In order to distinguish materials and techniques within this paper, it is critical to determine the context and application of their usage. In order to clarify materials, technology and associated techniques, I incorporate the following masonry definitions:

Lime Technology- involves a calcium carbonate raw material that must be calcined and is capable of slaking prior to the addition of aggregates, in order to create a building material.

Cement Technology- involves a calcium carbonate material combined with clay (aluminum silicates) in such a proportion that the product of their calcinations is incapable of being slaked. Rather, the calcined material must be ground prior to addition of aggregates.

Natural Cement represents a material that occurs in nature capable of being calcined and ground to produce cement.

Artificial Cement represents a man-made proportion of lime and clay (aluminum silicates) calcined and ground, thereby producing cement.

Hydraulic lime consists of a calcium carbonate material with enough clay within it's matrix so that, following calcinations, slaking and mixing with aggregates, the material will harden under water.

Historically, lime mortar preparation involved multiple and variant treatment methods. These practices arose from generations of experimental practice, in order to determine which methods were most beneficial. Development of these skills was transferred from master to apprentice and from father to son. These treatment methods involved a calcium carbonate raw material and its conversion into a lime suitable for blending with aggregates, which resulted in a workable mortar for uniting building materials. Such lime building compounds included, stuccos, frescos, plasters, and mortars. The scope of this project involves primarily lime mortar, although treatment methods and materials are very similar for all of these five lime compounds.

Restoration of historic structures built with lime mortar creates challenges for architects, conservators, masons and all persons tasked with masonry restoration. Original masonry Materials and methods involving lime technology have been superseded by cement technology with its own materials and techniques. Cement has failed to provide a successful role as a binder for the restoration of historic structures built with lime mortar. In order to maintain the integrity of historic structures, rediscovery and application of traditional lime technology can further bridge the gap between past and present masonry mortar.

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Chapter 1 Empirical Development of Lime Technology

1.1 Ancient lime application

In order to understand the techniques associated with lime mortars it is necessary to review the lineage from which they arose. While the actual techniques involving preparation and application of lime remains less than fully understood, examples of finished materials still in existence testify on behalf of the early success acquired by those working with lime. Lazell paints a picture of the early development of lime technology.

The art of using mortar in some form or other is as old as the art of building or as civilization itself. Evidences of the use of mortar are found not only in the older countries of Europe, Asia and Africa, but also in the ruins of Mexico and Peru. The remains of the work of these ancient artisans are evidence to us of the enduring qualities of lime mortar as well as the skill and knowledge possessed by the user. Miller in his work on mortar states “Plastering is one of the earliest instances of man’s power of inductive reasoning, for when men built they plastered; at first like the birds and beavers, with mud; but they soon found out a more lasting and more comfortable method, and the earliest efforts of civilization were directed to plastering. The inquiry into it takes us back to the dawn of social life until its origin becomes mythic and prehistoric. In that dim, obscure period we cannot penetrate far enough to see clearly, but the most distant glimpses we can obtain into it shows us that man had very early attained almost to perfection in compounding material for plastering. In fact, so far as we yet know, some of the earliest plastering which remains to us excels, in its scientific composition, that which we use at the present day, telling of ages of experimental attempts. The pyramids of Egypt contained plaster work executed at least 4000 years ago, and this, where wilful violence has not disturbed it, still exists in perfection, outvying in durability the very rock it covers, where this is not protected by its shield of plaster” (Lazell 1915:9).

Development of masonry construction technology emerged and spread through empirical trial and error. Within the 1st century B.C., Romans borrowed and applied Greek and Etruscan

techniques of lime preparation and application for creating their mortar.² Roman use of lime mortars reflected a keen insight into the material and its technological preparation and application toward their momentous building accomplishments. Although these accomplishments are highly esteemed and respected, the techniques of preparation and application of lime and lime mortars have remained less than fully understood. Kranzberg describes the Roman ability for technological order as a major contributor toward their building accomplishments.

The Romans are known to history as great engineers. Why is this so? Partly this is owing to the large number and monumentality of their construction works- the great aqueducts, roads, buildings, and bridges which have withstood the ravages of time and still bear testimony to the strength and solidity with which the Romans built. Partly too it is owing to the organizational abilities of the Romans. For engineering consists of more than machines and processes; the task of the engineer is to marshall effectively the resource at his command, to understand the limitations and potentialities of his tools and materials, and to organize his human as well as material resources for the accomplishment of the task at hand. It is perhaps in this last category that the Romans truly excelled (Singer 1965:65).

We have historical accounts of some Roman masonry procedures and scientific material analysis of their existing mortars, yet this has failed to unravel fully the technological components involving lime treatment, mortar preparation and placement. These treatment techniques imparted particular properties upon mortars. Vitruvius, a 1st century B.C. Roman architect under Augustus, conveys the earliest comprehensive details regarding lime treatment and its use as a building material. Craft tradition was advanced by the Romans, who developed a strong infrastructure of labor, raw materials, technological order and transportation. This craft

² Roman masonry accomplishments were enabled through a rich yet mostly undocumented ancestry. The scope of this project deals largely with Roman tradition and its influence upon 19th century tradition, since the techniques and traditions were very similar. There are many existing examples of medieval structures built with lime mortars, especially complex gothic designs enabled through use of lime mortar. This is beyond the scope of current project.

tradition and supportive infrastructure facilitated a sophisticated building program. Malinowski outlines the knowledge base surrounding Roman construction accomplishments.

The lack of modern scientific methods and detailed specialization were compensated by an experience based on tradition and knowledge of a more general character. In our own times inventions and engineering solutions often precede a proper scientific explanation. The ancient engineering practices were used for centuries without a clear understanding of the scientific basis of the techniques used. Nevertheless, they were eminently successful. Many of these techniques are of interest and importance to modern concrete engineers, historians of science and technology and archaeologists (Malinowski 1982:100).

Colonial American builders brought with them the skills handed on to them by their European ancestors, whose skills derived in large part from those incorporated during the spread of the Roman Empire. McKee describes the tradition carried by colonists and early 18th century American masons.

The knowledge and skills of early American builders were derived in large measure from European sources, and American achievements cannot be placed in proper perspective unless they are compared with the older methods. A work process and the tools associated with it cannot be fully understood without some acquaintance with their origins and development, yet knowledge about materials and methods of working them are so widely diffused that it is often impossible to discover the source of a particular method. It is necessary, therefore, to examine European techniques that are similar to those employed in America at a later date. An early American's methods were closer to those of his medieval European or ancient Roman counterpart than to modern ones (McKee 1973:preface).

As a means toward determining the methods applied by early 19th century American masons in Virginia, many research methods are involved. While contemporary masonry experience is beneficial, the difference between the technology of lime mortars and current masonry technology involving Portland cement and concrete is so vast that the methods involving the two

are by no means interchangeable. McKee describes some of the scholarly difficulties involving lime mortar technology.

Although American architectural historiography has seen an unprecedented flowering in recent decades, certain areas are still neglected by the professional historian. One of these is architectural technology, especially that of the folk and vernacular aspects of building construction. The conventional knowledge of the field was traditionally transmitted from one generation of craftsman to the next, largely through apprenticeship. Much of it was never committed to paper and all of it until recently escaped the attention of the history book. Even today, when the subject is beginning to attract the attention of scholars and specialists, there is an absolute lack of teaching materials on the subject. Published work is disparate, incomplete and scattered throughout innumerable periodicals in many disciplines. This is a natural reflection of the fact that current research is being carried on by many specialists in many scattered institutions (McKee 1973: intro).

This lack of consolidated information necessitates scouring through numerous disciplines and sources to unearth technological information regarding historic lime treatment techniques. While working as a mason and assisting during masonry restoration projects, I have gained a practical understanding and awareness of the need to implement historic masonry techniques within contemporary restoration projects involving lime mortars.

Following an overview of the historical processes involved in creating a lime mortar, I will discuss the factors, which led to the decline and redirection of these processes.

1.2 Quarrying

The first step of lime production required finding a suitable raw material. This process involved, primarily, discovering calcium carbonate based stones (i.e. limestone or marble) or seashells. Quarrying techniques had become well advanced during construction of the great Egyptian pyramids and further advanced during the Roman building era. Ability to determine the types of

stone containing an adequate amount of calcium carbonate involved trial and error, as well as ages of experimental attempts. Once workable quarries and materials were located, workmen acquired skills for identifying and extracting suitable calcium carbonate raw materials.

Acquisition of calcium carbonate stone was followed by the transportation of such materials to sites for their preparation and conversion into lime. The major technological factors surrounding acquisition of the raw carbonate material, therefore, involved; identification of suitable stone, workable extraction and quarrying methods, and suitable means of transportation to a site for further treatment

1.3 Calcination

In order to convert the calcium carbonate raw material into lime, it was necessary to heat the mass of stone or shell. This practice, dubbed calcining, served to drive out the water and carbon dioxide from within the stone. Calcining of carbonate stones or shell took place in either kilns or clamps customarily constructed of stone or brick with clamps sometimes representing an open heap of carbonate material and fuel. McKee further describes the types and processes of a kiln.

Lime was obtained by calcining (“burning”) limestone or certain other materials. This was sometimes done in open heaps but more generally kilns were employed. A common type was circular in plan, perhaps ten feet in diameter (smaller at top and bottom) and twenty feet high, with stone or brick walls, built into a hillside so it could be loaded from the top. Alternate layers of wood and limestone were placed in the kiln and the fuel ignited; the draft was controlled. After burning for 1 ½ or 2 days and cooling for an equal length of time, quicklime was removed from the bottom of the kiln and the ashes were picked out of it. The kiln just described is the intermittent type. The continuous type was more efficient; as the material in the kiln settled, more was added, and the calcined product was withdrawn from time to time at the bottom. The amount of fuel consumed was substantial (McKee 1971:20).

When the charge of calcium carbonate undergoes firing, it transforms to a calcium oxide known as quicklime. This transformation involves the release of water and carbon dioxide, which are

driven off after being heated through the calcining process. A benefit of the intermittent or periodic kiln involved the slow gradual cooling of the limestone charge converted to quicklime. Limes prepared from a periodic kiln, preserved better in open air, as a result of the gradual cooling. They preserve better by not recarbonating as quickly as quicklime immediately removed from the kiln. Through trial and error lime burners found that the raw limestone fired more completely if broken into pieces about the size of two closed fists. If the stones were too large there would remain unaltered cores (clinkers), which would be found during the subsequent processes. These clinkers would jeopardize the consistency and effectiveness of a resulting lime. Since quicklime was difficult to store and transport, clamps and kilns were set up near the site where lime was used and the raw material would be transported to the kiln site.

North describes that,

Originally most kilns were of a temporary character, such as those erected for the burning of lime for a single building; but when permanent kilns were put up they were often of considerable size; there are sixteenth century references to kilns that were 20 feet high. Lime, being much more difficult to store or transport than limestone, was usually prepared where it was to be used – a practice that continued until well into the last century and accounts for the very large number of disused and ruined lime-kilns dotted about the country, some upon or in the neighborhood of limestone outcrops, and others far removed from any source of that rock (North 1930:388).

This pattern of remnant kilns dotting the countryside was evidenced, here, in the United States as early as the middle of the 1800's. Hawthorne, in his story **Ethan Brand**, describes this cultural characteristic of decaying limekilns as follows:

There are many such limekilns in that tract of country, for the purpose of burning the white marble which composes a large part of the substance of the hills. Some of them, built years ago, and long deserted, with weeds growing in the vacant round of the interior, which is open to the sky, and grass and wildflowers rooting themselves into the chinks of the stones, look already like

relics of antiquity, and may yet be overspread with the lichens of centuries to come (Hawthorne 1851:272).

Here, Hawthorne astutely glimpses into the future of these craft-based creations. Hawthorne likely saw pot kilns such as figure one during his travels.

The skills and instincts of a lime burner were and still remain major keys for a successful limekiln firing. This procedure much like the quarrying relied upon tradition and empirical development. Searle describes the necessary faculties and skills for a successful firing.

The fact is that a really good lime burner works far more by instinct than by conscious application of knowledge, and herein lies his success. If he were to think too much about his work, and especially if he were to “worry” about it unduly, his instincts would become subservient to his conscious thought and he would probably fail ignominiously. This is a psychological aspect of the subject to which very little attention has been paid hitherto, yet on the due recognition of it depends the success or failure of almost every lime kiln...It is important to realize this at the outset, as otherwise, much time may be lost in searching for the cause of trouble and the remedy in the kiln, stone, or fuel, when in reality they can be found only in the personnel (Searle 1935:413-414).

Constant attention and responsive orchestration of the firing were essential. Lime burners worked unusual hours and were highly skilled, although not always highly respected. In Roman times, inmates and criminals would often be sent to provide labor at the limekilns. During the early 19th century in Virginia slaves provided labor, thereby insuring completion of the entire process. Burning Kilns also attracted vagrants seeking warmth.

In England, fuel became a matter of scarcity due to large consumption of wood for limekilns and other uses. North conveys the context involving kilns and their impact upon fuel resources.

Owing to the increasing demands made by the iron-workers and the lime-burners, wood fuel began to grow scarce in the sixteenth century; in the Weald, coal was difficult to get because the buried

Coal Measures of Kent were then unsuspected, and in any case the coal could hardly have been reached and raised to the surface by means of the appliances then available; we find, therefore, that in the eighteenth century the fuel used in the lime-kilns was principally faggots and firs; the latter was specially grown for the purpose, being cut every two or three years (North1930:392).

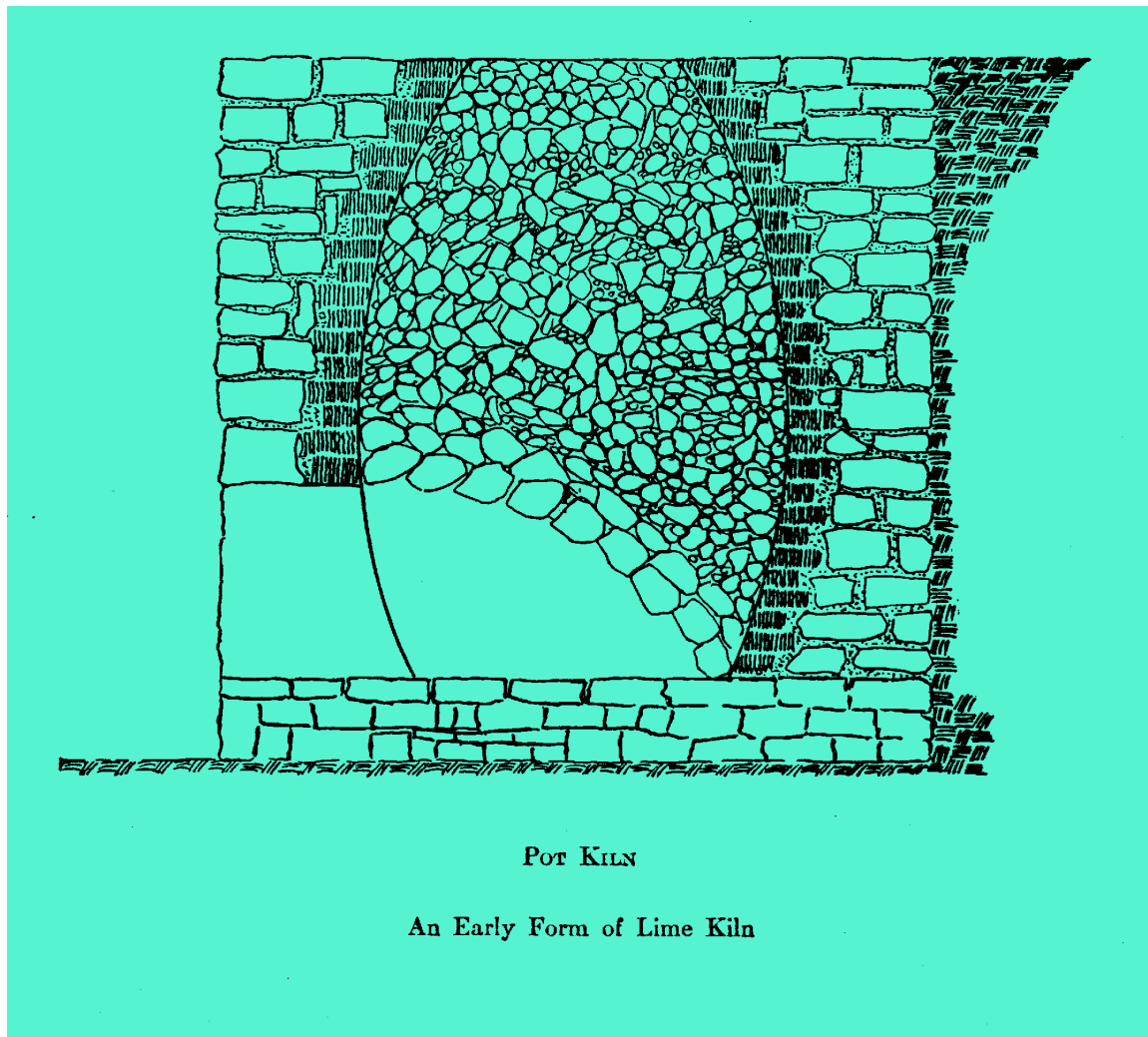


Figure 1 Illustration of a Pot Kiln, a type of kiln used in the early 19th century in Virginia. Pot Kilns were often excavated into the side of a hill to ease loading and seal one side (Lazell 1915:25).

The scarcity of wood led to increasing use of coal as a fuel for kilns- especially in England. Continuous kilns became more abundant as a result of an increased demand for lime and fuel

consumption efficiency. By the late 1700's continuous kilns played a much larger role in European lime production than periodic or intermittent kilns



Figure 2 Engraving by Cornelis Visscher (photo:Rijksprentenkabinet) of a Painting by Peter van Laer depicting life around a limekiln in Rome. The original painting was done in 1637 and following his return to Holland it was lost. Levine describes this and other limekiln works of the Bamboccianti . In front of the kiln men in rags are depicted playing morra- a game of chance (Levine 1998: 572).

Originally, the kilns in which lime was burnt were all intermittent in their action, that is to say, they were loaded, the contents fired, allowed to cool and the lime withdrawn, after which the process commenced all over again. Such a method is convenient where small quantities only are dealt with and the lime is needed at irregular intervals, but it is obviously wasteful of heat, and in modern practice the tendency is towards the use of kilns that are continuous in their operation. In the case of one “continuous” method, for example, a vertical kiln is fed with fuel and limestone in alternate layers, and as the lime is removed from the bottom, fresh raw material is added at the top, the “burning” proceeding as the mixture slowly descends through the kiln (North 1930:394).

Kilns, regardless of their type, transformed limestone, shell or marble into quicklime. This material would, next, need to be quenched or slaked.

1.4 Slaking

Quicklime needed to be slaked, or hydrated, in order to yield workable lime for building purposes. Hydration (slaking) involved the introduction of water or moisture to activate the quicklime, having been deprived of water and carbon dioxide following calcining.

McKee outlines the basic procedures involving the slaking of quicklime as follows:

Before making mortar, quicklime was slaked (more correctly, hydrated) by the controlled addition of water. One of three methods was followed: (1) sprinkling or “drowning”; Ideally, water equal in weight to 1/3 of the quicklime was sprinkled over it. Heat was given off, the material cracked open and became a powder, and increased in volume. This method was considered the best. (2) Immersion: the quicklime, placed in a basket, was lowered into the water for the proper length of time, and drawn up to complete the slaking. The handling was tricky, at best, and demanded considerable skill. (3) air-slaking: the quicklime was simply left exposed, to pick up moisture from the air. Most authorities agreed that this method was not recommended. Lime from different sources varied in its capacity to take up water in slaking. Some called fat, took up ½ of their volume, and produced a dry powder 3 ½ times the volume of the original quicklime. Others called meagre, might take up only 1/3 their volume of water

and produce a dry powder only a little greater than the original volume. Masons preferred the fat limes, although in reality they were no better, and might not even be so good. The fat limes did produce a larger quantity of mortar, from a given quantity of quicklime, than the others (McKee 1971:21).

