harden in water. Natural hydraulic cements were widely manufactured in the late eighteenth and early nineteenth centuries. Natural cement rock was burned in kilns, and the calcined lumps were then ground into a fine powder.

Since its discovery in the early nineteenth century, portland cement has become the most widely used material of its kind. Portland cement is a carefully controlled combination of lime, silica, alumina, and iron oxide. Although production of portland cement is a lengthy and complicated procedure, it consists principally of grinding the raw materials, blending them to the desired proportions, and burning the mix in a rotary kiln until it reaches incipient fusion and forms clinkers. These hardened pellets are ground with gypsum, and the fine powder is then bagged for shipment. When mixed with water, portland cement undergoes hydration—a change in the chemical composition of the ingredients in which crystals of various complex silicates are formed, causing the mass to harden and set.

There are five types of portland cement, each with different physical and chemical characteristics. Since the properties required for mortar are significantly different from the qualities called for in concrete, not all of these types are suitable for masonry construction. For most ordinary mortars, Type I, all-purpose cement, is most widely used. In some instances, such as masonry catch basins or underground drainage structures where mortar may come in contact with sulfates in the soil, Type II portland cement can be used to resist chemical attack. A more common substitute for Type I is Type III, high-early-strength cement. This mixture attains ultimate compressive strength in a very short period of time, and generates greater heat during the hydration process. For use in cold weather construction, these properties help keep the wet mortar or grout from freezing and permit a reduction in the period of time required for protection against low temperatures.

Air-entraining portland cement, Types IA, IIA, IIIA, and so on, is made by adding selected chemicals to produce minute, well-distributed air bubbles in the hardened concrete or mortar. Increased air content improves workability, increases resistance to frost action and the scaling caused by chemical removal of snow and ice, and enhances moisture, sulfate, and abrasion resistance. Air-entrained mixes are not as strong as ordinary portland cement mixes, and excessive air is detrimental in mortar and grout because it impairs bond to masonry units and reinforcing steel.

Air-entrained cements are used primarily in horizontal concrete applications where exposure to ponded water, ice, and snow is greatest. Entrained air produces voids in the concrete into which freezing water can expand without causing damage. Rigid masonry paving applications installed with mortared joints may also enjoy some of the benefits of air-entrained cements in resisting the expansion of freezing water. Although industry concrete for masonry mortar generally limit the air content of mortar, the benefits of higher air content in resisting freeze-thaw damage may outweigh the decrease in bond strength. Since rigid masonry paving systems are generally supported on concrete slabs, the flexural bond strength of the masonry is less important than its resistance to weathering. In these applications, lower bond strength might be tolerated in return for increased durability.

2.3.2 Lime

The term "lime" when used in reference to building materials means a burned form of lime derived from the calcination of sedimentary limestone.

Powdered, hydrated lime is the most common and convenient form used today. Of the two types of hydrated lime covered in ASTM C207, *Standard Specification for Hydrated Lime for Masonry Purposes,* only Type S is suitable for masonry mortar because of its ability to develop high early plasticity and higher water retentivity, and because of limits on the unhydrated oxide content (*see Fig. 2-10*).

The mortar used in most historic buildings was made with lime and sand only and did not contain any cement. However, lime mortars cured very slowly. The invention of portland cement in the early 1800s changed the way mortar was made by substituting cement in the mix for a portion of the lime. Contemporary cement and lime mortars are now made with a higher proportion of cement than lime. Although this has reduced curing time and speeded up construction, the trade-off is that the higher the portland cement content, the stiffer the mixture is when it is wet and the more rigid the mortar when it is cured. A cement mortar without lime is stiff and unworkable and high in compressive strength, but weak in bond and other required characteristics. The continued use of lime, although reduced in proportion, has many beneficial effects in masonry mortar and grout. Lime increases water retentivity, improves workability, and makes the cured mortar or grout less brittle and less prone to shrinkage.

Lime adds plasticity to mortar, enabling the mason to spread it smoothly and fill joints completely, improving both productivity and workmanship. The plastic flow quality of lime helps mortar and grout to permeate tiny surface indentations, pores, and irregularities in the masonry units and develop a strong physical bond. Lime also improves water retention. The mortar holds its moisture longer, resisting the suction of dry, porous units so that sufficient water is maintained for proper curing and development of good bond. Lime has low efflorescing potential because of its relatively high chemical purity. Its slow setting quality allows retempering of a mix to replace evaporated moisture. Lime undergoes less volume change or shrinkage than other mortar ingredients. It contributes to mortar integrity and bond by providing a measure of autogenous healing, the ability to combine with moisture and

Type N	Normal hydrated lime for masonry purposes.
Type S	Special hydrated lime for masonry purposes.
Type NA	Normal air-entraining hydrated lime for masonry purposes.
Type SA	Special air-entraining hydrated lime for masonry purposes.

Property	Type N	Type NA	Type S	Type SA
Calcium and magnesium oxides (minimum %)	95	95	95	95
Carbon dioxide (maximum %)				
If sample is taken at place of manufacture	5	5	5	5
If sample is taken at any other place	7	7	7	7
Unhydrated oxides (maximum %)	–	–	8	8
Plasticity of putty when tested within 30 minutes after mixing with water	–	–	200	200
Water retention after suction for 60 seconds (%)	75	75	85	85

Figure 2-10 ASTM C207 requirements for masonry lime. (*Copyright ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428. Reprinted with permission.*)