8

MASONRY

A masonry structure is formed by combining masonry units, such as stone or brick, with mortar. Masonry is one of the oldest construction materials. Examples of ancient masonry structures include the pyramids of Egypt, the Great Wall of China, and Greek and Roman ruins. Bricks of nearly uniform size became commonly used in Europe during the beginning of the 13th century. The first extensive use of bricks in the United States was around 1600. In the last two centuries, bricks have been used in constructing sewers, bridge piers, tunnel linings, and multistory buildings. Masonry units (Figure 8.1) are still being used in construction in the United States and are competing with other materials, such as wood, steel, and concrete (Adams 1979).

8.1 Masonry Units

Masonry units can be classified as

- concrete masonry units
- clay bricks
- structural clay tiles
- glass blocks
- stone

Concrete masonry units can be either solid or hollow, but clay bricks, glass blocks, and stone are typically solid. Structural clay tiles are hollow units that are larger than clay bricks and are used for lightweight masonry, such as partition walls and filler panels. They can be used with their webs in either a horizontal or a vertical direction. Figure 8.2 shows examples of concrete masonry units, clay bricks, and structural clay tiles. Concrete masonry units and clay bricks are commonly used in the United States.

FIGURE 8.1 Masonry units used in construction.

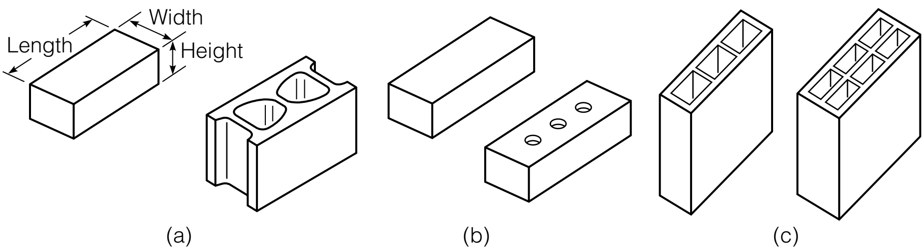

FIGURE 8.2 Examples of masonry units: (a) concrete masonry units, (b) clay bricks, and (c) structural clay tiles

8.1.1 Concrete Masonry Units

Solid concrete units are commonly called concrete bricks, whereas hollow units are known as concrete blocks, hollow blocks, or cinder blocks. Hollow units have net cross-sectional area in every plane parallel to the bearing surface with less than 75% of the cross-sectional area in the same plane. If this ratio is 75% or more, the unit is categorized as solid (Portland Cement Association 1991).

Concrete masonry units are manufactured in three classes, based on their density: *lightweight units, medium-weight units, and normal-weight units,*

TABLE 8.1 Weight Classifications and Allowable Maximum Water Absorption of Concrete Masonry Units (ASTM C90 and C129) (Copyright ASTM, reprinted with permission).

Weight Classification	Unit Weight Mg/m^3 (pcf)	Maximum Water Absorption kg/m^3 (lb/ft^3) (Average of 3 units)
Lightweight	1.68 (105)	288 (18)
Medium Weight	1.68–2.00 (105–125)	240 (15)
Normal Weight	2.00 (125) or more	208 (13)

with dry unit weights as shown in Table 8.1. Well-graded sand, gravel, and crushed stone are used to manufacture normal-weight units. Lightweight aggregates such as pumice, scoria, cinders, expanded clay, and expanded shale are used to manufacture lightweight units. Lightweight units are the most common concrete units used in masonry construction because they are easy to handle and transport, and the weight of the structure is reduced. Lightweight units have higher thermal and fire resistance properties and lower sound resistance than normal weight units.

Concrete masonry units are manufactured using a relatively dry (zero-slump) concrete mixture consisting of portland cement, aggregates, water, and admixtures. Type I cement is usually used to manufacture concrete masonry units; however, Type III is sometimes used to reduce the curing time. Air-entrained concrete is sometimes used to increase the resistance of the masonry structure to freeze and thaw effects and to improve workability, compaction, and molding characteristics of the units during manufacturing. The units are molded under pressure, then cured, usually using low-pressure steam curing. After manufacturing, the units are stored under controlled conditions so that the concrete continues curing.

Concrete masonry units can be classified as load bearing (ASTM C90) and non–load bearing (ASTM C129). Load-bearing units must satisfy a higher minimum compressive strength requirement than non–load-bearing units, as shown in Table 8.2. The compressive strength of individual concrete masonry units is determined by capping the unit and applying load in the direction of the height of the unit until failure (ASTM C140). A full-size unit is recommended for testing, although a portion of a unit can be used if the capacity of the testing machine is not large enough. The *gross area compressive strength* is calculated by dividing the load at failure by the gross cross-sectional area of the unit. The *net area compressive strength* is calculated by dividing the load at failure by the net cross-sectional area. The net cross-sectional area is calculated by dividing the net volume of the unit by its average height. The net volume is determined using the water displacement method according to ASTM C140.

TABLE 8.2 Strength Requirements of Concrete Masonry Units (ASTM C90 and C129)

	Minimum Compressive Strength Based on Net Area MPa (psi)	
Type	**Average of Three Units**	**Individual Units**
Load bearing	13.1 (1900)	11.7 (1700)
Non-load-bearing	4.1 (600)	3.5 (500)

Sample Problem 8.1

A hollow concrete masonry unit has actual gross dimensions of 7-5/8 in. × 7-5/8 in. × 15-5/8 in. The unit is tested in a compression machine with the following results:

Failure Load = 250 kips

Net volume of 366.9 in^3

a. Calculate the gross area compressive strength.
b. Calculate the net area compressive strength.