These three methods represented the primary means of slaking with the first two most often practiced. There were also variations of these methods stemming from local or regional custom, personal preference, and adaptation to variant raw material. While McKee states that sprinkling was the best method, in actual practice more water than the amount necessary to reduce the quicklime to a powder was preferable, thereby converting the quick lime to paste. More water insured a thorough hydration and any excess water could be poured off the surface of the slaked putty prior to mixing with an aggregate. This proved more consistent provided that an excess of water was not introduced so as to drastically diminish the heat, which resulted from the combination of water and quicklime. An abundance of heat and steam are generated during the slaking process and manipulation of this heat and steam are critical toward the resulting properties of the lime. Another variant method involved the addition of sand during the slaking procedure. While sand is considered inert, some believed that this process enhanced the marriage between lime and aggregate. A high calcium marble or limestone was considered preferable by many masons, since it yielded more following slaking. Such a high calcium lime was termed 'fat lime'. Limestones or marbles with lower calcium content were dubbed 'meagre' limes and yielded less volume than fat limes. Some 'meagre' limes were actually hydraulic. This meant that, when mixed with sand, they were capable of hardening under water. Hardening occurred as a result of a chemical reaction between the silicates and lime. This property resulted from the amount of clay (Aluminum silicates) within the raw material. Therefore, the composition of the raw calcium carbonate material not only affected its future properties as a mortar, but also, influenced the process and method of slaking. Certain slaking methods could be tailored for certain materials. At best, a slaking could optimize the performance of the lime being treated to yield a superior quality lime, whereas, at worst, the slaking could harm the latent potential of the treated quicklime rendering it of poor quality. The slaking procedure, like all other steps

involving the preparation of mortar had a great influence upon the resultant properties and performance of finished mortar.

1.5 Mortar Mixing

The following description of mortar mixing involves those techniques associated with a high calcium lime. These techniques were similar to those used for hydraulic mortars, which contained approximately 20% or more of clay within the raw carbonate stone. The process was essentially the same, while the particulars differed. Since the hydraulic mortars set underwater and acquired a quicker set, they could not be beaten or worked after the initial set occurred. Examples from the work of plasterers will be introduced as well, since they worked with lime and sand, as did masons. McKee describes a typical mortar and some factors influencing its preparation.

The common variety of mortar was made of lime, sand and water. Details of its preparation varied according to regional customs and individual preferences but most of these details were known throughout Europe and America. The builder was aware of more methods than he practiced (McKee 1971:64).

In order to create a mortar for uniting brick or stone, workers introduced slaked lime to a sand aggregate. This practice involved proportioning the amount of lime, sand and water.

According to McKee, three primary methods of mortar mixing predominated:

(1) mixing dry slaked lime powder, sand and water; (2) mixing wet slaked-lime paste and sand, adding water if needed; (3) mixing pulverized dry quicklime, sand and water, using the mortar while it was still hot. This practice was largely confined to Great Britain (McKee 1971:21).

The prevalent method incorporated within the United States in the early 19th century involved mixing wet slaked lime putty and sand. Another method, not mentioned by McKee, involved the introduction of sand to the lime during the slaking procedure, which some craftsmen believed enhanced the resulting bond between the lime and aggregate. Regardless of the method, it was

observed that the quality of the lime and sand were major factors contributing to the future performance and properties of the mortar. Quality of lime, in particular, played a major role upon the amount of sand the lime would accept and remain workable.

Shaw further describes the proportioning and factors involving the suitable marriage between lime and sand as follows:

The proportions of lime and sand to each other are varied in different places; the amount of sand, however, always exceeds that of lime. The more sand that can be incorporated with the lime, the better, provided the necessary degree of plasticity is preserved; for the mortar becomes stronger, and it also sets or consolidates more quickly, when the lime and water are less in quantity and more subdivided. From two to four parts of sand are commonly used to one of lime, according to the quality of the lime and the labor bestowed upon it. The more pure the lime is, and the more thoroughly it is beaten or worked over, the more sand it will take up, and the more firm and durable does it become (Shaw 1846:63).

Fat lime or high calcium lime could be mixed with the aggregate and allowed to age, provided it was protected from exposure to the air. Exposure to the air would act to recarbonate or solidify the mass. Many ancient artisans practiced this custom of storing lime putty or lime mortar. Plasterers would keep their lime in sealed vats for considerable lengths of time. A story shared by restoration craftsmen working with lime involves the tradition where a father takes his son down to the basement. Upon reaching the cellar, he points at the first vat saying ‘that is my great grandfather’, opening the lid to show just a trace of lime still remaining. Then, he points at the second vat proclaiming ‘that is my grandfather’, which is about half full. Next, he points to the third vat indicating, ‘this is my father’, which is over three quarters full. Then, he puts his hand on his sons’ shoulder and points proudly at the last full vat saying ‘that my dear son is your father’. Nicholson further describes the mixing and aging of mortar, which was viewed as a requisite practice.

The mortar should be made underground, then covered up, and kept there for a considerable length of time, the longer the better; and when it is to be used, it should be beat up afresh. This makes it set sooner, renders it less liable to crack and harder when

dry...How very different was the practice of the Romans! The lime which they employed was perfectly burnt, the sand sharp, clean, and large grained; when these ingredients were mixed in due proportion, with a small quantity of water, the mass was put into a wooden mortar (pan), and beaten with a heavy wooden or iron pestle, till the composition adhered to the mortar: being thus far prepared, they kept it until it was at least three years old. The beating of mortar is of the utmost consequence to its durability, and it would appear that the effect produced by it, is owing to something more than a mere mechanical mixture (Nicholson 1850:130).

This three-year period mentioned by Nicholson proves to be less than a haphazard prescription. During the Roman building era, Vitruvius conveyed this customary allowance in his written works. Therefore, the practices of the Romans remained a model to eighteenth, nineteenth, and twentieth century architects as well as craftsmen.

A critical aspect of mortar and plaster mixing involved the beating or ramming of the lime and sand mixture. This technique insured that the sand and lime binder were thoroughly united. Thorough beating also reduced the amount of water necessary to create a workable plastic material for a plasterer or mason. Cowper touches upon the need to beat a plaster, in order to enhance its durability.

The ancients laid great stress on beating the plaster before use, for tempering this when used in fine plastering; it has been suggested that modern lime plaster has less durability than the ancient examples as a result of omitting this treatment. A general tendency toward this omission appears contemporary with a significant and historic strike of the 'hawkboys' or plasterers' assistants in the London area. Part of the hawkboys' duty was the beating of the mixed plaster before application (Cowper 1927:6).

Beating plaster or mortar was stressed as a key element of mixing. It served to fully unite the lime and sand aggregate, thereby filling the voids between the sand grains with lime. This practice also served to drive off any unnecessary moisture. Beating or ramming the mortar contributed significantly toward its future performance and durability.

According to Shaw,

The ancient masons were so very scrupulous in the process of mixing their mortar, that it is said the Greeks kept ten men constantly employed for a long space of time, to each mason; this rendered their mortar of such prodigious hardness, that Vetruius [sic] tells us, the pieces of plaster falling off from old walls, served to make tables. It was a maxim among old masons to their laborers, that they should dilute the mortar with the sweat of their brows, that is, labor a long time, instead of drowning it with water to have it done sooner. The weakness of modern mortar, compared to the ancient, is a common subject of regret; and many ingenious men take it for granted, that the process used by the Roman architects in preparing their mortar, is one of those arts which is now lost, and have employed themselves in making experiments for its recovery. But the characteristics of all modern artists, builders among the rest, seems to be, to spare their time and labor as much as possible, and to increase the quantity of the article they produce, without much regard to goodness; and perhaps there is no manufacture, in which it is so remarkably exemplified, as in the preparation of common mortar (Shaw 1846:54).

Both time and labor were contributing factors upon the preparation of an enduring plaster or mortar. As recent as the 1850's, architects and craftsmen sang the praises of thoroughly beating and working the mortar during preparation.

Nicholson also draws a connection between the amount of labor bestowed during mixing mortar and the quality of the substance produced.

In the preparation of maltha, as well as every other kind of mortar, so much depends on the manipulation, and on the care and long beating of the ingredients, that those countries in which labor is of the least value possess, in general, the best mortar. Hence, no doubt, principally arises the unrivalled excellence of the mortar made by the Tunisians, and other inhabitants of the northern coast of Africa. Dr. Shaw gives the following account of their manner of preparing their mortar: one measure of sand, two of wood ashes, and three of lime, being previously sifted, are mixed together, and sprinkled with a little water; after the mass has been beaten sometime, a little oil is added: the beating is carried on for three or four days successively, and, as the evaporation in that hot climate

is considerable, the cement is kept in a proper degree of softness by the alternate addition of small quantities of water and oil. The cement, being completed, is applied in the usual manner, and speedily acquires a stony hardness (Nicholson 1850:133-34).

Not only was the amount of labor bestowed on the mortar deemed essential, but also the amount of time the lime and mortar were allowed to age. Lime or lime mortar gained in plasticity as a result of the aging or ripening process. Cowper describes the sand carrying capacity in relation to the plasticity of lime.

Also for economical reasons the greater the proportion of sand the plaster can carry without deteriorating the better; the sand-carrying capacity of the lime is therefore of considerable importance. It is evident that shrinkage will be almost entirely prevented when the sand grains (which do not alter in volume) are in actual contact with one another. The spaces in between the grains will then be filled wholly or partially by fine particles of lime hydrate and (at first) limewater, unless indeed the hydrated lime contains a large proportion of aggregated particles of a size comparable with that of the sand so that they are too large to fit within the pores... Accordingly, the sand-carrying capacity depends not only on the plasticity of the lime (which is closely related to the size of the hydrated particles) and upon the amount of impurities present in the lime (also affecting plasticity), but also on the average size and distribution of sizes of particles in the sand used. It will thus be affected by the method of slaking used, and upon the amount of maturing of the putty, since these factors influence particle-size and resulting plasticity. In practice, sand would be added until the plasterer began to find an appreciable difficulty in working the material, on account of decreasing plasticity (Cowper 1927:35).

Cowper goes on further to describe the phenomenon behind beating or reworking an aged lime or lime mortar, which has temporarily crusted on the surface.

The plasticity or working qualities of the putty (and hence of the plaster made with it) will evidently depend on the relative proportions of the primary and secondary states of division which depend in turn on the mode, temperature, and rate of slaking. For minute colloidal particles will readily flow when the putty is worked, whilst large irregularly shaped aggregated particles or

clumps would give rise to an increased resistance to flow, and produce a 'short' material. The effect of subsequent maturing ('ripening,' 'curing,' 'soaking,' 'aging,' &c.) of the putty over long periods can be attributed to a further process of colloidal dispersion of the larger, aggregated particles, producing thus a finer, more mobile, and uniform material of high plasticity.

The subsequent hardening of the finely-dispersed mass was attributed by Sir George Beilby to a molecular association set up between the lime hydrate and previously free water molecules, but of such a temporary and feeble character that even mechanical disturbance is able to break it down. According to this theory, then, the plasticity of lime putty results from the transient flow of the molecules under mechanical disturbance and the restoration of rigidity when the disturbance ceases; this process being repeated as often as the putty is disturbed. Continental investigators have attempted to assign actual chemical formulae to such complex hydration products, and to explain these in terms of 'secondary valencies.' An alternative, purely colloidal, theory likens the structure of the lime putty to that of a jelly, which simply dries out to a hard mass when the plaster sets, after the manner of gelatin.

The regular beating or chopping up of the mixed plaster so frequently referred to in the history of plastering, by Vitruvius and subsequent writers, and met with in the traditions of fine plaster-work, will evidently have the effect of promoting the deflocculating or dispersive process in the slaked lime, with a resulting gain in plasticity (Cowper 1927:37).

Benefits resulting from a lime with increased plasticity include; a more workable lime plaster or lime mortar, a better bond between mortar and masonry unit, and greater sand carrying capacity.

We can conclude that many variables (preparation of the lime, its composition and freshness, quality of the sand, proportioning of the mixture, its wetness, thoroughness of mixing, etc.) influenced the mortar making procedure and resultant material. McKee outlines some factors influencing the quality of mortar.

Before the middle of the eighteenth century, practical knowledge about mortar was passed on from master to apprentice and diffused from one country to another by migrating workmen. The mortar

that they made, however, often varied in quality. This variation was not the fault of traditional methods, which were generally sound. The process of manufacturing and using lime consisted of several operations over which there was no unified control. Failure to maintain high standards of quality for any one operation could lower the quality of mortar but the inferiority of the mortar might not become known until several years after it had been used in construction...In the late eighteenth century, chemists and engineers began to apply scientific methods to the study of lime and mortar. As the materials became better understood, it became possible to produce mortar of more uniform quality and to calculate its strength with greater accuracy (McKee 1971:65).

Historic treatment techniques employed by masonry workers were often rendered in the absence of any underlying theoretical framework. In other words, technological treatments of carbonate rocks and resultant lime mortars escaped complete explanation according to known facts or phenomena. The absence of a theoretical understanding, however, in no way undermined enduring masonry construction. Lacking a complete theory for lime treatment allowed craft workers more direct control over lime preparation and treatment. Furthermore, freedom to conduct the calcining, slaking, and mortar preparation could lead to variations and difficulties with resultant mortars. Multiple treatment methods for lime mortars could be both a blessing and a curse for craftsmen. Optimum treatments could be employed with quality materials producing excellent mortar, whereas inadequate treatments could produce an inferior mortar. Furthermore, it could take months or even years to realize the inadequacy of the mortar. Then it remained difficult to determine if the materials or treatments led to the poor performing mortar.

Chapter 2 Lime and Cement Research – Traditional Techniques and Technological Transition

From the mid 18th to mid 19th centuries in Europe increased attention was being paid to the formulation of mortar and cement. In the United States during this same period, although there was considerable empirical trial and error with production of mortar, there was little, if any, formal publication on this topic. Since it was not until the mid 19th century that research was published in the United States, American engineers and builders consulted research information from European sources.

2.1 Roman Masonry Legacy

Roman aqueducts, bridges, and other masonry structures stood as examples of the enduring potential for masonry construction. Much inquiry focused on these living monuments and the materials and techniques associated with their construction.

The ancient Roman mortars, found in edifices erected two thousand years since, are of such rare hardness, that it was for a long time believed that the Roman architects were acquainted with modes of mixing them superior to those at the present time. This opinion gave rise to numerous pretended discoveries of the Roman manner of making mortar, and many whimsical theories of the proper methods of treating lime to produce mortars of an equal hardness. But recent examinations and analysis of the hardest and oldest mortars have shown that they are mixtures precisely similar to those now in use (Dexter 1840:5).

These Roman structures served as an inspiration and catalyst for masonry research. During the times mentioned above (mid 18th–mid 19th century), attempts to recreate masonry techniques involved trial and error. Some of these experiments involved established traditional methods and materials, while other experiments involved variant methods and materials. One variant method, practiced by Lorient in France, illustrated the increased social and political emphasis on mortar.

Monsieur Lorient's Mortar, the method of making which was announced by order of his Majesty, at Paris, in 1774, is made in the following manner:-- Take one part of brick dust, finely sifted, two parts of fine river sand, screened, and as much old slaked lime as may be sufficient to form mortar with water, in the usual method, but so wet as to serve for the slacking of as much powdered quicklime as amounts to one fourth of the whole quantity of brick-dust and sand. When the materials are well mixed, employ the composition quickly, as the least delay may render the application imperfect, or impossible (Shaw 1846:64).

Any State approved process in France was published following its acceptance by the State. Lorient claimed an ability to build arches, aqueducts, bridges and fortifications with ease and solidity utilizing this method. However, success was short-lived, as the mortar began to crumble as it aged. Lorient's use of brick dust ties directly within the traditional Roman masonry practice. Although this method involving powdered quicklime did not recapture the enduring glory and longevity of Roman mortars, it symbolized both a political and societal desire for better mortars. This example represents an emphasis on employing methods able to achieve enduring construction. It also typifies the multitude of craft procedures and formulations practiced. Some of the many additives to the lime and sand mortar matrix included; blood, egg whites, sugar, honey, ashes, and urine - to name just a few. Some of these additives followed a traditional precedent, while others were experimental. The blend of mortar used by masons often served as their individual trademark and signature. Such trademarks or recipes were often threads within a particular family, regional or cultural tradition.

2.2 European Masonry Research

As early as the mid 18th century, lime and cement began drawing attention from increasingly organized circles of professors, doctors, and engineers. They sought to gain a comprehensive understanding of the masonry materials capable of yielding enduring masonry works. The Royal Society in England represented one such group dedicated to establishing the facts and theory behind many craft operations.

The history of the early years of the Royal Society is particularly important for the present chapter because it records three factors that became important in the mid-seventeenth century in promoting the shift from craft mysteries to science as a basis for technology. First, the Royal Society united a new class of men interested in natural philosophy and its applications. Secondly, it sponsored 'Histories of Nature, Arts or Works', which provided, often for the first time, scientific descriptions of craft technologies as they were practiced in the seventeenth century. Thirdly, it stimulated the publication, so that all might know of them, of important new scientific and technological discoveries (Singer 1957:668).

Masonry was one such craft technology that became a subject of research and experimentation. In particular, the process of converting carbonate raw material (i.e. limestone, marble, sea shells) into mortar had been practiced for ages without a full understanding of the phenomena associated with its conversion. Researchers focused on lime, in order to unravel the mysteries involving this carbonate building block.

Among early scientists to make systematic experiments with lime, Joseph Black (1728-1799) was notable. While Professor of Chemistry at Glasgow University, he published in 1756 Experiments upon Magnesia alba, Quicklime, and some other Alkaline substances. He showed that chalk, when calcined, gave off a gas called "fixed air," and that the remaining quicklime could be reconverted into chalk by exposure to the air. Black was noted for other findings of value to the development of industry, especially the quantitative demonstration of latent heat, which enabled James Watt to greatly improve the steam engine (McKee 1971:22).

These researches were not only of academic intrigue, but also, geared toward improving existing techniques and assisting the development of new inventions. One such invention to benefit from lime related research was the steam engine. The work and influence of Joseph Black assisted James Watt toward his development and improvement of the steam engine. This improvement stemmed from Black's research and experimentation involving latent heat. His research on latent heat included the slaking of lime. During the slaking of lime temperatures often surpass the boiling point. Black focused on this discharge of steam, which occurred during the slaking of quicklime.

John Smeaton, an English engineer, is now credited by most authorities for his discovery of a substance, which yielded hydraulic mortar. While experimenting with lime, he found that a limestone containing clay produced a mortar, when calcined, slaked and mixed with sand, capable of hardening under water. This discovery enabled him to lead the reconstruction of the Edystone Lighthouse in the mid 1700's. He later published his experiments within A Narrative of the Building of the Edystone Lighthouse in 1791. LeChatelier outlines the circumstances involving acceptance of this finding, which claims that clay acts as the material substance conferring hydraulic properties to mortar.

Smeaton, an English engineer, reported in 1756 the presence of clay in the hydraulic-lime limestones, but this observation passed unnoticed. A distinguished practitioner, the designer of important works, he enjoyed a great reputation as an engineer, but had no authority as a chemist.

Several years later, the Swedish savant, Bergmann, having analyzed the hydraulic-lime limestones of Lena, found in them several percent of manganese and attributed the hydraulic properties of the lime to the presence of this body. This opinion, because of the authority of the illustrious reputation of its author, was accepted without discussion.

