lowers both compressive and bond strength, because the air voids decrease surface contact area and bearing area.

Workmanship is a critical factor in bonding. Full mortar joints must assure complete coverage of all contact surfaces, and maximum extent of bond is necessary to reduce water penetration. Once a unit has been placed and leveled, additional movement will break or seriously weaken the bond. Mortars with high water retention allow more time for placing units before evaporation or unit suction alters the plasticity and flow of the mortar. Laboratory tests show that tapping the unit to level increases bond strength 50 to 100% over hand pressure alone.

Because of the many variables involved, it is difficult to develop laboratory tests of bond strength that produce consistent results. In addition to the properties of the mortar, bond strength testing is highly sensitive to unit properties, fabrication procedures, curing environment, and testing technique. Flexural bond strength is presently measured by ASTM C952, *Standard Test Method for Bond Strength of Mortar to Masonry Units* (the crossed brick couplet test), ASTM E518, *Standard Test Method for Flexural Bond Strength of Masonry,* ASTM C1072, *Standard Test Method for Measurement of Masonry Flexural Bond Strength* (the bond wrench test), ASTM C1357, *Standard Test Methods for Evaluating Masonry Bond Strength,* and ASTM E72, *Standard Test Methods of Conducting Strength Tests of Panels for Building Construction* (full-scale wall specimen test). Full-scale wall specimen test results correlate well with the flexural bond strengths obtained using ASTM C1072 and E518. ASTM C1072 is the most widely used test.

A simple field test to check extent of bond can be made by lifting a unit from its fresh mortar bed to determine if the mortar has fully adhered to all bedding surfaces. Good extent of bond is indicated if the mortar sticks to the masonry unit and shows no air pockets or dry areas.

6.1.4 Compressive Strength

Masonry compressive strength depends on both the unit and the mortar. As with concrete, the strength of mortar is determined by the cement content and the water/cement ratio of the mix. Since water content is adjusted to achieve proper workability and flow, and since bond strength is ultimately of more importance, higher compressive values are sometimes sacrificed to increase or alter other characteristics. For loadbearing construction, building codes generally provide minimum allowable working stresses, and required compressive strengths may easily be calculated using accepted engineering methods. Strengths of standard mortar mixes may be as high as 5000 psi, but need not exceed either the requirements of the construction or the strength of the units themselves. Although compressive strength is less important than bond, simple and reliable testing procedures make it a widely accepted basis for comparing mortars. Basically, compressive strength increases with the proportion of cement in the mix and decreases as the lime content is maximized. Increases in air entrainment, sand, or mixing water beyond normal requirements also reduce compressive strength values.

For veneer construction and for two- and three-story loadbearing construction, mortar compressive strength is rarely a critical design factor because both the mortar and the masonry are usually much stronger in compression than necessary. Compressive strength is important in engineered, loadbearing construction, but structural failure due to compressive loading is rare. More critical properties such as flexural bond strength are usually given higher priority.

Although the compressive strength of masonry can be increased by using a stronger mortar, the improvement is not proportional. Tests indicate that wall strengths increase only about 10% when mortar strength increases 130%. There are incentives other than economy which dictate using mortar with only the minimum required compressive strength. An unnecessarily hard, brittle mortar may increase the amount of shrinkage cracking in the wall. A softer mortar with higher lime content is more flexible, permits greater movement, and gives more satisfactory performance as long as minimum requirements are met.

6.1.5 Extensibility and Volume Change

Two other important properties of hardened mortar are extensibility and volume change. *Volume changes* in mortar can result from the curing process, cycles of wetting and drying, temperature change, or unsound ingredients which expand chemically. Available data indicate that expansion and contraction of masonry construction due to differential thermal volume change between units and mortar do not have a noticeable effect on performance. However, total volume change from different causes can sometimes be significant. Stronger mortars that are rich in cement can show substantial shrinkage when exposed to alternate moist-dry conditions. Shrinkage during curing and hardening is greatest with high-water-content mortars. Volume changes caused by unsound ingredients such as reactive chemical compounds can cause disintegration of the masonry.

It is commonly believed that mortar shrinkage is significant, and that it is a primary cause of wall leaks. Research indicates, however, that maximum shrinkage across a mortar joint is minute, and is not in itself a cause of leakage. The most common leakage of masonry walls is through voids at the mortar-to-unit interface, where watertightness depends on a combination of good materials, workmanship, and design. The elastic properties of mortar, in fact, often counteract both temperature and moisture shrinkage.

Extensibility is defined as the amount per unit length that a specimen will elongate (creep), or the maximum unit tensile strain before rupture. Extensibility is sufficiently high in mortar so that when it is combined with the added plasticity which lime imparts to the hardened mix, slight movement can be accommodated without joints opening. For maximum resiliency (such as that required in chimney construction), mortar should be mixed with the highest lime content compatible with design requirements.

6.1.6 Durability

Durability is a measure of resistance to age and weathering, and particularly to repeated freeze-thaw cycles. Mortars with high compressive strength can be very durable, but a number of factors other than strength affect mortar durability. Ingredients, workmanship, volume change, elasticity, and the proper design and placement of expansion and control joints all influence durability and determine the maintenance characteristics of the construction. Although harsh environmental conditions and unsound ingredients can contribute to mortar deterioration, the most destructive factor is expansion of moisture in the wall by freezing. The bubbles introduced by air entrainment absorb the expansive forces of freezing water and provide good assurance against damage, but they also decrease both the compressive and bond strength of the mortar. Masonry cement mortars usually contain entrained air, and cement-lime mortars can be modified by using either air-entrained