portland cement or air-entrained hydrated lime (ASTM C207, Type SA). The best defense against freeze-thaw destruction is the elimination of moisture leaks at the joints with high-quality mortar ingredients and good bond, and the use of details which permit differential movement and provide adequate protection at the top of the wall and at penetrations.

Air-entrained cements are used in the concrete industry to provide resistance to freeze-thaw deterioration in horizontal 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 standards for masonry mortar generally limit the air content of mortar to 12, 14, or 18% depending on the mix, the benefits of higher air contents in resisting freeze-thaw damage in paving applications may be greater than the detrimental effects on bond strength. Rigid masonry paving systems are generally supported on concrete slabs, so the flexural strength of the masonry is less important than its resistance to weathering. Lower bond strength could probably be tolerated in such applications in return for increased durability.

6.1.7 Efflorescence and Calcium Carbonate Stains

Efflorescence is the white powdery deposit on exposed masonry surfaces caused by the leaching of soluble salts. If the units and the mortar ingredients contain no soluble salts such as sodium or potassium sulfate, and if insufficient moisture is present to effect leaching, efflorescence cannot occur. To minimize the possible contribution of mortar ingredients to efflorescence, specify portland cements with low alkali content, clean washed sand, and clean mixing water.

Unlike efflorescence, *calcium carbonate stains* are hard encrustations which can be removed only with acid cleaners. Calcium hydroxide is present in masonry mortar as part of the hydrated lime in cement-lime mortars, and as a by-product of the portland cement hydration process itself. Portland cement will produce about 12 to 20% of its weight in calcium hydroxide at complete hydration. Calcium hydroxide is only slightly soluble in water, but when large quantities of water enter the wall through construction defects, extended saturation of the mortar (1) prolongs the hydration process producing a maximum amount of calcium hydroxide, and (2) provides sufficient moisture to leach the calcium hydroxide to the surface. When it reacts with carbon dioxide in the air, the calcium hydroxide forms a concentrated calcium carbonate buildup, usually appearing as white streaks from the mortar joints. The existence of calcium hydroxide in cement-based mortar systems cannot be avoided. Preventing saturation of the wall both during and after construction, however, will eliminate the mechanism needed to form the liquid solution and carry it to the masonry surface.

6.2 MORTAR CLASSIFICATION

Egyptian builders of the twenty-seventh century B.C. first invented masonry mortar, when a mixture of burned gypsum and sand was used in the construction of the Great Pyramid at Giza. Greek and Roman builders later added or substituted lime or crushed volcanic materials, but it was not until the nineteenth-century development of portland cement that mortar became a high-strength structural component with compressive values comparable to the masonry units it bonded together.

6.2.1 Clay Mortars

Clay is one of the oldest materials used in masonry mortar. It has been used historically with sun-dried brick, burned brick, and stone. In North America, clay mortar was often used because of its low cost, but it was also a substitute in some regions where lime was difficult to obtain. Although it is susceptible to deterioration from moisture, clay mortar has long been used in arid climates, and also in humid climates for interior work and for exterior work which can be protected from the rain. Interior chimneys were commonly constructed with clay mortar up to the roof line, and one nineteenth-century specification permitted stone walls to be laid with clay mortar except for the outside 3 in. of walls above ground, and the inside 3 in. of cellar walls, which were to be pointed with lime mortar.

Ground fire clay is still used in mortars where a mild refractory quality is desired. Clay is also used as a proprietary plasticizer for mortar, and the Romans used ground clay from low-fired brick to impart pozzolanic properties to lime-sand mortars.

6.2.2 Lime-Sand Mortars

Mortars consisting of lime, sand, and water were the most common type used until the late nineteenth century. *Lime-sand mortars* have low compressive strength and slow setting characteristics, but offer good workability, high water retention, excellent bond, and long-term durability even in severe climates.

Lime-sand mortars cure and develop strength through a process called *carbonation.* The lime (calcium hydroxide) must combine with carbon dioxide in the air, so curing of the full joint depth occurs very slowly, over a period of months or years, and at variable rates. In the past, slower methods of construction could accommodate this gradual hardening, but modern building techniques and faster-paced production have virtually eliminated the use of lime-sand mortars except in historic restoration projects. Lime-sand mortars, however, were sufficiently flexible to accommodate slight movements caused by the uneven settlement of foundations, walls, piers, and arches. The slow curing permitted a gradual adjustment over long periods of time, and accounts for the greater elasticity of historical masonry compared to contemporary construction.

Hydraulic limes, made from limestone with clay impurities, require less water in slaking and less sand in mortar than pure lime. Hydraulic lime mortars were used extensively in civil construction during the nineteenth century, and particularly in the construction of canals, piers, and bridges. The distinction between hydraulic lime and "natural cement" is almost arbitrary. One natural cement product manufactured in the early nineteenth century, in fact, was called "artificial hydraulic lime." Natural cement rock was burned in kilns similar to those used for producing lime, and the calcined lumps were ground into a fine powder in various patented processes.

Hydraulic lime or natural cement mortars were used in areas where greater strength was required and where the masonry was subject to continuous soil or moisture exposure. Volume shrinkage is high and workability often poor, so natural cement was sometimes used simply as an additive to lime-sand mortars to increase compressive strength.

6.2.3 Portland Cement-Lime Mortars

Since the latter part of the nineteenth century, portland cement has largely replaced hydraulic limes and natural cements in masonry mortars.