Guyton de Morveau, trying to verify Bergmann's ideas, analyzed the principal hydraulic limes of France; he found that all contained clay, but only one, manganese. He said, nevertheless, upon the authority of the Swedish chemist, that manganese was the cause of the hydraulicity of limes.

Saussure did the same work for the limes of Switzerland and found none which were manganiferous.

He declared, nevertheless, upon the authority of Bergmann and Guyton de Morveau that manganese was preeminently the hydraulizing substance, but he timidly added that clay could in a certain degree replace the manganese completely, although being very inferior to it...

The first precise and exact observation upon the hydraulic-limes is due to Collet-Descotils, Mining Engineer, Professor of Chemistry at the Ecole des Mines. In 1813 he gave in a note a few lines long inserted in the *Annales des Mines*, the analysis of the limestones and the lime of Senonches and called attention on this occasion to the fact that the silica of the lime was soluble in acids, whereas that of the limestones was not, which demonstrates that during the calcinations there had been a combination of the silica with the lime. He attributed the hydraulic properties of the lime to the compounds thus produced (Le Chatelier 1905:40-41).

Smeaton's research and experimentation established the cornerstone on which subsequent hydraulic masonry works were successfully built. His discovery, however, was neither credited nor digested by many authorities until the early decades of the nineteenth century.

Other researchers included doctors, who also looked at lime with great interest. A portion of this interest stemmed from a desire to better understand bones and the process of their creation and growth. In order to gain an understanding of the principles involving the strength and hardening of calcareous materials, Bryan Higgins conducted tests and experiments on lime between the years 1774 and 1780. Dr. Higgins' tests included mixtures of lime, sand, and water.

But seeing that many years are requisite for the greatest degree of induration which cementitious mixtures like mortar can acquire, or for our discovering the imperfections of them; and that the life of man is too short to allow any considerable improvements of them to be derived from such expedients as had hitherto been made, I resolved in the beginning of the year 1775 to investigate more closely than I had hitherto done, the principles on which the induration and strength of calcerous cements depend; not doubting that this would lead me by an untried path to recover or to excel the Roman cement, which in aquaducts and the most exposed structures has withstood every trial of fifteen hundred or two thousand years (Higgins 1780:2).

Higgins, here, conveys much confidence regarding his research and the likely fruits thereof. Not only did he and other researchers feel they could match Roman masonry construction, but also endeavored to outdo them. Although this confident research agenda did not yield immediate and

highly successful results, it served to further stimulate research and experimentation. Louis J. Vicat (1786-1861), Chief Engineer of Roads and Bridges in France, organized the most comprehensive description of Mortars and Cements published in 1828. LeChatelier comments on Vicat's contributions to the study of mortars.

It is some years later, in 1818, that Vicat gave his first memoir upon the hydraulic limes. We know that to this engineer belongs by far the largest share in the development of our theoretical and experimental information on mortars. Seconded by the intelligent protection of M. Becquey, Director General of the Ponts et Chaussées et des Mines, he devoted himself exclusively to the study of this important question and succeeded in establishing the general constitution of limes and hydraulic cements, in defining the most favorable conditions for their manufacture and their use; so that he is justly considered as the creator of this industry which was not long expanding from France over all of Europe (LeChatelier 1905:41).

Vicat developed the first comprehensive classification of limes and hydraulic limes. He also articulated a theory of mortars describing their setting and ability to harden in water. Vicat applied this understanding during numerous civil construction projects.

2.3 United States Masonry Development

In the United States there was a limited amount of organized research and experimentation involving mortar and cement until the middle of the nineteenth century. Previously, those seeking research and experimentation information on mortar and cement looked to Europe.

Our present knowledge of this subject is derived almost wholly from the experimental researches of foreign engineers. The English, and particularly the French engineers, have devoted themselves to this kind of research with distinguished success. They have collected by their experiments, extending through a series of years, a mass of useful facts, which, while they point out the best methods of preparing mortars, admonish us that this (in the language of one of their most eminent engineers,) “soul of

masonry” cannot receive too much attention, if we desire that our masonry shall endure (Dexter 1840:3).

European research made its way to the United States through statesman, craftsman, and engineers. Statesman such as Thomas Jefferson had both access to and ownership of many published works by European engineers and architects. Among the works owned by Jefferson included a copy of Smeaton’s book on the Edystone Lighthouse. Jefferson’s preference for masonry construction is evidenced by the structures that he had built during his lifetime. Monticello and the University of Virginia, both located in Charlottesville, were constructed of brick and lime mortar. Poplar Forest, his villa in Bedford County, likewise, was constructed of brick and mortar. These structures, completed in the early part of the 19th century, stand as living examples of early nineteenth century American masonry technology. Craftsmen associated with construction of these buildings came from many locations, including; Virginia, Boston, Philadelphia, and Europe among others.

In his March, 1819 advertisement for University workmen, Jefferson stipulated that the builders were to provide “certificates from known characters of their perfect skills in their line of business”. In addition, Jefferson also set the condition that all the undertakers, masons, as well as carpenters, were able to “execute with exactness, the general plan and instructions which will be exhibited to them, making their own working draughts, however, and submitting them to previous examination.” Thus, the University workmen not only had to be skilled craftsmen, but also possess a knowledge of architectural drawing (Cote 1986:90).

These craftsmen were recruited based on both their skills and accomplishments. Many of the carpenters came from Boston and Philadelphia, while most of the masons came from Richmond and throughout Virginia. Their training involved the customary apprenticeship then in place.

From the seventeenth through the nineteenth centuries, the training of a builder in America began with an apprenticeship. This system had its immediate precedents in England and involved the binding of a prospective builder to a master for the avowed purpose of learning a specific trade. With some notable exceptions, the apprenticeship period for a mason and carpenter in Virginia usually began at the age of thirteen or fourteen and ended when the

apprentice reached his majority. During the apprenticeship period, the master typically furnished the trainees with clothes, shelter and board, while the apprentice provided his master with labor. At the end of the apprenticeship, the trainee received a suit of clothes and tools; occasionally the former apprentice remained with his master as a salaried employee (Cote 1986:81).

Such a system enabled the training of skilled builders, who continued the traditional masonry practices of the Europeans. At this time an undertaker played a primary role in building construction. An undertaker assumed all responsibility for completing the construction project agreed to within a specified contract and enrolled the services of carpenters, masons, and necessary labor. Often, the undertaker would be a carpenter or mason with enough acquired capital and resources to complete the project and pay worker salaries. During the Jefferson construction era, both skilled and unskilled slave labor played key roles within the building process.

Also employed by the undertaker, although under a different payment system, were skilled slaves. By the mid-eighteenth century, the slave had become a fixture in Virginia's building trade as both skilled and unskilled labor. As indicated by notice in the Virginia Gazette, slaves were often trained as apprentices to serve in the various building trades. For example, the Gazette noted on

December 18, 1766:

To be sold, on Thursday the 15th of January at Blandford, if fair, otherwise next fair day, several likely Negroes, among which are 3 apprentices, who have about three years to serve, two of them to a ship carpenter, and the other to a bricklayer (Cote 1986:96-97).

Slaves not only served the role as laborers, but also acquired skills necessary to perform precision carpentry and masonry duties. We can conclude that skills to construct with common lime mortar were firmly established in the United States in the early 19th century. However, builders and engineers in the United States relied primarily on European research and application of hydraulic mortars for their own hydraulic constructions in the early decades of the nineteenth century.

The expensive inconvenience caused by the bad quality of the mortar made use of in many hydraulic works in Europe, 'attested the insufficiency of the art, and this insufficiency exhibited itself more and more owing to the multiplicity of marine works called for by a constantly increasing commerce.' The engineering talent, aided by the most eminent chemists of Europe, has been devoted to the investigation of the various mixtures of lime forming mortars; made necessary, owing to the failure of many of their locks, aqueducts, and other important structures, which, though of recent origin, exhibited 'all the characteristics of age without the possibility of attributing these unexpected dilapidations to any other cause, than the bad quality of the mortar, or cement made use of (Dexter 1840:3-4).

Although the United States relied upon European research during the eighteenth and early nineteenth centuries, by the middle of the nineteenth century they also actively entered the masonry research arena. They then became a contributor to the body of masonry knowledge accumulated through construction, testing, and experimentation. Quincy Adams Gillmore (1825-1888) served as a Brigadier General in The United States Army. He supervised the construction of many military fortifications and public infrastructure projects involving masonry materials. He published a comprehensive Practical Treatise on Limes, Hydraulic Cements, and Mortars during the height of the Civil War in 1863. This work includes detailed information involving the locations of limestone formations throughout the eastern United States and the vast array of treatment methods associated with these materials. While this work builds on European masonry knowledge, it stands alone prescribing treatment methods best suited for American masonry.

2.4 Lime Treatment Techniques Prior to Standardization

Prior to the fruits of scientific study and the standardization of lime, craftsmen working with lime utilized their own skills and talent coupled with an established tradition of treatment methods.

The use of lime in nearly all industries has to an unusual degree been governed by rule of thumb. The procedure, based on centuries of experience, was satisfactory whilst the requisite empirical knowledge was passed on as part of the training of craftsmen, but

with the passing of the old system of careful training by long apprenticeship it frequently breaks down. It is only in quite recent years that scientific study of the use of lime was begun: a study which it is hoped will ultimately enable the use of lime in all industries to be understood and systematized (Knibbs 1974:3).

Prior to the development of scientific methods of analysis, producers of lime had to judge the quality of their sources by experience. Searle describes the importance of skill and experience essential to the calcining process.

It is comparatively easy to say what is wrong when the lime is examined; it is far more difficult to decide when overheating is occurring or is about to occur, and to stop or prevent it before it becomes serious. This ability to be constantly alert cannot be learned from books; it is partly a natural gift, but it can be cultivated by will power and prolonged experience until it becomes “a second nature” (Searle 1935:435).

This role of skill and experience was vital in order to yield high quality quicklime. Experience and skill is, likewise, essential for contemporary lime burning. Another lime treatment requiring great skill involved the slaking of quicklime. Cowper describes the challenging process of slaking, whereby water unites with the quicklime.

There is a danger of burning a fat lime in slaking, as a result of an insufficient supply of water or inadequate stirring. Lime slaked at too high a temperature has a tendency to coagulate the minute (colloidal) particles which are the first product of the interaction of the water with the surface of the quicklime, thus forming aggregates and diminishing the plasticity. The use of too large a quantity of water-“drowning”- in the slaking process is usually considered to have an unfavorable effect, besides giving more trouble by requiring the excess of water to be run off or evaporated subsequently before use (Cowper 1927:40).

Therefore, the amount of water introduced with the quicklime is critical, as well as the rate which it is introduced. An excessive amount of water also serves to significantly lower the temperature of hydration, which could harm the resultant properties of the lime hydrate. Gillmore further describes some of the possible problems occurring during hand slaking of quicklime.

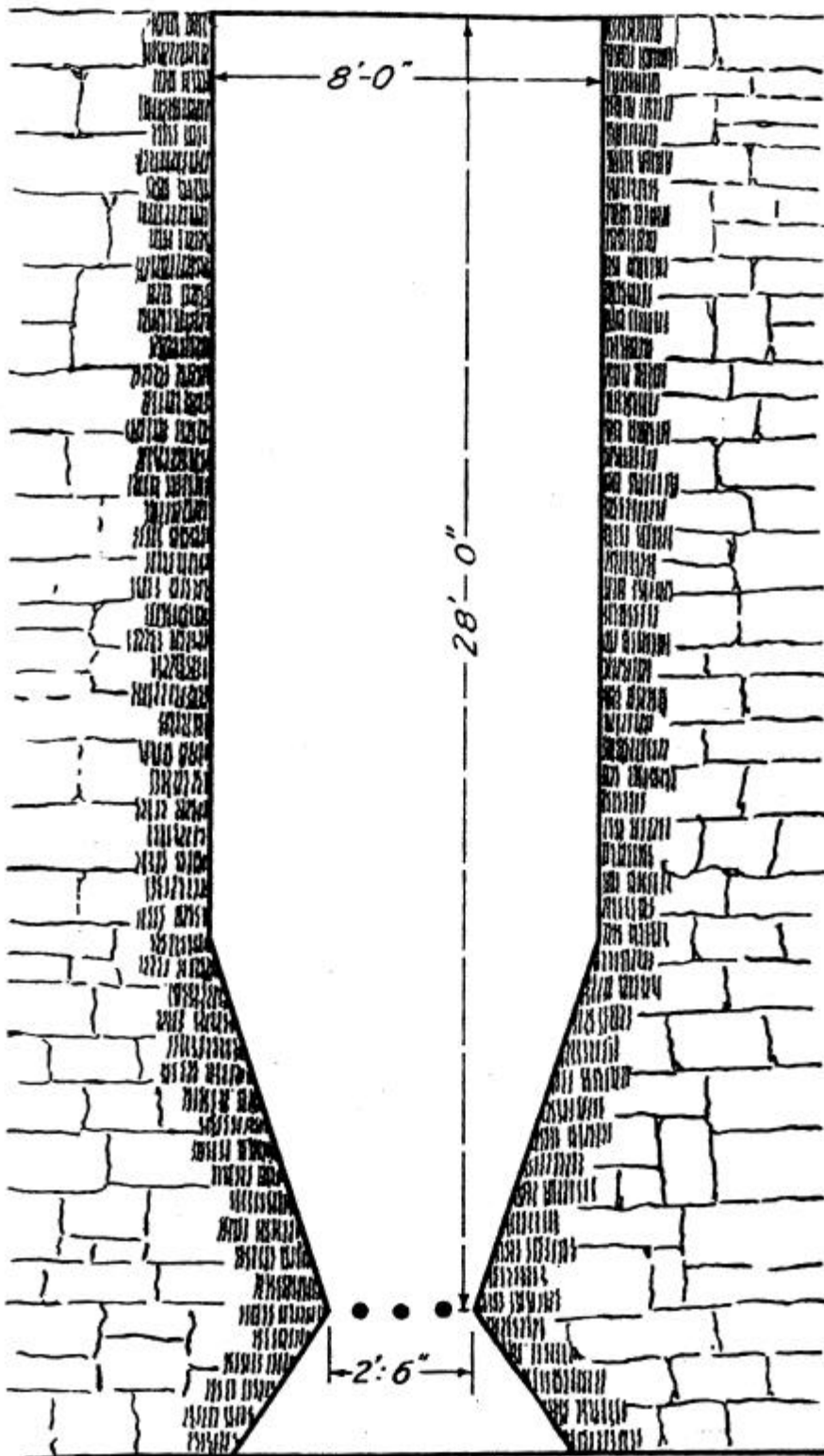
This process is liable to great abuse at the hands of workmen, who were apt to use either too much water, thus conferring upon the slaked lime a condition of semi-fluidity, and thereby injuring its binding qualities; or, not having used enough in the first instance, they seek to remedy the error by adding more after the extinction has well progressed, and a portion of the lime is already reduced to powder, thus suddenly depressing the temperature, and chilling the lime, which renders it granular and lumpy (Gillmore 1863:180).

Although addition of water during slaking may have been haphazard in some cases, there also existed skilled craftsmen capable of optimizing the resultant properties of lime through their experienced treatment and handling. Furthermore, although craftsmen lacked a comprehensive theory for lime treatment, many skilled artisans could select from a vast array of techniques, in order to gain desired properties and future performance from their respective limes. This flexibility allowed for adjustment to local materials. Such an ability to employ local materials effectively was also achieved by the Romans during their vast expansion.

The Romans carried their knowledge of the preparation of mortar with them to the remoter parts of their Empire, and the Roman brickwork found in England, for example, is equal to the best of that in Italy. Ground tiles were the most commonly used ingredient, but in a few districts deposits bearing some resemblance to the natural pozzolanas of the Bay of Naples were found. The use of Rhenish volcanic tuffs known as Trass was probably introduced at this time, and this material, like pozzolana, is still very largely employed at the present day (Lea & Desch 1956:4).

Pozzolanas were volcanic earths mixed with lime. They acted similar to brick dust within the mortar by yielding an hydraulic mortar. The Romans completed works in various regions illustrate the ability to transfer technology effectively without material standardization. Current

Figure 3 page 31 Illustrates a Draw Kiln. Draw Kilns were used in the United States for calcining limestone in the mid 19th century (Lazell 1915:27).



DRAW KILN

Described by Jackson in 1839

evidence suggests that this traditional mixture of brick dust and lime was applied as a render at Jefferson's Poplar Forest. A render represents a binding material that is applied on the surface of an existing structural element. For example, a render at Poplar Forest was applied to cover the exterior columns constructed of brick.³

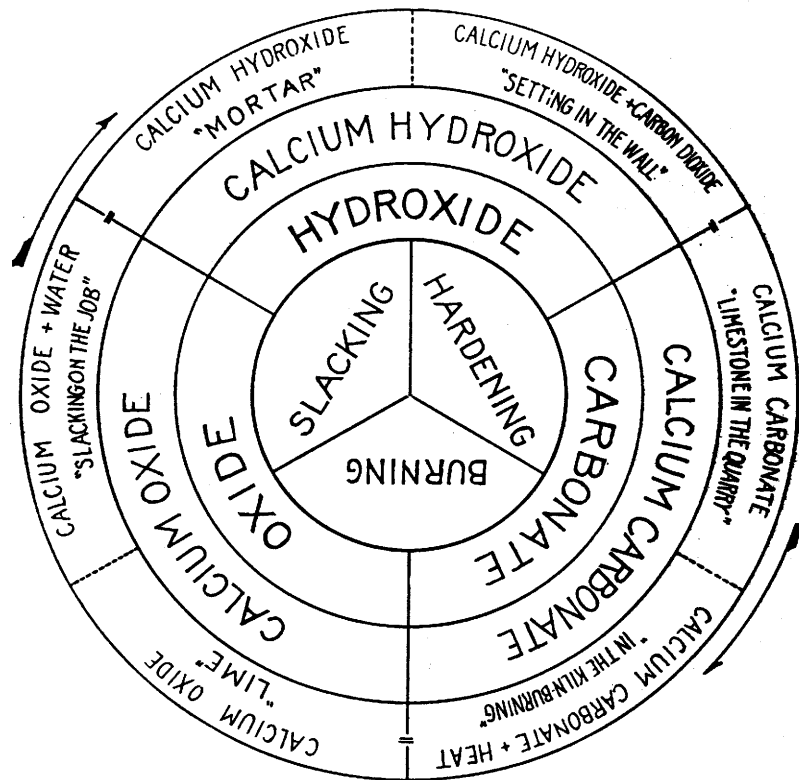
The method of carrying out the slaking and subsequent mixing process varied according to the type of lime and the purpose for which it was applied. Special procedures could be tailored to suit the composition of the material, as well as enhance its performance for a particular application. Guillerme describes some of the unique procedures adopted by different craftsmen working with lime.

Not only were there numerous ways of producing lime, but furthermore, each trade had its own special application thereof: fountain-makers used "perpetual cement" consisting of sandstone, slag, tile fragments and quicklime all crushed into powder, "pavers mixed one-quarter part of aqua fortis cement into tile fragment powder, thus bringing it to set faster on the side, obtaining higher quality." Laboratory workers use "lute", a paste consisting of equal parts of pottery clay, sand and horse manure which are kneaded with water until an even mass is formed to which an egg-white is sometimes added for more solidity. This lute was used to produce "bricks in a kiln or to cement them together, to form pressure pipe joints" of retorts, to "repair cracks or crevasses in vessels" not to mention various types of mastic (Guillerme 1986: 29-30).

In the hands of skilled craftsmen, the array of materials and treatment methods chosen corresponded directly to the purpose for which they were applied. Furthermore, treatment of the lime was not uniform for all applications. In particular, the amount of calcium carbonate within the carbonate raw material influenced not only the calcining process, but also dictated the preferable slaking process. The amount of combined water contained in the hydrate varied directly in relation to the calcium content. Calcium oxide results from the transformation of CaCO_3 (calcium carbonate) into CaO (calcium oxide) during the calcining process. Calcium

³ "The findings after completing the analysis of this thesis are consistent with conclusions drawn by Buck and Welsh. The binder is lime-based and there are unsieved lime blebs present. Pulverized red Brick is also visible in the samples studied in this thesis" (Fetzer 1997:65).

oxide represents the only compound present in lime, which combines with water, therefore, the greater amount of calcium present in the lime, the greater will be the amount of water required to combine with it. Searle conveys the importance of water quantity upon the resulting properties of lime.



LIME CYCLE

Showing the Sequence of the Changes Produced by Burning, Slaking and Hardening, and that these Changes Form a Complete Cycle; the Lime Returning to its Original Carbonate Form.

Copyrighted, E. W. Lazell, 1911

Figure 4 During calcining slaking and curing a carbonate material undergoes complete cyclical transition, which is demonstrated above (Lazell 1915:17).

The use of a suitable proportion of water is very important as the fineness, specific gravity, crystalline structure, and plasticity of the hydrated lime are all affected by the quantity of water used and the rate at which it is incorporated. The most plastic hydrate is produced in the presence of an ample proportion of water, under conditions where the hydration occurs rapidly (Searle 1935:488).

Dry slaking, whereby the quicklime was mixed with just enough water to form a powder, had been practiced prior to standardization. However, this practice could result in some unslaked particles, which could reveal themselves later in finished work in the form of blisters. Cowper describes pitting as it occurs in plaster.

Occasionally it is observed that in a plaster surface, apparently free from any defects, and which has been in position for times ranging from months to years, small conical pits will suddenly appear, and fragments may even be seen to be projected from these popholes with considerable violence right across a room. Extended investigations with test-panels made up with plasters to which various impurities had been added have been shown that impurities in the lime, through slow slaking long after the main portion of the lime has set and hardened. This resulting bursting stress on the envelope of hardened plaster surrounding the particle finally releases itself almost explosively, blowing out a small crater in the surface. The offending particle can sometimes be noted at the bottom of the crater. Particles of overburnt lime, iron pyrites, and the products resulting from burning at a high temperature of limes containing clay, iron oxide and silica, are found to produce this effect, if above the size corresponding to a No. 50 sieve. The harmful impurities may be introduced in the sand used... With mechanically slaked hydrated lime, particularly if stored dry some time, and made into putty the day before use, the danger of the presence of large, unslaked particles is very small (Cowper 1927:29-31).

Therefore, wet slaking served as the more sound technique, since it provided thoroughly slaked lime. Following traditional wet slaking, lime putty would remain covered and age for a lengthy period. This curing may last from a month to years. Lazell also describes that some particles are slow slaking and require aging to insure complete slaking.

Slaking is a chemical process and time is required to complete the action; hence, it is necessary to allow the paste to age for some time to be assured of complete slaking. All lime contains some over-burned particles, or particles of lime which have united chemically with the silica or clay in the limestone, and these particles are extremely slow slaking, often requiring days and weeks to become thoroughly satisfied with water. Our forefathers recognized this fact and always allowed the lime paste to age for weeks, and often months, before using.

The necessity of aging lime paste before using was recognized by the Romans. Vitruvius gives the following directions for the preparation of lime paste to be used in plastering. "This will be alright if the best lime, taken in lumps, is slaked a good while before it is to be used, so that, if any lump has not been burned long enough in the kiln, it will be forced to throw off its heat during the long course of slaking in the water, and will thus be thoroughly burned to the same consistency. When it is taken not thoroughly slaked but fresh, it has little crude bits concealed in it, and so, when applied, it blisters. When such bits complete their slaking after they are on the building, they break up and spoil the smooth polish of the stucco" (Lazell 1915:38).

This aging not only insured complete slaking of all particles, but also enhanced the resulting plasticity of the lime. In fact, even following the adoption of mechanical hydration, some authorities continued to praise the merits of hand slaked putty. These authorities indicated that some of the best commercial lime on the market had been slaked by hand. Enhanced plasticity within a lime plaster greatly facilitates its spreading and adhesion. Cowper describes how aged lime putties possess this property of water retention within their matrix.

A plaster which is rather "short" but which is very tenacious of its essential water-content will spread farther on a porous thirsty surface than a material initially softer and more "plastic" (according to the more general definition), but which rapidly loses its water and becomes thereby dry and friable. Well-matured slaked lime has this property of water-retention developed to a high degree, and can accordingly be used where other plastering materials fail (Cowper 1927:32).

Plasticity of lime and lime mortar was further enhanced through their mixing and blending. Maintaining plasticity with a limited amount of water was desirable, since shrinkage and

cracking of lime or a lime mortar results from the evaporation of excessive water. Minimal water content resulted from thoroughly beating or ramming the lime and sand, while blending a mortar or plaster. Cowper outlines how rich lime mortars in storage undergo a slight hardening which is only temporary in character and capable of becoming highly plastic again following reworking.

A property peculiar to slaked lime putty, and particularly noticeable in putty which has been left a long time in a covered pit or trough to mature, is its power of forming a homogeneous mass of slight but definite rigidity when a certain amount of the contained water is allowed to evaporate or drain away. Very slight stirring or working-“knocking up”- often without the addition of water, suffices to break up this structure so that the mass as a whole resumes its high plasticity... According to the work of Kohlschutter and others, fresh lime putty can be looked upon as made up of a large number of minute particles, each separated from its fellows by its own little surface envelope of milk of lime in the form of a gelatinous emulsion(Bur. Stand. Circ. 151,p.28). These minute particles of colloidal size, result directly from the interaction of the water and the quicklime at the surface of the latter, whether on the outer surface or in the pores of the burnt stone. These particles may give rise, then, by coagulation to secondary aggregations, so that the putty may consist either of separate primary particles, or of aggregations of varying size formed by the primary particles, the whole suspended in a solution of calcium hydrate. The plasticity or working qualities of the putty (and hence of the plaster made with it) will evidently depend on the relative proportions of the primary and secondary states of division which depend in turn on the mode, temperature, and rate of slaking. For minute colloidal particles will readily flow when the putty is worked, whilst large irregularly shaped particles or clumps would give rise to an increased resistance to flow, and produce a “short” material. The effect of subsequent maturing (“ripening,” “curing,” “soaking,” “aging,” &c.) of the putty over long periods can be attributed to a further process of colloidal dispersion of the larger, aggregated particles, producing thus a finer, more mobile, and uniform material of high plasticity (Cowper 1927:36-37).

Benefits resulting from high plasticity include greater sand carrying capacity as well as greater workability during either plaster or mortar application. An increased pace of construction had a significant impact on the ability to store and age hand slaked putty. It also served as a rationale

for those in favor of standardization of hydrated lime. As the aging of lime putty diminished, so too did the traditional treatment of beating the mortar mixture. Beating lime mortar and plaster was so critical to the durability of the work that some considered this to be of equal or greater importance than the material composition of the work. Onset of mechanically hydrated lime coincided with the disappearance of beating mortar and plaster.

2.5 Onset of Standardized Lime Treatment

Throughout the nineteenth and twentieth century scientists and engineers studied the refinement of lime seeking to standardize its production. The lack of a comprehensive theory and understanding of lime treatment motivated scientists and engineers who sought to produce a uniform lime able to be treated uniformly as well. In the latter nineteenth and early twentieth century mechanical processes were developed for slaking quicklime. Lazell outlines the process and the refined products form of availability.

Within recent years a method has been introduced of treating lime with water in a suitable apparatus in which the lime combines with sufficient water to satisfy the chemical requirements of the calcium oxide forming a dry, finely divided flour, the so called Hydrated Lime. *Hydrated lime can be defined as the dry flocculent powder resulting from the treatment of quick lime with sufficient water to satisfy the calcium oxide.* This material comes into the market in bags or other convenient packages and is ready for use requiring only gauging with water and mixing with sand in much the same manner as cement (Lazell 1915:41).

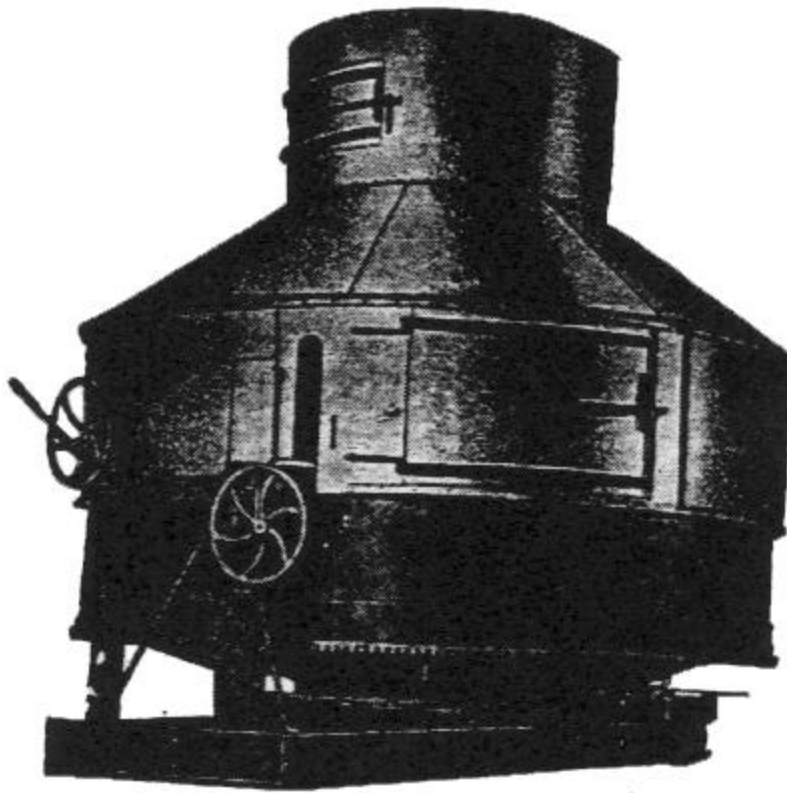
This dry hydrate facilitated commercial usage through a convenient mode of handling and transporting. Here, also, is evidence of resultant confusion and disappearance of work methods involving lime mortar. Lazell points out that the lime can be mixed with sand in a similar fashion as cement. As mentioned earlier, lime mortar benefits from beating and aging, which enhances its plasticity and thorough blending of ingredients. North outlines the problem of lower plasticity resulting from a mechanically hydrated lime.

The result of mechanical hydration is to produce a dry powder, but there does not appear to be the same facility for control as in the older method; there is often a tendency for the material to become overheated, and, in consequence, the product loses to some extent its power of forming a plastic mixture with water, in which case a lime-putty or plaster made from it neither spreads nor adheres as well as hand-slaked lime, if used for walls and ceilings. This appears to be due to the fact that the plasticity of lime-putty arises from the presence of colloidal lime which is formed in larger quantity when the plaster is made by slaking quicklime than when water is added to the dry powdery mechanically-slaked material. Since hydrated lime is convenient for nearly all the purposes for which ordinary lime is used and more convenient for many of them, and has moreover, the added advantage of being more easily stored and transported, careful attention is being paid to its better manufacture (North 1930:397).

Mechanical slaking has the advantage of insuring a complete slaking, requiring that the powder be mixed with water and cure only a day prior to use. However, the cost of this assurance was produced in the form of a lime with less plasticity than that of a hand slaked lime allowed to age. Lazell further describes the mechanical slaking process and its origin in the United States.

It is important that all the calcium oxide be in combination with water, otherwise the hydrate will be unsound and unsuitable for many uses. This point will be insisted upon in any specifications that may be drawn for hydrated lime to be used in the building trade. It is vital for each manufacturer to recognize the fact that the formation of hydrated lime involves a chemical change, requiring the presence of definite amounts of lime and water. Since the process is chemical, it requires the same careful supervision as any other chemical process, such as the manufacture of Portland cement.

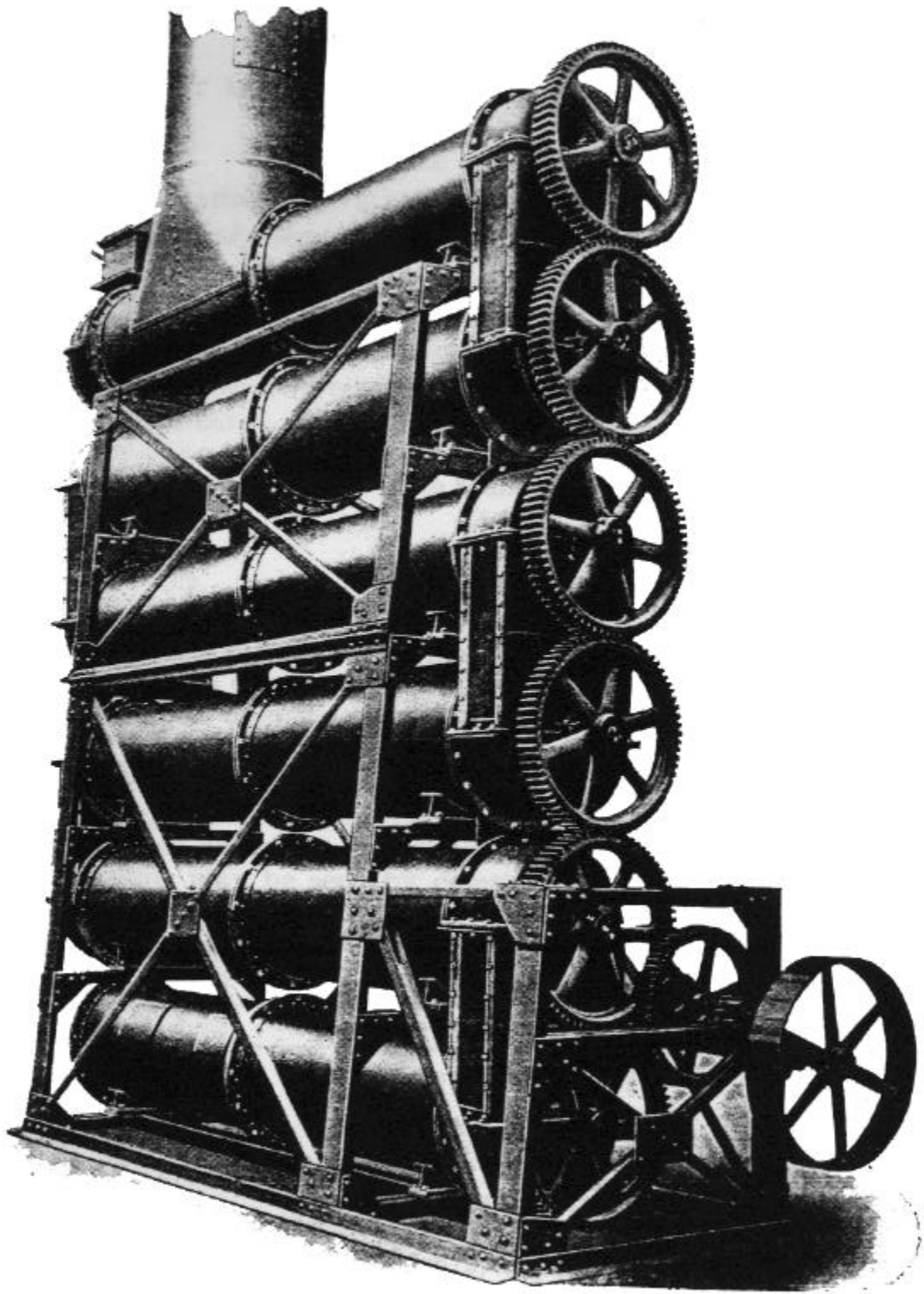
The first commercial process used for preparing hydrated lime in this country was the so-called "Pierce" Process. This consisted in slaking the lime to a wet paste, then drying the paste so as to expel all the excess moisture over and above that needed for the chemical requirements, thereby reducing the material to a form that could be ground. If the process was carefully carried out, a good grade of hydrated lime was produced. This method has been abandoned owing to the excessive cost of manufacture.



CLYDE HYDRATOR

Figure 5 page 38 A Clyde Hydrator, employed in the first decade of the 20th century, accepted a weighed quantity of ground quicklime from a hopper into a large horizontal pan. The pan rotates around a vertical axis and plows are arranged to turn over and mix the lime on the pan. A predetermined quantity of water is added, while the mixture blends on the revolving pan. After the lime is chemically quenched by water and excess steam driven off, hydrated lime is dumped through a center opening in the pan. The product would then be stored in bins and allowed to age. Finally, the hydrate was either screened or graded through air separation (Lazell 1915:43).

Figure 6 page 39 A Kritzer Hydrator, which came along after the Clyde Hydrator fed water and ground or cracked quicklime into the upper enclosed cylinders separately. A screw-feeding device regulated the amount of lime introduced, while a needle valve controlled the quantity and proportioning of water flow. Paddles within the cylinders, which extended from a horizontally mounted shaft, served to propel the lime and water through a series of from four to six cylinders. Upon reaching the lowest cylinder, the lime is hydrated. Openings in the lower cylinder and a stack on the top cylinder facilitate a draft, which draws upward as the lime flows downward (Lazell 1915: 44).



KRITZER HYDRATOR

The second method employed was the so-called “Dodge” Process. This process consisted first in grinding the lime so as to pass a 26 mesh sieve, second in treating a weighed amount of the ground lime with sufficient water thoroughly to satisfy the calcium oxide present and produce a dry hydrate, third the dry hydrate was sifted through fine silk cloth...From these two pioneer processes have been evolved, during the last fifteen years, the methods described below which are in use at the present time (Lazell 1915:42).

These and subsequent processes followed the same principle of slaking, which involves addition of an adequate amount of water to insure quenching of the quicklime. Some of the later processes such as the Clyde Hydrator (shown above) utilized paddles, While other subsequent hydrators like the Kritzer Hydrator (shown above) incorporated multiple cylinders with separate valves for the introduction of water. An amount of water added exceeded the necessary theoretical amount, due to water released as steam during hydration. Screens were employed insuring larger unslaked particles were not part of the refined product. Lazell describes the ability for mechanically hydrated lime to meet specific compositional criteria.

The user in dealing with hydrated lime is handling a product which can be definitely proportioned and will produce known results. The quality of hydrate desired can be specified in advance and the material can be inspected and tested in order to determine if it fulfills the requirements. The quality of quicklime can also be specified and its character determined by tests, but such tests do not indicate what will be the quality of mortar found on the job, since lime is chemically changed during slaking. Hydrated lime undergoes no further change upon the addition of water, therefore the same material is tested which is to be used. The testing of hydrated lime is no more difficult than the testing of cement. With lump lime the user is dependent always upon the thoroughness of slaking and it is well known that unless the paste is run off and stored for some considerable time, there is no assurance of complete and thorough slaking (Lazell1915: 49-50).

Lazell correctly asserts that a hydrate undergoes no further chemical change following addition of water, which serves the purpose of maintaining uniformity. However, this uniformity is achieved not by maximizing the properties of the lime, but by assuring it's uniformity.

For all building purposes hydrated lime is to be preferred to lump lime. By its use the time and labor involved in slaking may be saved and the experience of the laborer is eliminated as a factor in the problem (Lazell 1915:50).

Lazell, here, generalizes the benefits of mechanically slaked lime. While the time and labor involved with slaking may be saved for the craftsmen, he is now working with a lime that he has less control to influence during the course of preparation and application.

2.6 Cement Technological Development

Cement technology emerged late in the eighteenth century and continued to mature throughout the nineteenth and twentieth centuries with new materials and methods of preparation. This technology developed and spread rather slowly, in order to meet new construction needs. Some of these needs included; military fortifications, bridges, dams, piers, tunnels and other vital infrastructure. Cement did not see widespread usage in the United States until very late in the 19th century and early in the 20th century.

Between 1770-1830, concrete and cement technology gradually emerged from lime technology. This innovation which brought about the enhanced solidity of constructions required new tools and working methods on the site (Guillerme 1986 vol.3:26).

The development, understanding, and translation of cement technology for masonry projects involved many factors surrounding its future application and success. Prior to discussing the development of cement, I will clarify the distinction between hydraulic mortars and cement. Hydraulic mortar was comprised of limestone containing clay, which was capable of being slaked following calcination.

When the proportion of clay in calcareous minerals exceeds 27 to 30 per cent., it is seldom that they can be converted into lime by calcination; but they then furnish a kind of natural cement, which may be employed in the same manner as plaster of Paris, by

pulverizing it, and kneading it with a certain quantity of water... Very recently, natural cements have been found in Russia, and in France; we may compose them at once, by properly calcining mixtures made in the average proportions of 66 parts of ochreous clay to 100 parts of chalk. It is fair however to admit, that no artificial product yet obtained has been able to match English cement in point of hardness (Vicat 1837:111-112).

Cement contained a larger proportion of clay within the limestone and was, therefore, unable to be slaked. This material required grinding following calcination. Although the distinction between cement and hydraulic lime appears subtle, their difference necessitates separate treatment methods.⁴

⁴ “In each factory the conditions of homogeneity of the slurry and of the calcinations remain sensibly the same. Thence it results that the slurry giving the best product should have a perfectly definite composition for each factory, but will vary from one factory to another with the conditions of manufacture. This is the explanation for the well known fact which at first seems paradoxical, that in one factory the variations of the proportions of clay in the slurry must not reach 1 percent., whereas, as between one factory and another the difference may be more considerable.

These narrow limits do not allow the use of natural mixtures of limestone and shale designated under the names of marls or marly limestones. In order to obtain a composition of slurry of suitable homogeneity, it is necessary to make artificial mixtures, the preparation of which becomes an important item of the cost of manufacture. Moreover, the mixture can be made from pure limestones and clay, with each other or with marly limestones; these mixtures may be effected in the dry or wet way, etc. The desired result is equally well obtained by very varied methods, the choice of which depends upon the conditions, which prevail at each factory, and with the materials which they have at their disposal... During the calcination, the first effect of the heat is to decompose the clays and dehydrate them at a temperature in the neighborhood of 600 degrees. This decomposition simultaneous with the dehydration is evidenced by the action of a potash solution and of sulphuric acid, the first of which dissolves silica and the second, alumina more easily than before the calcinations. Between 800 and 900 degrees the limestone is decomposed, liberating its carbonic acid and being transformed into quick-lime. From this moment, the elements of the clay begin to react upon the lime, and this reaction becomes more complete as the temperature is higher and its action more prolonged. At the points of contact of the grains of lime and the particles of clay, fusible products are formed which are diffused in opposite directions, becoming more basic on the one hand and more acid on the other. If we break up a nodule of clay, we will have in the center the elements of clay, infusible silica and alumina. Then the slightly calcareous fused glasses, afterwards a fused mixture of double silicates analogous to slags, with the mono- and di-calcium silicates, all fusible at the temperature of calcinations of cements, lastly, the more basic salts, the active constituent of cement, infusible tri-calcium silicate, and fusible calcium aluminates, and in the last place of all

quick-lime. The proportion of these diverse elements varies in a continuous manner with the degree of advancement of the calcination, tending toward a limit dependent only upon the relative proportions of the elements present.

With a large excess of lime, the final products will be quick-lime, tri-calcium silicate and tri-calcium aluminate. By diminishing the quantity of lime, we would have these two salts and no quick-lime. Afterward the calcium aluminate will disappear and will be replaced by a multiple silicate of a composition analogous to that of the basic slags from blast furnaces.

This will be followed in turn by the disappearance of tri-calcium silicate, which will be replaced by di-calcium silicate with spontaneous pulverization; then by the mono-silicate.

Finally, glasses analogous to the acid slags of blast furnaces will be produced. In order to obtain calcinations, the temperature must be the higher, as the multiple silicate which serves as a flux and allows the diffusion of silica and of the lime in opposite directions is itself less fusible. A silicate containing only either alumina or sesquioxide of iron will be less fusible than if these two bases are both present at the same time, and it is possible to conclude from analysis that the maximum fusibility will be obtained with equal equivalents of these two bodies, say in round numbers, half as much again sesquioxide of iron as alumina.

It is seen from this how slurries of variable composition will be able to give similar products by different calcinations; a moderate calcinations applied to a slurry low in lime will be able to give, by reason of an incomplete calcinations, free lime and calcium aluminate just as a complete calcination applied to a mixture richer in lime will do.

For example, in order to increase the rapidity of the set, an indispensable quality in certain works, the calcinations will be produced at a lower temperature to make the reaction less complete and augment the proportion of the aluminates, but at the same time, the proportion of the lime will be diminished by several per cent. To avoid the possibility of any of it remaining uncombined...

The hydraulic limes are obtained by the calcinations of argillaceous, or better, silicious limestones containing less silica and alumina than cement rock. The proportion of free lime remaining after calcinations ought to be sufficient to bring about the complete disintegration of the mass by slaking without employing any mechanical process. For these reasons, the cost of the production of limes is much less than that of cements; but, on the contrary, they have the disadvantage of hardening less rapidly and less completely, part of the active constituents having been destroyed during the slaking. A good limestone for hydraulic lime ought to be constituted almost exclusively of silica and calcium carbonate, all the other materials giving compounds which remain inert during the set, either because they are not attacked by water or, on the contrary, being too easily altered like the alumina, however, facilitate the calcination, as they do for cements, making it more economical, by allowing the use of a lower temperature and a less prolonged calcination. From this standpoint only, the presence of small quantities of these materials may be advantageous. In limes of good quality observation shows that the proportion of these does not exceed 3 per cent.

Smeaton, during construction of the Edystone lighthouse, discovered limestone that contained clay could yield hydraulic mortar able to withstand the ravages of ocean current. The mortar employed by Smeaton blended Roman technology and also introduced the principle on which modern cement technology emerged. He incorporated hydraulic lime in combination with

The infusibility of silica and lime is an obstacle to their mutual reaction, which is always slow and easily remains incomplete. Even in the presence of an excess of lime it is difficult to avoid the formation of insufficiently basic, and inert, silicates. We can hope to obtain a suitable hydraulic lime by the calcinations of a silicious limestone only when the silica present is in a very fine state of division. In the limestone of Teil the silica appears in small spherical grains of less than 1/1000 of a millimeter in diameter. Limestones containing silica in the state of quartz sand, the grains of which always have an appreciable diameter, cannot be advantageously used, but it is only the size of the grains, and not their crystalline state, as has been maintained, which makes it unsuitable to yield hydraulic properties. The most suitable relative proportions of silica and calcium carbonate in a limestone, taking account of the formula of only the active silicate $\text{SiO}_2 \cdot 3\text{CaO}$, will be:

SiO_2	16.6
$\text{CaO} \cdot \text{CO}_2$	<u>83.4</u>
	100.0

The intensity of the calcination has a great influence upon the quality of the lime, a strong calcination rendering the reaction of the silica with the lime more complete, increases the proportion of tri-calcium silicate, and in consequence improves the hydraulicity of the product, but, on the contrary, it diminishes the proportion of free lime, which makes the slaking more difficult. With the slightly silicious limestones containing more than four molecules of lime for one of silica, the calcination can never be too intense; sufficient free lime will always remain to insure the slaking.

It will be quite the contrary with limestones not containing more than three molecules of lime for one of silica; a very intense calcination gives what is called *black grapiers* of cement, or the limit limes of Vicat. This product is not pulverized by slaking, and can begin to set only when it is finely ground, without previous slaking, but then it relaxes at the end of a certain time, swells, and ends by disintegrating under the influence of the small quantity of free lime which it contains. If the grinding is caused to be followed by a sufficiently prolonged air slaking, in order to make it complete, a hydraulic product of very good quality will be obtained.

As the burning is less complete, a lime which is more easy to slake will result and no grinding will be necessary, but, at the same time, the degree of hydraulicity will continue to decrease. The most suitable degree of calcination will depend upon the means of slaking which is to be used. The more a factory aims at a careful slaking, the more it will be able to push the calcination toward the production of black grapiers, and the more it will augment the quality of the product. This is the point which sharply differentiates factories calcining similar limestones” (Le Chatelier 1905:89-97).

pozzolana and beat the mixture together while blending with sand. Smeaton consulted with numerous masons and lime burners and craftsmen during formulation of the Edystone mortar. His observation and discovery that clay bestowed a hydraulic quality to lime after firing was certainly influenced by these craftsmen during his inquisitive travels. Subsequently, in England, James Parker discovered a limestone containing clay and produced the first documented natural cement. His process involved the calcination of the stone followed by grinding the resultant material.

James Parker took out a patent c. 1791, and a second one in 1796, which established the basic method of preparing natural cement. His product, called Parker's Roman Cement, was made by calcining stones found in the isle of Sheppy, called nodules or septaria, and pulverizing the clinkers into powder. He recommended mixing two measures of water with five measures of cement powder; this would set in about twenty minutes, in the air or under water. Parker's Roman Cement enjoyed a high reputation for several decades, but its quick-setting property was considered a disadvantage. When his patent expired it was widely manufactured by others (McKee 1971:24).

Although Parker did not artificially combine clay and lime, he pioneered the manufacturing of natural cement. His cement, although dubbed Roman Cement, was not similar to Roman hydraulic mortar in color or specific composition. What they did have in common was the property of hardening under water. However, by naming his product "Roman Cement", we see how highly esteemed were the accomplishments of the Romans in regard to hydraulic construction. The Parker process called for a mixture of one part cement with one or one and a half parts of sand.

You must begin by dry mixing the mortar, seeing to it that all ingredients are properly mixed and especially avoid pouring the water into the trough before the mixture (as was the case with the old technique). Then the mixture is thrown into the trough and made into a heap. Next a hole is made in the middle and the water is poured into the hole gradually in the desired proportion which must be two-fifths of the volume all the while mixing and being

careful to prepare no more than the needed quantity” (Guillermé 1986:vol 3 55).

Development and production of English and French cements created new work methods. Edgar Dobbs, in 1810, followed the work of Parker and produced artificial cement by blending pure limestone with clay and calcining this mixture in a brick oven. Following calcination of the artificial mixture, the cement clinker was ground, in order to produce powdered cement.

As mentioned earlier, Smeaton’s discovery - that clay within limestone acted as the primary hydraulic component - was slow to be accepted by engineers and chemists. While theoreticians continued investigations, pragmatic workmen such as Edgar Dobbs and Joseph Aspdin among numerous others continued their empirical development of cement. Cement technology developed on site through trial and error retaining many elements of craft technique and mystery. Joseph Aspdin, a Leeds builder and bricklayer, obtained his first patent for Portland cement in 1824. Both he and his son’s future work retained many craft elements. One primary element involved the secrecy and mystery regarding their work. Aspdin took a hard limestone and calcined it. He then mixed the lime with clay and ground the mixture to fine slurry with the addition of water. The material dried to a paste and was molded similar to bricks. Next, the material was fired in a kiln. Following calcination, the material was ground, beat or rolled to a fine powder. His early efforts involved much experimentation with proportions and temperature of calcination to produce good cement.

Natural cements had long been entrenched in England and Europe, so that Aspdin at the beginning was obliged to cope not only with his own higher costs of production, but with fixed prejudice in favor of the former. That forced him to meet lower prices. This, however, was simply one of the disciplinary imperatives of private enterprise. It illustrated how a new product under the competitive system is required by the dual factors of merit and management to force its way to attention (Hadley 1945:12-13).

It is also not known at what stage of development he began calcining his product at higher temperatures. At some point between 1824 and the construction of the Thames tunnel in 1838 he and his son William realized the benefits of firing the mixture at a much higher temperature than

was customary for hydraulic limes and natural cements.⁵ Aspdin's patent made no reference to the temperature or degree needed to create Portland cement. Workmen for Aspdin commented on

⁵ "His son, William Aspdin, continued the manufacture both on the Thames and at Gateshead-on-Tyne. In the meantime, Isaac Charles Johnson, who died in 1911 at the age of 100, had observed that over-burned lumps found in the kilns, although slow-setting when ground, made a better cement than the usual product. He had difficulties at first finding the correct proportions of clay and chalk, but in 1851 he set up works at Rochester, and later took over Aspdin's abandoned works at Gateshead. A higher temperature of firing must have been introduced in Aspdin's works before this, as on the resumption of the construction of the Thames Tunnel in 1838, Brunel employed Portland cement in spite of the fact that its price was double that of Roman cement, and in the face of strong opposition. Aspdin long kept his process secret, and according to Johnson, who claimed to have suggested the firing at a temperature high enough to produce vitrification, he used to carry trays of copper sulphate into the kilns when charging, in order to convey an impression that the process depended on the addition of salts. William Aspdin spent his last years in Germany, where he had set up works in 1856" (Lea & Desch:7-8).

"Johnson also says:

I grant that the name "Portland is due to Mr. Joseph Aspdin when he took out a patent in 1824, but which is no more like cement that is made today than chalk is like cheese.

Mr. Johnson states that about 1845 young Aspdin---began work at Rotherhithe in connection with Messrs. Maude & Son on a small scale, and did sometimes make a strong cement, but owing to want of scientific method, the quality as respects strength and durability was not to be depended upon.

I was at this time (about 1845) manager of the works of Messrs. White, at Swanscombe, making only the Roman Cement, Keene's Plaster, and Frost's Cement.

My employers, attracted by the flourish of trumpets that was then being made about the new cement, desired to be makers of it, and some steps were taken to join Aspdin in the enterprise, but no agreement could be come to, especially as I advised my employers to leave the matter to me, fully believing that I could work it out.

As I said before, there were no sources of information to assist me, for although Aspdin had works, there was no possibility of finding out what he was doing, because the place was closely built in, with walls some 20 feet high, and with no way into the works except through the office.

I am free to confess that if I could have got a clue in that direction I should have taken advantage of such an opportunity, but as I have since learned, and from one of his later partners, that the process was so mystified that anyone might get on the wrong scent- for even the workmen knew nothing, considering that the virtue consisted in something Aspdin did with his own hands.

how he would enter the kiln and disperse powders prior to igniting the kiln. These powders spread by Aspdin served as a smoke screen to conceal and mystify their newfound technique. By 1850, when the advantages of Portland cement became widely appreciated in England, the firing temperature had certainly increased, but not so high as is carried out today. Due to the mysterious circumstances surrounding Aspdin's works, it is still uncertain how they discovered the need for higher temperature of calcinations, in order to produce a superior Portland cement.

To the laymen, the distinction between natural cement and Aspdin's "Portland" cement is not always clear. Therefore he seldom realizes just what Aspdin did do for cement. Aspdin introduced what Smeaton and Parker failed to work out- the artificial mixing of limestone and clay, together with high temperature, to form a new chemical compound. Roman and other natural cements depended, as has been said, chiefly on nature for haphazard proportioning and on burning, as in the case of lime, at a relatively low temperature.

Portland cement, on the other hand, has evolved from the start Aspdin gave it into a strictly measured and manufactured product, burned at intenser heat. Its composition is known at every stage. Calcereous and argillaceous materials are pulverized, proportioned, mixed, burned at a high temperature to form the new chemical compound which is called clinker, and which is reground to produce cement (Hadley 1945 12).

Natural cement and Portland cement were prepared similarly following calcination and grinding. The higher temperature of calcination served to more fully unite the resulting material constituting Portland cement. Lesley describes the chemical distinction between Portland and natural cement.

Consequently, for purposes of comparison between natural and Portland cement, it may be broadly stated that from 20 to 25 per cent of the natural cement is inert or not in combination. By taking

Thus he had a kind of tray with several compartments, and in these he had powdered sulphate of copper, powdered limestone, and some other matters. When a layer of washed and dried slurry and the coke had been put into the kiln, he would go in and scatter some handfuls of these powders from time to time as the loading proceeded, so the whole thing was surrounded by mystery" (Lesley 1924:35-36).

the portions of silica and alumina that should combine properly with the lime, it will be found that there are certain proportions in excess and therefore uncombined. These natural cement rocks are burned at a comparatively low heat with coal, and the resulting material when drawn from the kiln is not very hard and can be reduced to fine powder with comparative ease (Lesley 1924:2).

2.7 Cement and Canals in the United States

In the early nineteenth century transportation in the United States was limited almost exclusively to horse and wagon and rivers for inland travel. While the steamship had been invented, virtually no ships were available for commerce until the 1830's. Nor did development of the railroad begin until the 1830's. Therefore, to meet inland transportation needs, engineers and financiers looked toward canal development to meet increasing transportation needs. Canals would further expand the network of navigable waterways. In order to assure canal construction, masonry work became a vital component of development. Canal construction involved locks, sluices, bridges, and aqueducts, which depended upon watertight masonry.

In the United States, natural cement rock was discovered by Canvass White (1790-1834) and other engineers directing construction of the Erie Canal, somewhere between Sullivan and Fayetteville, New York. In 1820 White obtained a patent, and around 1825 he and his brother, Hugh, established a manufactory at Chittenango, New York, calling the product White's Water-Proof Cement ...Cement mortar was preferred by the Federal Government for its fortifications and important public works, including the extension of the Capitol in the 1850's (McKee 1971:24).

Other discoveries of natural cement rock occurred subsequently in other regions of the United States.

1824: Williamsville, Erie County, N.Y
1826: Kensington, Connecticut
1828: Rosendale, Ulster County, N.Y.
1829: Louisville, Kentucky

1831: Williamsport vicinity, Pa.
1836: Cumberland, Md.
1837: Round Top, near Hancock, Md.
1838: Utica, Illinois
1839: Akron, N.Y.
1848: Balcony Falls, Virginia
1850: Siegfried's Bridge, Lehigh Valley, Pa.
1850: Cement, Georgia
(Mckee 1971:24).

The vast deposits of this natural cement rock in the United States far surpassed European sources. Not only did these natural cements help construct the canals, but also their operations were dependent upon the waters from the canal itself to turn mills and transport their product.

The other governing factor in early mill construction was that the grinding was performed by old-fashioned buhr stones, or sand stones of the same general type. All these stones required constant dressing, and when one entered a cement mill in those days, he was greeted with a merry chorus of clinking mill picks playing on the hard stones, which required constant redressing at heavy expense (Lesley 1924:23).

These newly found masonry materials required new refinement techniques. They also required new preparation and proportioning methods for those masons tasked with using the material. It had a much different feel than the traditional lime mortar and its properties were much different as well.

The wretched condition of masonry upon the Erie canal is owing in a great measure to the failure of the mortars. Our natural cements were employed for the mortars, and the proportion of sand with which they were mixed, was unquestionably greater than they would bear. The consequence of which has necessitated there building of much of the masonry in a comparatively short period; together with the outlay of large sums in repairs. The errors, which were then committed, certainly should not be perpetuated (Dexter 1840:17).

The cement shrank in volume with the addition of water, whereas lime increased in volume. During original construction of the Erie Canal in the 1820's, difficulties arose regarding the proportioning of sand to cement and this resulted in work that had to be repaired after its initial

placement. This difficulty illustrates the confusion that arose during initial work involving cement. New work methods and proportions were not immediately understood and applied. Nor were they sufficiently developed at this point in the United States.

In a large number of trials, in mixing sand with cement, I have found the mortar hardest where the proportion of sand did not exceed the cement. When the proportion of sand exceeded the cement, the balls, if immediately immersed, have usually fallen to pieces; but when the balls were made of pure cement they have uniformly hardened; and when the balls were made of mortar containing a less, or equal proportion of sand and cement, were put in water, in most instances they preserved their shape, and gradually hardened. Cement mixed with one and a half to three parts sand, when permitted to harden in the air usually continued to harden after being put in water, But I have not succeeded in producing a mortar which acquired much hardness when the proportion of sand exceeded two measures to one of cement (Dexter 1840:23).

While canals continued to play a role in transportation, development of the railroad replaced the canals as the primary transportation means within the United States. This shift, however, did not diminish the role of cement in the United States. Canals served to show the potential for cement in construction projects. At the close of the 19th century applications for cement included buildings, docks, sewers, sidewalks and other infrastructure vital for continued development.

The manufacture of Portland cement in Europe grew rapidly. European producers began to find numerous new uses for their material in sidewalks, buildings, artistic construction, docks, etc.; and engineers, familiar with world problems, soon began to realize the enormous possibilities that the development of this new material for building construction possessed. Consequently, along in the early eighties, Europe began exporting Portland cement to North and South America and to other parts of the world...Through engineering publications and the practical knowledge of engineers acquired in Europe and who came to this country to engage in various engineering enterprises, the reputation and fame of Portland cement spread among American engineers and builders (Lesley 1924:38-39).

European and Asian cements were imported into the United States in the last half of the nineteenth century. There existed a strong bias in favor of foreign cements, which challenged domestic producers of cement to gain favor for their products. American cements were challenged by and received greater scrutiny from engineers, builders and the American public.

Those days were filled with sad tales of “condemned” cement, a word which all of the manufacturers were thoroughly familiar. While in many cases any old foreign cement would go through on its brand, American cement was always received, as described in the words of Alphonse Ftely, Chief Engineer of the Croton Aqueduct Board, “with strictest scrutiny.” For this reason the slightest defect in time of setting, fineness, color or any other slight deviation, would be sufficient excuse to turn the cement down, a situation requiring the immediate attention of the higher officials of the company, who, in those days, were what were known to engineers as “cement doctors” (Lesley 1924:133).

American cements therefore had to prove themselves against stiff opposition and a biased consumer. It is of interest to note the context of importation of foreign cement and the means in which it was conducted.

With these figures in mind, it is a matter of considerable interest in connection with the history of the American Portland cement industry to describe the methods by which this large importation was handled. In those early years the usual cargo ship was a wooden sailing vessel. Barques or full rigged ships were generally employed. These had no auxiliary power, and when sailing without regular cargo required ballast of sand, stone or other material to stabilize the ship. These vessels differed entirely from the liners which carried expensive cargo from Europe, and which, being constructed of steel or iron, had compartments that were filled with water ballast when necessary and discharged when taking on cargo. The vessels in the cement-carrying trade were of the type known as tramp cargo ships. In most cases they came to the United States to get export cargoes of grain or cotton. Such cargoes paid high revenue. Instead of non-paying ballast (as there was little inbound paying cargo to this country) they took on cement or other heavy material. The result was that freight from European ports to this country on cement was very low. In some cases the American consignee was not able to get his cement brought across the

Atlantic free of charge but was actually paid by the ship as high as ten cents a barrel for the unloading of it. This occurred at times when the outgoing grain paid such good rates that the tramp ship, in order to take advantage of the market, was obliged to get the cargo she had carried over discharged rapidly, even if necessary to pay for the unloading.

The points of heaviest importations of foreign cements were New York, Philadelphia, Charleston, Savannah, New Orleans, Galveston, and some Pacific Coast ports. In the last case, not only did Belgian, German and English cements come to the Pacific Coast as ballast for grain ships, but also cements from Japan and China (Lesley 1924:40-41).

English bricks have been found in early settlements on the Virginia coast and it is believed that they too were brought over in ships as ballast. Their volume appears to have been limited and they were seldom, if ever, imported for domestic construction purposes. The traditional knowledge and skill for brick making accompanied early colonists and craftsmen. Foreign cements, however, came into this country in large volume toward the close of the nineteenth century.

As the United States began developing Portland cement in the last half of the nineteenth century, they developed technologies, which they adapted to their physical and material resources.⁶

⁶ "The rotary kiln proved exceptionally well adapted to American cement practice. Coal slack, which in the summer was made in the bituminous fields to the extent of many millions of tons, was available as pulverized fuel and could be bought as low as thirty and forty cents a ton at the mine. Coal was essentially cheap and labor had already advanced far beyond the cost of similar labor in Europe; consequently, as a historical fact, it may be stated that the rotary kiln, as an economical method of production, had its special and distinct field in this country, which had cheap coal and dear labor, as against the opposite condition of high coal and cheap labor in Germany, England, France, and Belgium.... In 1909 Thomas A. Edison was granted a patent for the use of kilns 150 feet and longer, every one predicting that it would be impossible to turn kilns of this length without warping. The proof of the pudding, however, was in the eating, and it was not long after Edison's invention that kilns of 125 feet became almost standard as substitutes for the old 60-foot kiln... Later on the length of the Edison kiln was far exceeded. Some kilns now in use are 260 feet long, with capacities of a thousand or more barrels of cement per day.

While this development of the rotary kiln was progressing in the Lehigh district, the old-time manufacturers there were still in a state of uncertainty. They had used intermittent vertical kilns successfully. They had banked upon following European practice in every detail as best

Engineers, builders, producers and consumers of cement began seeking quality assurance standards by the late 19th century, in order to assure a more uniform reliable product.

As the demand for Portland cement, especially as an ingredient for concrete, increased, and the requirements of engineers called for a more perfect material, it became increasingly desirable that standards of quality should be set up, by which any consignment could be judged after the performance of certain agreed tests. In this way standard specifications have arisen in most countries,

calculated to give them a talking point to engineers when urging the adoption of the newly-created American product for the great engineering works of the period. Consequently a revolving kiln turning out clinker in hours as against days under old methods, struck them as entirely irregular and improper. They could not believe in the final success of such methods, and when at about the same period Europe, especially Germany, began to use continuous vertical kilns of the Schoefer, Dietsch and similar types, the old-time American producer began to see that with which he could offset the progress the rotary kiln had begun to make, something he was used to, and which had behind it the authority of European practice...Other installations were also under consideration, but the successful manufacture of Portland cement with pulverized coal under the rotary kiln process was so marked as practically to terminate competition between the rival types of kilns, thus turning the entire American industry over to the rotary kiln which is now in use in every mill in the country.

In considering this victory of the rotary kiln in America, the fact must not be lost sight of that the old type of kiln used coke as fuel, and coke ruled at much higher prices than coal. In the early days of the rotary kiln, and up to a very recent period, enormous bodies of slack coal to produce lump bituminous coal, existed in many parts of the United States. This was sold at such a low price as to make the calcining operation in Portland cement mills using the rotary process not only economical in labor as compared with European countries, but also far more economical in fuel than ordinary comparative figures between the market sizes of bituminous coal in this country and in Europe would seem to indicate... Thus it was fortunate that contemporaneous with the introduction of the rotary kiln and keeping pace with its commercial establishment, there was the great development in crushing and grinding machinery” (Lesley 1924:119-127).

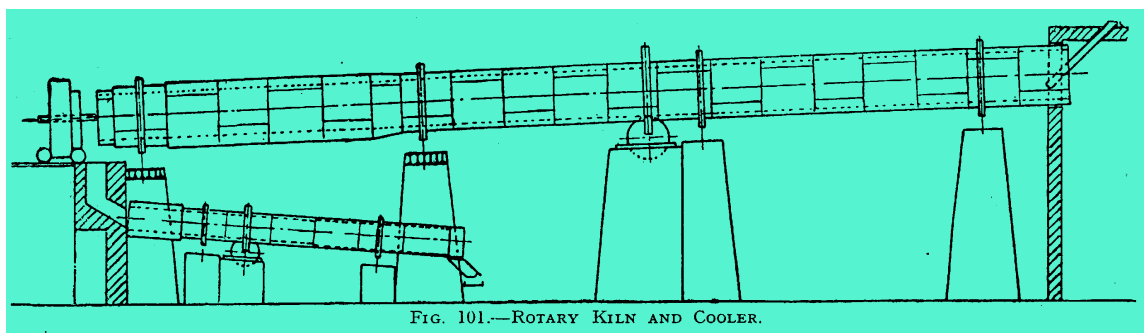


Figure 7 A rotary kiln (Searle 1935:375).

either under official auspices, or as the work of voluntary organizations of engineers and consumers, or of associations of cement manufacturers. Such an organization was founded in Germany so far back as 1877, and shortly afterwards established rules for controlling the quality of the product. The first German Standard Specification was drawn up by this body. The British Standard Specification was drawn up in 1904 by Engineering Standards Committee (now the British Standards Institution) and its eighth revision appeared in 1947 (Lea & Desch 1956:7-9).

Criteria for cement specifications often differed. Although it was agreed that there was need for specifications, agreement upon particular specifications to employ was less than unanimous.

Mr. Lesley in his paper states that in a period of six or eight years he had gathered various specifications for all kinds of work numbering altogether between two and three hundred, no two of which were alike; while Brown in his book mentions no fewer than sixty different specifications (Lesley 1924:143).

In the United States an interesting example arose regarding quality standards. Manufacturers of cement in the Lehigh valley called for specifications as a means of entering the New York cement market. Lesley conveys this situation as follows:

Among those in the strictly scientific or engineering side of cement manufacture in the early days was F.O. Norton, manufacturer of the Norton Brand. Mr. Norton was a member of the American Society of Civil Engineers and prominently associated with the foremost bridge, canal and railroad builders of his time. Perhaps more credit is due to him than any other early group for putting Rosendale cement, especially the Norton brand, in the front ranks of favor by the engineering profession. It is related of Mr. Norton that when Lehigh cements first began to make their way into the New York market and endeavor to have a specification made by the engineering societies for all natural cements, he was against any specification on the ground that his cement was the best. "But," said the Lehigh manufacturers, "if we don't get a specification, how can we get into the market?" "Well," said Mr. Norton, "when I have sold all the cement my mill can make, you may have your chance to sell yours" (Lesley 1924:14-15).

This exchange typified the environment of masonry materials in the late nineteenth century, whereby a product's reputation carried much influence. Foreign cements had a great influence upon the American cement industry. It's dominance reigned until the close of the century, when American cements and manufacturer's had proven themselves both durable and innovative. This shift in favor of American cement occurred as manufacturers gained key alliances among engineers and financiers. Nonetheless, today, major cement companies are still greatly influenced by Foreign owners and research facilities.

2.8 Impact of Cement Technology and Standardization of Lime Technology on Masonry Work Methods

A major concern and cause for division among European engineers in the late 18th and early 19th century - particularly the French engineers - involved selection of materials and processes for masonry projects. One camp believed that an engineer needed to select materials and procedures suited for location and particular project, while others asserted that there need be uniform materials and procedures regardless of location.

Up until the end of the Restoration Period building contractors unanimously believed that the proportions resulting in the greatest mortar hardness were as varied as the number of potential combinations of the various known ingredients and the canals committee of the Conseil General des Ponts et Chaussees also considered that underwater foundation construction processes must vary depending on where such foundations are built and that therefore engineers must be given full latitude in the choice of resources to be used enabling them to achieve their ends. But as early as 1830, some engineers were already calling for a standardisation of the process, a position which opposed that of their peers. Beaudemoulin and especially Balzac's scathing brother-in-law, Surville, spurned the lack of any guiding principle in the recommendations of the Paris authority:

The slightest complication would be sufficient to render science powerless, isolating Engineers and undermining the future of companies due to the uncertain success of methods the choice or creation of which are simply a matter of chance... There must exist

a general operational mode which is independent of the location and which leads to the surest and most inexpensive result.

And so, standardisation is the prerequisite for the power of technology - and therefore of technicians - as is also the case with science. What is “local” and “individual”, such as cottage industries must disappear, making way for what is “general” and “uniform” such as industry and its ally, the State (Guillerme 1986 vol.3: 58-59).

This debate became woven within the fabric of ongoing research and technological development. It also foreshadowed the development of cement and lime as they both became standardized products, which were manufactured and able to be transported to builders. The resulting technological development affected both large-scale infrastructure projects such as canals, bridges, dams, and commercial buildings, as well as smaller scale residential construction. Traditionally, materials had been produced and prepared near the construction site. Captain Smith echoes the technological tension developing and its impact for masons.

This circumstance would in itself be sufficient to justify M. Vicat’s opinion; but I have now referred to it principally to point out, that the use of *ground cements*, valuable as they are in our constructions, are better adapted to the vicinity of a large capital, where it is of little importance that the builder becomes dependent upon others for his supply, than for a remote situation or a new country, in which the *unground* limes cannot fail to be preferred, from the facility with which they may be prepared by the mason himself. The difference, in fact, consists in this, that the *ground cements*, of whatever kind, will ever be furnished by *manufacturers*, whereas the hydraulic limes may at all times be prepared by the common workman, without machinery, and at a cost not much exceeding that of common lime (Vicat 1838:xi).

However, this traditional practice gradually shifted, and masonry materials were shipped or transported to builders from manufacturers. Canals not only served as a proving ground for cement construction in the United States, but also served as an outlet for their reaching the marketplace and gaining greater circulation and usage. Subsequently, railroads further opened markets for cement distribution. In the United States, some hydraulic and pure lime mortars were

still used with traditional methods in the late nineteenth and into the twentieth century. However, these instances became drastically fewer and more isolated through the twentieth century.

During the late eighteenth and early nineteenth centuries the roles and interactions of scientists and engineers was not clearly established. This became further apparent during the development of cement technology. At the beginning of the nineteenth century chemists and engineers proposed variant theories for cement technology and its ability to harden under water.

Smeaton noted during construction of the Edystone Lighthouse that clay within limestone promoted the ability of the treated material to solidify in water. Chemists, however, adopted other theories explaining the hydraulic properties of cement. In the early nineteenth century masonry researchers were reluctant to challenge the findings of renowned colleagues even though their results contradicted their colleagues findings. In the late eighteenth and early nineteenth century cement technology developed primarily in the field at kilns and on work sites by craftsmen and engineers. Descotils, a French mining engineer and professor of chemistry, confirmed Smeaton's observation and proved that clay served as the primary compound within limestone, which bestowed hydraulic properties upon the refined material. Vicat, a fellow French engineer, confirmed the work of Descotils and produced a practical work on pure and hydraulic limes.

The resulting arrival and usage of cement upset existing work methods associated with masonry materials. Work methods involving the slaking of lime were no longer necessary in working with cement. Aging slaked lime, likewise, was no longer necessary in dealing with natural or Portland cement. Mixing lime mortar traditionally involved beating or ramming the mixture of lime and sand. This, too, was not necessary with cement. Cement required that you dry mix the sand and cement thoroughly before introducing enough water, which rendered the mixture workable. Cement would not bear as much sand as a lime mortar and perform as needed. Therefore, the different properties of cement and lime mortar impacted their feel and workability with the trowel. Having worked with both lime mortar and cement, their distinguishing properties became apparent quickly. Lime mortar spreads easier on the masonry unit than does cement. While

working with the material, lime mortar retains its plasticity longer during placement, whereas cement sets much quicker.

In addition to work methods changing with the onset of cement technology, the terminology and language regarding materials became confused and more difficult to decipher.

The far-reaching changes brought about by the various technical innovations also caused upheaval in traditional master mason language, bringing about a Tower of Babel situation. The terms hydraulic, fat, quiet and mixed limes, cements, pozzolanas, natural or artificial trass, sand, etc., lost their meaning (Guillerme 1986 vol.3:59).

Masonry terminology developed within the traditional framework of master and apprentice. In addition to responsibility for constructing a projects masonry work, master masons often served as the primary authority in charge of construction projects. However, this role gradually faded as engineers and architects assumed responsibility and the accompanying authority for most construction projects. This terminological trouble signified the shift in authority for construction projects, as well as exposing the confusion involving translation of new masonry work methods, which accompanied usage of cement. Even today, masonry terminology and its meaning still requires clarification. Some masons call their material mortar, whereas others may refer to it as cement even though they are both referring to the same mixture. Those not well versed in masonry terminology may call this same material concrete, which is incorrect. Concrete is a cement or mortar substance with large aggregates such as gravel. In modern practice, gravel is proportioned to a particular quantity of cement, which already contains a set amount of water and sand.

Cement introduced for projects did not always fall into the hands of people knowledgeable in its application. Introduction of cement further removed craftsmen from refinement of the masonry material they would use. Traditionally, masons were involved in many, if not, all phases of material treatment.

The State would probably save in a pecuniary point of view, and secure a much better cement, if it were to purchase from the manufacturer and furnish the contractors; a more perfect supervision might then be adopted, and the frauds which are sometimes attempted by the use of cements which have been injured would be avoided, by the removal of the inducement (Dexter 1840:24).

When cement began being manufactured and shipped to job sites, this reduced masons knowledge of the material. This created further problems regarding application of new technology. Some masons were not knowledgeable regarding cement and/or hydraulic mortar and reluctant to employ them. Furthermore, all architects and engineers were not knowledgeable regarding cement and were not able to oversee its effective use.

Transition from lime mortars to cement dramatically altered and increasingly shadowed traditional craft techniques involving lime mortar preparation. Its technological impact changed the principles of mortar preparation as well as the devices implemented in this process. Such devices as mortar mills, operating on the principle of compression, gave way to mortar mixers, which blended rather than compressed the mortar. The traditional technique of beating or compressing lime mortar served to further increase the plasticity of the mortar. As modern cement technology emerged the beating technique gradually disappeared. The blending of lime mortar and the blending of cement became increasingly perceived as similar operations.

Within the last few years machines have been placed on the market to mix the sand and lime, these machines being similar in operation to the concrete mixer. By the use of such machines, it is possible to mix the lime and sand more thoroughly and the mixing is accomplished in less time than is required by hand. Hydrated lime is especially adapted for use in the mortar mixer because the material comes on the work in a convenient form in packages of known weight (Lazell 1915:52).

Lazell illustrates that certain lime treatments became absorbed within cement technology and could be mixed similarly and more thoroughly. However, the properties, characteristics and performance of lime reveal otherwise.

By the early 1900's lime became available which was hydrated or slaked by producers. This process yielded a fine powder hydrate, which could be run to putty with the addition of water. While this procedure simplified the treatment of lime for craft workers, it also reduced their ability to control the properties and performance of lime mortars. The push toward standardizing the refinement of lime and techniques associated with its production served to yield a more homogenous lime. Many techniques applied by craft workers became absorbed and eliminated in the manufacturing process. Elimination of these techniques represents a loss of knowledge as well as a loss of associated skills surrounding application of these techniques. Furthermore, standardization served to minimize and often eliminate the human factor regarding perception and participation in determining a standard. Materials treated at the plant and provided on site for use minimized the treatment techniques available for craft workers. The disappearance of these techniques can be traced to standardization of materials and elimination of on site treatment methods, which were absorbed within the manufacturing process. This transition was by no means inevitable, but seemed to translate itself by scale. Large civil and commercial projects in the early to mid nineteenth century such as the dams and locks built on the James River used natural cement from Balcony Falls, Virginia. Making natural and Portland cement could become a more standardized procedure incorporating more standardized materials. In the mid to late nineteenth century, larger projects such as dams, and bridges benefited from standardization of materials and methods. Engineering projects such as these could rely on a more consistent mortar formula and working methods. Natural cement, which proved effective for construction of lock and canal systems, subsequently appeared on the general building market as well in the late 19th century.

Chapter 3 Masonry Restoration

Through preservation and restoration of historic structures, we gain a tangible link to our building construction heritage. Restoration of historic masonry structures provides the opportunity to open vaults of information surrounding original masonry materials and techniques associated with lime mortars. The field of lime mortar technology has specific appeal for historians of technology, who can contribute toward interpretation and application of lime technology. Holmstrum conveys the need for research and collaboration in this endeavor.

Lime mortar is really a curious product, hard to understand fully. Having worked with these problems both theoretically, in the laboratory, and in the field more or less intensely for some twenty years, I think the problem can be solved only by interdisciplinary teamwork. Specialists in geology, chemistry, testing techniques, mechanical strength, etc., have to work together with historians, archaeologists, ethnographers, etc., as well as architects, building engineers and perhaps most important, masons. And when I say teamwork I really mean a team where the specialists work together physically at the building site, in the laboratory, in the quarry, to be able to understand the whole context and to be able to feed each other with questions and ideas (Mortars, Cements and Grouts Used in the Conservation of Historic Buildings 1981:21-22).

With growing emphasis on restoration and preservation of historic structures, it becomes increasingly important to harness information and skills regarding lime mortar technology. This pursuit will not only benefit restorations of historic structures, but also contribute to the entire building technology field.

Preservation and restoration are terms, which, until recently, have been used interchangeably, in order to describe the maintenance of historic structures. These terms, however, denote distinctive forms of curatorial management. Preservation entails maintenance of historic structures in the same physical condition as they were upon receipt by a specific curator or curatorial group. Restoration, however, involves restoring the structure to an earlier condition. Poplar Forest, for example, a retreat built by Thomas Jefferson, illustrates an ongoing contemporary example of

restoration. This brick villa, located in Forest, Virginia, was built using lime mortar in the early 1800's. Following a major fire in 1846, the subsequent owners altered the original style of this structure. After purchasing the estate in the 1980's, the Corporation for Thomas Jefferson's Poplar Forest made a decision to restore this historic structure to its original Jefferson era configuration. Both original and contemporary crafted masonry materials have been used for this project. For example, structural stabilization of the south portico involved a partial disassembly of all but one of the original arches. A formulated restoration lime mortar was introduced to bond the original bricks within their original configuration. This aspect of the restoration insured that all bricks were returned to their initial position bound by a restoration mortar. Restoration, therefore, involves the introduction of new materials such as a restoration mortar. Fitch classifies the types of intervention involving curatorial management of Historic Structures.

We can therefore classify levels of intervention according to a scale of increasing radicality, thus: (1) preservation; (2) restoration; (3) conservation and consolidation; (4) reconstitution; (5) adaptive reuse; (6) reconstruction; (7) replication (Fitch 1990: 46).

In the following pages, I will discuss both problems and solutions regarding the study and application of lime mortar within a restoration framework. Restoration, which requires a new mortar to closely match and/or replace original mortar, involves the following:

- (1) Historical research and context of lime mortar technology.
- (2) Determining the composition of original mortar through analysis.
- (3) Determining the properties of original and restoration mortar.
- (4) Formulating a restoration mortar based on above conclusions and interpretation.
- (5) Employing capable craftsmen and suitable technology, in order to assist developing and applying restoration mortar.

Hardness and high strength of natural and Portland cements are characteristics, which undermine both the durability and integrity of historic structures built with softer masonry units such as handmade brick. Masonry fabric undergoes expansion, contraction and settlement, as a result of

climate and load bearing. As this movement occurs, it is crucial for the longevity of the masonry fabric that relief occurs within the mortar rather than the brick or stone units. Therefore, a mortar, which is greater in strength than surrounding brick or stone, will result in shearing or chipping (spalling) of the brick or stone. Damage to original masonry fabric caused by cement, as well as the benefits of lime mortar, was described by participants at a preservation conference on masonry as follows:

Beginning in the late nineteenth century, many architectural designs have been predicated on the use of fairly high-strength masonry, and the pace of construction has required masonry to develop strength rapidly. Accordingly, natural and Portland cements have been widely used in mortars, making them much stronger than most older lime mortars. Since bricks have undergone a corresponding increase in modulus of elasticity and ultimate strength, strong mortars have produced few problems when used with strong bricks or stones. But older, weaker bricks, as well as many kinds of soft stones, are known to have been damaged by strong repointing mortars, since stresses in the wall are relieved by the breaking or crumbling of the units (bricks or stones) rather than the mortar. Furthermore, the cohesive (internal) strength of cement mortar may exceed its adhesive bond to the units or to the old mortar, so that the stresses may break the bond between old and new, often just within the surface of the old. Stresses result from such causes as thermal expansion cycles of the units and the mortar; dimensional changes produced by changing humidity levels; foundation settlement; and slow settlement of old lime mortar remaining in the core of the wall. Lime mortars are said to permit relief of such stresses by movement within the mortar joints, and without breakage of the bond to the masonry units. Such movement may be by elastic behavior, by plastic behavior or by the formation of harmless micro-cracks. It is said that these cracks may eventually be re-sealed through the dissolution by rain of calcium hydroxide or calcium carbonate, and the subsequent redeposition of carbonate. As Professor McKee noted during the conference, both the flexibility and slow hardening of lime mortars may have been especially important in the initial adjustment and distribution of stresses in complex gothic structures (Phillips 1973:10).

Cracking and shearing, which results from the incompatibility of cement with original masonry fabric, also creates openings for water to further harm masonry fabric and other components of

an historic structure. Due to these factors involving its rigidity and incompatibility with lime mortar and softer masonry units, Portland cement has fallen from favor in the restoration community. As a result of this and other compatibility problems, restoration philosophy has adopted an approach, which favors interventions that can be reversed.

Reversibility is a criterion, which has developed from a century's experience in archaeology and art conservation, where radical interventions employing the "latest thing" in science and technology have often led to the irreversible degradation of the artifact in question (Fitch 1990:46).

Due to this realization and an accompanying need to match original materials, lime mortar has become the masonry binder of choice. Lime mortar can more closely match original mortar and can more easily be replaced should the need arise.

In order to understand lime mortars and techniques associated with their preparation, it is necessary to gain an understanding of the lineage from which they arose. This lineage and technological development has been discussed in preceding chapters. Familiarity with masonry heritage and its accompanying technology serves as one valuable tool for historic masonry restoration.

3.1 Investigation of Original Mortar

Another tool accompanying an understanding of historic lime mortar treatment techniques involves investigation and analysis of original mortar and masonry fabric. Prior to analyzing original mortar, however, all parties associated with the curatorial management of the historic structure need a clear and consistent approach regarding the mortar analysis. Questions must be answered regarding the purpose, availability, scope and interpretation of a mortar analysis. It is important that mortar samples be representative of all or specific portions of the structure to be restored. One purpose of a mortar analysis involves determining the ingredients and their proportions, which will assist subsequent development of a restoration mortar.

Another purpose involves determining properties of the mortar. The scope of the analysis involves areas of the structure in need of restoration, as well as its relation to the entire project. The choice of methods of analysis will be determined in part by availability and quantity of accessible mortar. Sampling and analysis will relate, first and foremost, to the overarching investigation of the entire structure. After documenting and agreeing upon the locations for sampling, samples, in turn, will be taken to represent these locations.

It is crucial that mortar sampling of an historic structure cause limited damage upon surrounding brick or masonry fabric. An initial starting point for analysis involves visual inspection and comparison of samples. Here, especially, it is critical to view un-weathered samples. This can be accomplished by breaking samples, thereby exposing their interior. When formulating a restoration mortar, it is best to match the color of un-weathered portions of the original mortar. During visual inspection, color continuity or variation and texture are noteworthy, as well as any sign of lime and its pattern of dispersion. Next, a closer look with magnification will further reveal appearance of aggregates and lime. Matching the color of old and restoration mortar poses a significant challenge. Even if you succeed in matching the composition of the original mortar, this is no guarantee the colors of the old and new will match. Here the impact of time and weathering has influenced the original mortar greatly. In particular, the season and climate during original placement influenced color. The interior and exterior of the original mortar surface will appear distinct as well. Therefore determining color, which derives largely through aggregate additives, is a complex decision often influenced by climactic conditions beyond reasonable control. This represents one particular realm of mortar study and empirical analysis needing further study.

There are a handful of available techniques to determine mortar ingredients and proportions. These methods involve the separation of aggregate and lime by addition of hydrochloric acid. Hanna Jedrzejewska, a Polish conservator, developed a method of analysis, which remains the

most consistent reliable means of composition analysis.⁷ This analysis will reveal the proportion of sand aggregates as well as gradation and color. Also revealed will be the shape and type of

⁷ "The determination of the three basic values of a mortar is performed by dissolving the sample in hydrochloric acid (HCL) in a special apparatus which measures the volume of carbon dioxide (CO₂) (fig. 9). A well chosen fragment of mortar of about .4 to .8 gm. is first crushed then placed in a small porcelain crucible, dried, weighed, covered with about 3 ml. of water, and placed in position (2). The dropper pipette (5) is filled with about 3 ml. of conc. HCL from a test tube. The apparatus is closed by putting the upper part (A) into the mercury (3) and fixing with a clamp. The water levels in the two arms of the burette are equalized, and the volume recorded. HCL is gradually dropped from the pipette, and CO₂ is evolved. When the reaction is complete, the new volume in the burette is recorded, the crucible is taken out, and the solution after stirring with a glass rod, is immediately transferred to a dry test tube, together with light suspensions and precipitates. (No water should be added.) The sand is then washed with water several times (the water discarded) and left for twenty-four hours in the crucible to become air-dry. No heat is used. A strip of blotting paper put into the crucible helps the drying (fig. 2). The dry sand is weighed. The amount of carbonates (calculated as calcium carbonate) corresponding to the amount of CO₂ evolved, is recorded directly as w/w percentage of the whole sample. The amount of sand is expressed in the same manner. The solubles are calculated by summing up the percentages of carbonates and sand and subtracting them from 100 per cent.

Notes: (1) The powdered samples are left in crucibles for twenty-four hours to become air-dry, before the analysis is done. Gentle infra-red heating may be used to dry both the samples and the sand.

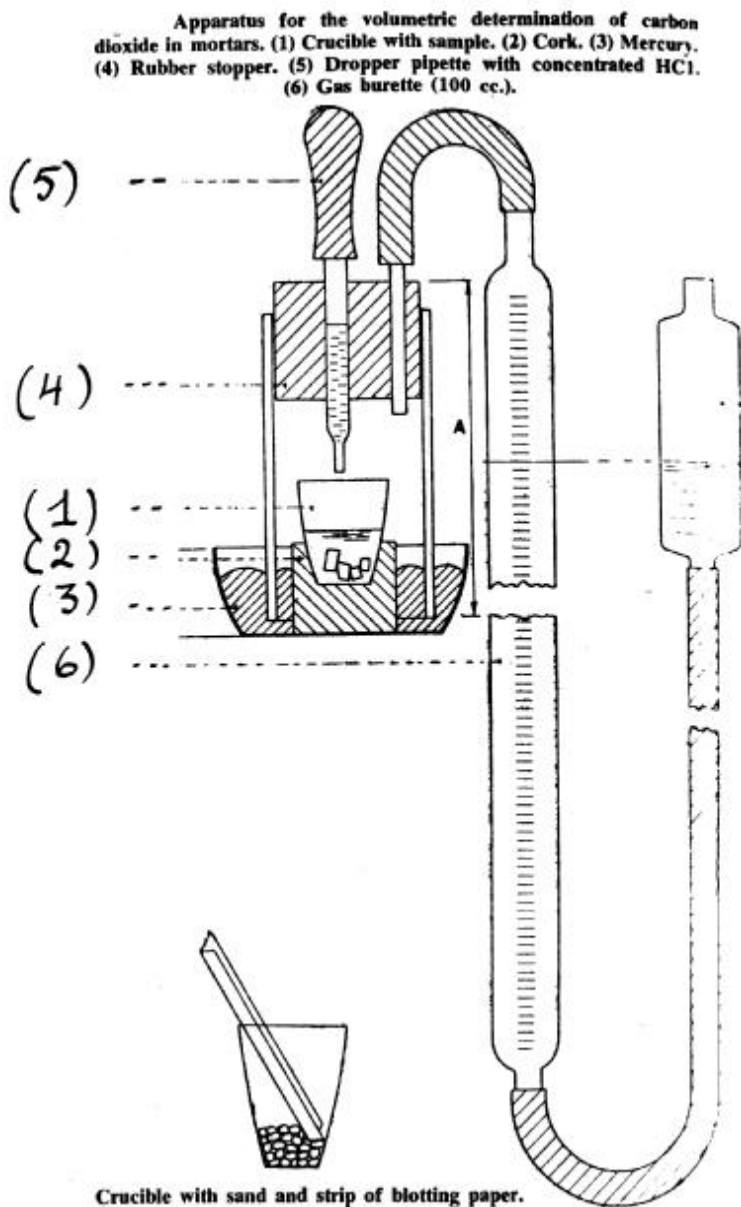
(2) *A small error is incurred by not taking into consideration any magnesium carbonate that may be present.*

(3) Additional observations, including visual and microscopic examination of original mortar, sand and precipitates, may help in the classification of closely similar mortars.

(4) The analyses are made in sets of twenty, with an average time of thirty minutes for one analysis. At least two analyses of each sample should be taken.

The experimental error in the sand determination is from 1-3 percent, calculated on the average sand content in the mortar. Allowing for this, variations in the sand content afford an identification of the homogeneity of the mortar. It is sometimes useful to consider this feature in more general studies. The experimental error in the volumetric determination of carbonates amounts to about +/- .5 ml. of carbon dioxide" (Jedrzewska 1967:161-162).

aggregate through closer examination. It must be noted that this analysis provides only a partial solution to mortar analysis and can be subject to error and misinterpretation through using only this analysis as a guide for formulating a restoration mortar. Also, there are limitations to this procedure. This test will not distinguish between calcium carbonate aggregates and the calcium carbonate of the lime. Hydrochloric acid will dissolve both particles and result in inaccurate proportions between lime binder and aggregate, since it does not distinguish whether the calcium



carbonate was within the binder or aggregate. Such a situation may occur where limestone aggregates or crushed hardened mortar had been incorporated in the original mortar recipe as aggregates. Another limiting factor involves tracing the content of clay (aluminum silicates). Clay, like calcium carbonate, may have been within, either, or both the lime and aggregates. If clay was originally within the calcinated limestone, it may have rendered the mortar hydraulic. Here the problem involves determining the proportions as well as the role of the clay in the mortar. While clay was seldom introduced purposely as an aggregate, its inclusion was often hard to avoid, as it may have inadvertently been combined with sand.⁸ Therefore, clay content could easily be misinterpreted.

Although chemical and physical examination can tell us a great deal about the principal constituents of an old mortar, the conference participants felt that the precise characterization of hydraulic ingredients would often be very difficult and sometimes probably impossible... Some of these compounds may change over the years, rendering their original composition yet more obscure (Phillips: 1973:13).

This is important because the role of the clay would have great influence upon the properties of the original mortar. Also, chemical reactions and changes occur during the process of hardening and aging, which this mortar analysis will not reveal. Therefore, this method serves as a valuable tool for comparative sampling and a base line for mortar composition. Although this method is important and useful within a restoration investigation, it provides only a glimpse of the entire picture.

The choice of a mortar must relate firstly to the type and condition of the masonry and secondly to the degree of exposure. This choice is primarily based on a knowledge of the properties of various mortars and is not arrived at by analysis of the existing mortar alone. There may be good archaeological reasons for wanting to establish the identity and proportions of constituents in an old mortar, and simple separation of aggregates may be useful in

Figure 8 page 69 Apparatus for mortar sampling (Jedrzewska 1967:150).

⁸ Unburned clay in certain cases had been mixed with lime for chinking between log cabins, which is beyond the scope of this project.

identifying likely sources of aggregates for matching purposes. There are, however, limitations which should be understood and mortar specifications should not be based on the simple breakdown analysis of a sample. Analysis requires interpretation and there are important factors which affected the condition and performance of the mortar that is being sampled which analysis will not reveal. Examples of such factors are the original water:binder ratio, the rate of drying out, the method of mixing and placing, and the cleanliness and conditions of the aggregates.

There are also practical difficulties in isolating and identifying constituents. For instance, calcareous aggregates will be digested with the calcareous binder material in acid and present a misleading binder:aggregate proportion. The occurrence of old mortar crushed down and re-used as aggregate is a notorious problem of this kind. Clay minerals, present as impurities, may not be readily distinguishable from the silicates present in an hydraulic cement. An additional difficulty is accurate matching of an old clamp-fired lime, well mixed with fuel and kiln slag, with a modern lime produced in closely controlled conditions and delivered as a very pure hydrate (Ashurst&Dimes 1990:88).

Other analytical test methods are available to analyze mortar. Analytical chemical tests include; cationic tests to distinguish iron, alumina, silicon and other hydraulic elements, anionic tests to identify such compounds as chlorides, sulphates and nitrates, which are considered contaminants. Analytical instrumentation tests include; emission spectrometry, x-ray diffraction, neutron activation, petrographic examination, thin section microscopy, scanning electron microscopy, atomic absorption spectroscopy and differential thermal analysis. While some of these tests may reveal important information about historic mortars, their cost, reliability and interpretation are major concerns. We can conclude that mortar analysis is a specialized field requiring skillful interpretation and consultation with experts from various disciplines, in order to gain effective results.

3.2 Properties and Performance of Original and Restoration Mortars

Another part of analysis involves determining original and restoration mortar properties. A mortar recipe gains its properties not only from ingredients and their proportioning, but also from the methods employed during refinement of ingredients and their resultant preparation.

A recipe is really no guarantee for a specific result either in strength or in porosity. The process of mixing, of working and treating the material all through the process affects the final product, i.e., the rendering or the masonry joint. For example, the choice of the limestone, the burning and- last but not least- the slaking process affect the properties of the lime as a binder. Standard chemical tests on the slaked lime may show no difference, but in practice, the difference in its behavior can be like night and day (Mortars, Cements and Grouts Used in the Conservation of Historic Structures 1981:21).

Original methods of treatment impacted and influenced the resulting properties and performance of mortar mixtures. Determination of these properties represents another important aspect of mortar analysis, which has received limited investigation. Holmstrum conveys a part of the problem and a potential solution to bridge the gap between original and restoration mortars.

When we are able to describe the main functional properties of a mortar we can start to reconstruct that mortar or construct another with the desired properties. This is not possible today. We can only reconstruct the compositions, and hope that they will work. By checking the functional properties of a new mortar of a certain composition (reconstructed old or entirely new), we can also study how other factors like the mixing method or application after treatment are influenced. That also means we then have possibilities to test theories or vague information about, for example, a mediaeval mixing method, a special way of slaking, or the like. We can compare the resulting physical properties of a reconstructed mortar with an old one of identical composition (Mortars, Cements and Grouts Used in the Conservation of Historic Buildings 1981:24).

Properties of original and restoration mortar, which require investigation, include; color, porosity, permeability, adhesion, durability, strength, original water content and any changes through carbonation or aging. With the exception of porosity and permeability, determining these properties remains difficult and elusive with current test procedures, since these test procedures are tailored for cement.

Parallel to the development of testing methods for existing mortar, we have to modify the methods for corresponding tests on new mortar. In particular, the way of mixing, casting, and treating the mortar to get the samples must be studied carefully. I doubt that quicklime and hydraulic lime should be treated in the same way, but in any case they should not be treated like Portland cement because the hardening process is entirely different. Existing standardized methods are designed for Portland cement... Adequate methods for testing mortars in historic buildings are of interest also in the general building market because when repairing the rendering or masonry of an ordinary building it is also important for the new material to cooperate with the original. Such cooperation is guaranteed only if the materials are similar in their technical behavior. The development of test methods described above ought in fact to be of great interest to the whole building market and especially to the building research organization (Mortars, Cements and Grouts Used in the Conservation of Historic Structures 1981:24).

In order to determine the properties of both original and restoration mortars, a suitable analytical procedure must be developed. These methods will best be developed as historic methods of treatment are relearned and empirically applied.

It is well to remember the contexts in which lime was produced historically and to be careful about simple assumptions arising from, say, analysis of ancient mortars. We have as much to learn about production and preparation as about constituent parts; in particular we must remember that there are significant differences between a modern, commercially produced lime and a lime, full of impurities such as slag and ash, produced in a clamp in the fourteenth century (Ashurst & Dimes 1990:78).

Historic methods of lime refinement and preparation played a significant role upon resulting properties of the mortar. For example, aging of hand slaked lime not only insured complete slaking of all particles, but also enhanced the resulting plasticity of the lime. In fact, even following the adoption of mechanical hydration, some authorities continued to praise the merits of hand slaked putty indicating that some of the best commercial lime on the market had been slaked by hand. Increased plasticity, therefore, not only contributed to greater workability, but also toward adhesion and bond of the mortar to masonry units. Therefore, standardization of lime influenced resulting properties of lime mortar. While at first glance this may appear as a subtle distinction, it illustrates that standardization changed not only work methods involving lime, but also its resultant properties.

3.3 Masonry Restoration and Historic Treatment Techniques

Masonry restoration of historic structures poses substantial dilemmas for architects, conservators, and craft workers seeking to incorporate new mortars with composition, performance, and characteristic properties similar to those of original mortars. In the late 20th century and early 21st century restoration philosophy embraces the incorporation of original masonry materials and techniques where possible. This commitment, however, necessitates a fuller understanding of properties and characteristics imparted upon lime mortars by the preparation techniques involving lime production and mortar preparation and placement. Since we are able to confirm and reconstruct the composition of historic mortars, the next step is reintroduction of historic techniques involving the preparation of lime mortars. Here, both scientific analysis and empirical application of historic lime and mortar treatment can bridge the gap between matching composition and properties of restoration and original mortars. Properties of the reconstructed mortar are critical when wedded to original mortar units not in need of reconstruction. Since matching the composition yields no assurance that the two mortars will have like characteristic properties and future performance, it is essential to work toward a better understanding of original and restoration mortar properties. These properties will best be understood as historic techniques are applied on restoration projects.

Some restoration professionals have questioned the need and practicality of incorporating original techniques.

Several conference participants felt strongly that on-site hydration of lime would in most cases be poorly controlled and thus would entail a number of unacceptable risks, especially that of incomplete hydration. Mr. Klein described how the modern factory hydration processes can be adjusted precisely to the reactivity of the lime and the purpose for which the lime will be used...Mr Klein felt that ball-milled, pressure hydrated, type S magnesian lime, when briefly soaked before use, would probably be as thoroughly hydrated and as plastic as lime well hydrated by hand (Phillips 1973:21).

Since the suggested commercial materials cannot assure similar properties, historic treatment techniques will prove more valuable for masonry restoration. Commercial limes may match the original limes in proportion, but a commercial lime will not yield similar performance in the finished mortar. They are calcined with such fuels as coal and gas, whereas most original carbonates were fired with wood. Furthermore, commercial limes are mechanically slaked, while original quicklime was hand-slaked. Since both original and contemporary treatment methods impact the future properties of the finished lime, original treatment methods offer the best option for matching the properties and performance of original mortars.

At Poplar Forest, Thomas Jefferson's villa constructed in the early 1800's in Bedford County, Virginia, a comprehensive restoration project is well underway. This historic structure is a living laboratory for masonry restoration and preservation. The Corporation for Jefferson's Poplar Forest has assembled a knowledgeable and skillful staff and consultants.

Much time and effort has gone into the formulation of the mortar at Poplar Forest. Both the composition of the mortar and treatment techniques are the result of a transition from using a standardized mortar formula toward an individualized mortar geared to provide median color

match with existing original mortar, provide comparable strength properties with the adjacent original mortar, and also provide similar characteristics and properties as original mortar.

While working at Poplar Forest on the masonry restoration, an initial distinction between a lime mortar and contemporary cement mortar became readily apparent. Portland cement set much quicker and retained much less plasticity than a lime mortar. Poplar Forest has incorporated no cement within any of their restoration mortars. Beginning in 1992 the initial restoration mortar included commercially hydrated lime and hydraulic lime. Both limes were in powder form and sealed in bags. The high calcium hydrated lime was mixed with about seven gallons of water and mixed together. The mixture was sealed in a plastic container and left for at least twenty-four hours, whereby it formed a paste with any excess water remaining on the surface. Next, the paste was introduced to a gauged amount of sand aggregate, followed by blending the mass. Prior experience with a commercial bagged cement mortar proved inadequate toward working with this lime mortar. Not only are the composite materials different, but also the resultant treatment methods differ as well.

Preparation of the lime mortar involved the addition of an hydraulic lime paste. This addition entailed a thorough blending to fully incorporate the grey hydraulic paste within the beige blend of lime paste and sand aggregates. This process was similar to the initial mixing of the lime paste, with a consistency like thick creamy peanut butter. Using only a mortar hoe, which is customary when mixing a contemporary cement mortar, seemed inadequate to fully blend and unite the mass. Research into historical accounts revealed descriptions in which the mortar was beaten. Attempts to recreate this technique coupled with the need to develop a practical method of thoroughly mixing the paste and aggregates lead to further experimentation. Alternate layers of aggregates and paste within a wooden box fostered use of the beating technique. A wooden vertical maul served to accomplish the blending of the mortar, whereby an intimate marriage of lime and aggregate could be achieved in the presence of limited water. This procedure creates a pliable yet stiff mortar with minimal water content, thereby yielding very favorable results in joining the restoration mortar to the original masonry fabric.

Reintroduction of the beating technique has been accompanied by further techniques applying traditional lime mortar technology within the restoration project at Poplar Forest. In the late 1990's Price Masonry began calcining high calcium limestone. Alternate layers of limestone and wood are placed within a pot kiln constructed of brick and cement. Following calcinations, the quicklime is slaked, screened and stored in pits. Extended storage of the lime insures thorough slaking. Cured lime is mixed with brick dust and aggregate forming the current mortar recipe at Poplar Forest. The initial restoration mortar applied at Poplar Forest exhibits hairline cracks, which appear linked with their more rapid rate of initial hardening, whereas, the current restoration mortar cures slower and more evenly. An example of this stems from a brick test panel bonded with the current mortar. This panel shows no evidence of such hairline cracks, which are apparent with the initial restoration mortar. By burning limestone in this traditional manner less heat and more burn time is required. This influences the properties of the quicklime, which, in turn, is slaked and stored. This traditional treatment process amplifies the ability to control the resulting lime, which is not possible from a commercially burned and hydrated lime. The Virginia Lime Works, located in Monroe, VA, represent one of the few, if not only, makers of traditional high calcium lime putty. Their work has significantly contributed to the ongoing restoration at Poplar Forest. Furthermore, they have expanded the network of materials and techniques available within the restoration community.

Standardization of lime and development of cement technology led to the elimination of many historic lime mortar treatments. Without these treatments, it is difficult to match the properties and performance of original masonry materials. Development of mortar at Poplar Forest has been an ongoing educational process for craftsmen, researchers, and visitors. Restoration of historic structures such as Poplar Forest provides opportunities to relearn and apply traditional treatment techniques. This benefits the entire community and, in particular, the restoration community in at least two significant ways. First, it supports and promotes the material, technological and structural integrity of historic structures. Secondly, it opens an educational window for restoration workers and interested visitors, enabling them to view and experience traditional techniques, which were similarly applied during the structures original construction. If redevelopment of historic lime treatment techniques is accompanied by comparative testing of

mortar properties, we may gain a better understanding of the influence of treatment techniques upon resulting properties of lime mortars. This reacquired knowledge and skill involving lime technology will benefit the entire restoration community, as it strives to further understand and apply historic techniques.

Chapter 4 Societal Context of Technological Accomplishment and Technological Loss

Significant social and cultural themes are woven into the development of lime and cement technology, as well as the subsequent standardization of materials and treatment methods involving these technologies. Restoration of masonry structures provides opportunities to rediscover original techniques associated with lime mortar technology. Although these original skills and knowledge are antiquated, they represent vital ingredients of enduring masonry structures. Many of these structures are held in high regard for both their durability and architectural design, which were facilitated through lime mortar technology.

Two intrinsic elements of early masonry technology included time and labor, which contributed toward enduring masonry works. These components were vital aspects of masonry treatment. Contemporary society, however, tends to view both time and labor as factors to minimize or eliminate rather than embrace as essential components of a technology. Both quality and productivity appeared to thrive within a highly developed Roman technological order. Aging of slaked lime contributed toward its plasticity and resultant durability. Also as a result of increased plasticity, an intimate bond formed between masonry units. Therefore, through proven results, aging of the lime and mortar became accepted as an essential ingredient of quality work. The Roman prescription for a 3-year slaking period of the lime remained a guideline for many plasterers and masons into the 19th century. However, in the 19th century time and labor were increasingly perceived as avoidable ingredients of masonry technology.

The weakness of modern mortar, compared to the ancient, is a common subject of regret; and many ingenious men take it for granted, that the process used by the Roman architects in preparing their mortar, is one of those arts which is now lost, and have employed themselves in making experiments for its recovery. But the characteristics of all modern artists, builders among the rest, seems to be, to spare their time and labor as much as possible, and to increase the quantity of the article they produce, without much regard to goodness; and perhaps there is no manufacture, in which it is so remarkably exemplified, as in the preparation of common mortar (Shaw 1832:54).

While the pace of construction had increased during the 19th century, a corresponding increase in the orchestration of technological procedures did not accompany the increased pace of construction.

Effective application of techniques does not require scientific and theoretical understanding. Masonry technology, in fact, thrived during the Roman era in the absence of an accompanying scientific basis and theoretical understanding. The Romans also developed techniques for creating hydraulic mortar with the addition of volcanic pozzolanas, brick dust and tile fragments. Lacking a comprehensive theory on lime and hydraulic lime mortars fostered experimentation in order to develop sound treatment techniques.

We the human race, appear to attain empirical knowledge quickly; scientific knowledge arrives at a much later period. So it was with limes: so it is with the casting and puddling of iron (Burnell 1870:4).

In spite of this lack of theory, the Romans developed a technological practice focused largely on the processes and their interrelations. The knowledge and skills they practiced were scattered following collapse of their empire, and the orchestration and precision of their techniques diminished with their decline. After acquiring theories, which explained the phenomena resulting from lime treatment methods in the 19th century, there was not an accompanying improvement in techniques. We can conclude that theoretical information and explanation of particular lime treatments did not translate into superior masonry materials and techniques for their creation.

Craft-based traditions such as lime burning, slaking and mortar making were primary tributaries and components of the masonry trade. The necessary skills and instincts associated with these crafts were acquired through hands on work and apprenticeship. Teaching and learning through an extended period of apprenticeship fostered development of these skills. As the role of craft trades and cottage industries has diminished, so too has the apprenticeship training system.

Current training in masonry no longer involves an organized apprenticeship system. A worker may be labeled an apprentice, but the system is much less structured than a century and one-half ago. Furthermore, it no longer takes seven years to complete apprenticeship, as had been the custom. Therefore, the only current gauge of masonry workers ability is discovered by putting them to work on the wall, and seeing their skills or lack thereof.

A lime burner developed his skills and accompanying instincts without gauges or scientific monitors. Lime burners relied upon their senses and experience to guide them.

The calcination of limes is, however, a subject still very little understood, and it is impossible, therefore, to enunciate any principles of universal applicability. There are so many disturbing causes in operation; the difficulty of observation in all cases where large masses are in a state of simultaneous incandescence is so great; that it will be long before we shall be able to ascertain the chemical and electrical phenomena which take place during these operations, with sufficient certainty to enable us to derive any practical benefit from them. At present our best guide is experience, and a kilnsman who has watched the action of his own kiln for years, knows more upon the subject than the first theoretician in the world (Burnell 1870:35-36).

For example, a lime burner worked from direct observation of the kiln. Color of flame, concentration of heat, settlement of charge, and thoroughness of burning, were some of the signs, which a lime burner observed and to which he responded. Skill of the burner was an essential component of a good kiln product. Optimizing the quality of raw stone or fuel could not compensate for a lack of skill to effectively orchestrate a kiln firing. We can conclude that quality masonry work was not dependant on the ability to explain phenomena associated with lime refinement and mortar preparation. In other words, the quality of a durable lime mortar relied more on skill than the ability to interpret and define procedures.

European powers such as France and England among others constructed enduring castles and fortifications, which would symbolize both their prestige and power. National defense and the need for enduring masonry work were political incentives for technological development of masonry work. Furthermore, socioeconomic needs required docks, piers, canals, dams and

related masonry infrastructure to support increasing commerce and development. An interesting story conveyed by John Smeaton, an English engineer tasked with reconstruction of the Edystone Lighthouse, illustrates the societal context of nationalism, commerce and navigation in the 18th century.

The following anecdote has been related to me by such a variety of persons, that I cannot doubt of its having some foundation in truth, though no mention has been made thereof by Mr. Rudyard. The relation will therefore I trust be acceptable to my readers, as it at once shews the great estimation in which this building has been held by foreigners, even such as were, at the very time, enemies of this country.

LEWIS the XIV, being at war with England, during the proceeding with this building, a French privateer took the men at work upon the Edystone rock, together with their tools, and carried them to France; and the captain was in expectation of a reward for the achievement. While the captives lay in prison, the transaction reached the ears of that monarch: He immediately ordered them to be released, and the captors, to be put in their place; declaring, that though he was at war with England, he was not at war with mankind; he therefore directed the men to be sent back to their work with presents; observing that the Edystone Lighthouse was so situated, as to be of equal service to all nations having occasion to navigate the channel that divides France from England (Smeaton 1791:28).

The Edystone Lighthouse is symbolic, not only as a beacon of commerce and navigation, but also as a foundation, upon which modern masonry technology is built. Smeaton and his contemporaries represented the first recorded and significant break from Roman masonry tradition by displaying that some of their guidelines need not be followed. For example, they found through experiment that the hardest limestone did not necessarily yield the best lime for all construction needs. Nor did the whitest lime yield the best mortar for all construction purposes. These qualifications, of course, were dependent upon particular application. The whitest lime and hardest limestone were not necessary to create the best hydraulic mortar. The addition of clay, suited to this purpose, contradicted Roman tradition since clay within limestone yields a brown to grey color lime following calcination and slaking.

Development of cement technology upset existing work methods associated with lime mortar technology. During empirical development of cement technology, separate cement treatment and preparation techniques emerged. Confusion, however, followed the development of cement technology and the ability to distinguish cement from lime mortar treatment methods. Both the development of cement technology and standardization of lime refinement undermined the integrity of lime mortar technology.

As standardization took over the refinement of lime and cement, techniques traditionally carried out by craftsmen were being absorbed and eliminated by the manufacturing process. Furthermore, as cement technology supplanted lime mortar technology, the primary principles and characteristics involving these materials and treatment methods changed. While many involved with and knowledgeable of both materials may see this point as understood, those not aware of the great distinction between these two technologies and associated techniques may easily confuse one for the other.

Standardization of lime refinement served to produce a uniform consistent lime. Standardization upset and eliminated work methods traditionally carried out by craftsmen. Uniformity of mechanically hydrated lime reduced the ability of craftsmen to control properties through hand slaking of quick lime. Standardization of lime eliminated the ability of craftsmen to tailor treatment methods for intended application of lime. Simplification of work processes through standardization may have far reaching implications. Simplification of processes may be of great assistance when standardization does not alter the finished product. However, simplification of work processes can harm the integrity of a craft and profession by undermining an ability to control the material with which craftsmen work. As a result of standardization and simplified work processes, craftsmen such as a plasterer and a mason lose skills, which are capable of enhancing the quality of their work.

Figure 9 Depicts an etching displaying Smeaton's completed version of the Edystone lighthouse(Smeaton1791:206).



Standardization of lime and cement technology has benefited certain aspects of construction and society. Mechanical slaking eliminated the need to age quicklime and there was little risk of blistering from insufficient slaking. Craftsmen had fewer treatment operations to conduct, which could minimize errors created as a result of inadequate treatment methods. Through standardized materials and simplification of work processes individuals may be able to perform projects or jobs, which, otherwise they could not have done. For example, plastering is possible for someone who is not a plasterer by trade. Cement technology proved itself effective for application upon canals and large infrastructure projects, such as dams, bridges, sewers, septic tanks, tunnels and roads. Guillerme mentions the financial savings within French public works resulting from cement technology.

Between 1815 and 1835 mortar strength was increased by a factor of 10 and thanks to new types of artificial lime, the State was able to save more than 182 million francs from 1818 to 1844 i.e. nearly 20% of the French road budget for the very same period - not to mention the savings arising from their preparation which are estimated to fall between 30 and 40%. The entire building and public works sector underwent a gradual but irreversible change which paralleled the Industrial Revolution (Guillerme 1986:26).

Cement has literally provided the foundation for industrial and commercial development. As a major component of concrete, cement provides a solid foundation for high-rise construction. Currently, concrete serves as a durable level surface for heavy precision industrial equipment. Therefore, concrete and cement are key components of our infrastructure.

Application of theoretical understanding and scientific method enabled standardization of lime and cement. This result was a choice and not an inevitable achievement. As the Romans chose to emphasize technological order and masonry work processes, 19th and 20th century engineers and scientists opted to emphasize material masonry composition and its more uniform refinement. As a result of this choice and the development of Portland cement, skills involving the treatment of lime became absorbed within the manufacturing process. Standardization, therefore, eliminated techniques, which, in turn, influenced the characteristics and properties of lime.

Current restoration projects involving historic lime mortar structures face a dilemma. In order to match original lime mortar, a restoration lime mortar is formulated. However, commercially produced lime seldom, if ever, has matching characteristics and properties as the original. Therefore, it is necessary to reintroduce historic lime treatment techniques. Through empirical development and application, these techniques will prove invaluable toward future restorations. Since properties of original mortars were influenced by treatment and preparation methods, it is crucial that test methods are developed along with reintroduction of historic treatment methods. Increased attention is being focused on test methods, in order to determine properties of original and restoration mortar. Without an accompanying development of practical historic treatments, these test methods serve primarily as academic interest. Further testing and comparison of original mortar at (1806), initial restoration mortar (1993-2000) and current restoration mortar (2001) at Poplar Forest will demonstrate if traditional lime treatment techniques are more closely aligning the properties and performance of original and restoration mortar.

In conclusion, recovery of some or all of the knowledge and skills associated with historic lime mortar treatment serves as an educational and practical tool for the restoration community. Incorporating historic lime treatment techniques can be an educational tool by more closely demonstrating the context of original masonry construction practice. Incorporating these techniques will enable a better understanding of original masonry treatments and their influence upon an original structure. Furthermore, it will be possible to determine the influence of these techniques and tailor specific techniques for the contemporary restoration of historic masonry structures.

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My educational background includes; graduation from Western Albemarle High School in Crozet, VA, 1983, graduation from Virginia Polytechnic Institute and State University, Blacksburg, VA, with A bachelor of Arts in Liberal Arts, 1992 Master of Science from Virginia Polytechnic Institute and State University from the Science and Technology Studies program, 2001. My studies as an undergraduate involved geology, urban planning, history, and science and technology studies. As a graduate student, I combined work and research at Thomas Jefferson’s Poplar Forest and Monticello. This work and research culminated with the completion of this thesis.

My employment background includes, quality assurance in the printing and masonry industry, working on commercial, residential, and restoration masonry projects. While a student at Virginia Tech, I was called to service in the United States Army as a chemical specialist in Operation Desert Storm.

I was born in Roanoke, Virginia and my parents are Gene and Joyce Krumnacher. My oldest brother martin received his Forestry degree from Virginia Polytechnic Institute and State University. My late brother Mark was a long time resident of Blacksburg and this project is dedicated in his memory. My sister Lori has a Masters degree in counseling and runs a private practice in Clinton, North Carolina.