Solution

a. Gross area = 7.625 × 15.625 = 119.141 in^3
   Gross area compressive strength = 250,000/119.141 = 2,098.4 psi
b. Net area = 366.9/7.625 = 48.118 in^2
   Net area compressive strength = 250,000/48.118 = 5,195.6 psi

The amount of water absorption of concrete masonry units is controlled by ASTM standards to reduce the effect of weathering and to limit the amount of shrinkage due to moisture loss after construction (ASTM C90). The absorption of concrete masonry units is determined by immersing the unit in water for 24 hours (ASTM C140). The absorption and moisture content are calculated as follows.

$$\text{Absorption (kg/m}^3\text{)} = \frac{W_s - W_d}{W_s - W_i} \times 1000 \tag{8.1}$$

$$\text{Absorption (lb/ft}^3\text{)} = \frac{W_s - W_d}{W_s - W_i} \times 62.4 \tag{8.2}$$

$$\text{Absorption}(\%) = \frac{W_s - W_d}{W_d} \times 100 \tag{8.3}$$

$$\text{Moisture content as a percent of total absorption} = \frac{W_r - W_d}{W_s - W_d} \times 100 \tag{8.4}$$

where

W_s = saturated weight of specimen, kg (lb)
W_d = oven-dry weight of unit, kg (lb),
W_i = immersed weight of specimen, kg (lb), and
W_r = weight of specimen as received

Table 8.1 shows the allowable maximum water absorption for load-bearing concrete masonry units.

Sample Problem 8.2

A concrete masonry unit was tested according to ASTM C140 procedure and produced the following results:

mass of unit as received = 10,354 g
saturated mass of unit = 11,089 g
oven-dry mass of unit = 9893 g

Calculate the percent absorption and moisture content of the unit as a percent of total absorption.

Solution

$$\text{Absorption}(\%) = \frac{11{,}089 - 9893}{9893} \times 100 = 12.1\%$$

Moisture content as a percent of total absorption

$$= \frac{(10{,}354 - 9893)}{(11{,}089 - 9893)} \times 100 = 38.5\%$$

Concrete masonry units are available in different sizes, colors, shapes, and textures. Concrete masonry units are specified by their nominal dimensions. The *nominal dimension* is greater than its *specified* (or *modular*) dimension by the thickness of the mortar joint, usually 10 mm (3/8 in.). For example, a 200 mm × 200 mm × 400 mm (8 in. × 8 in. × 16 in.) block has an actual width of 190 mm (7-5/8 in.), height of 190 mm (7-5/8 in.), and length of 390 mm (15-5/8 in.), as illustrated in Figure 8.3. Load-bearing concrete

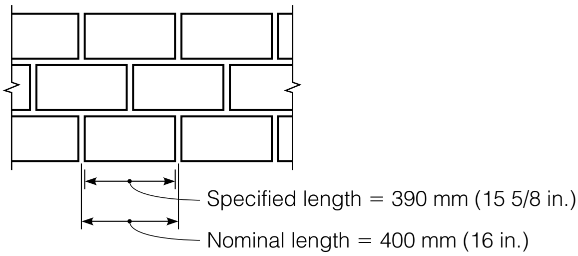

FIGURE 8.3 Nominal dimensions and specified (modular) dimensions.

masonry units are available in nominal widths of 100 mm, 150 mm, 200 mm, 250 mm, and 300 mm (4 in., 6 in., 8 in., 10 in., and 12 in.), heights of 100 mm and 200 mm (4 in. and 8 in.), and lengths of 300 mm, 400 mm, and 600 mm (12 in., 16 in., and 24 in.). Common load-bearing blocks are $200\ \text{mm} \times 200\ \text{mm} \times 400\ \text{mm}$, whereas non–load-bearing blocks are $100\ \text{mm} \times 200\ \text{mm} \times 400\ \text{mm}$, as shown in Figure 8.4. Also, depending on the position within the masonry wall, they are manufactured as stretcher, single-corner, and double-corner units, as depicted in Figure 8.5.

Solid concrete masonry units (concrete bricks) are manufactured in two grades (N and S) based on strength and absorption requirements. Grade N units have higher compressive strength, resistance to moisture penetration, and resistance to frost action than grade S. According to ASTM C55, the minimum compressive strength of individual units is 20.7 MPa (3000 psi) for grade N, and 13.8 MPa (2000 psi) for grade S. Grade N bricks are typically used as architectural veneers and facing units in exterior walls. Grade S bricks are for general use where moderate strength and resistance to frost action and moisture penetration are required.

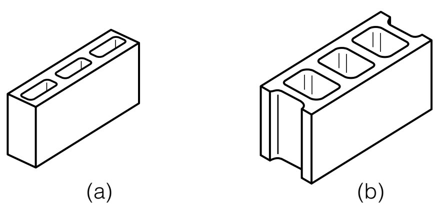

FIGURE 8.4 Concrete masonry units: (a) Non-load-bearing and (b) load-bearing.

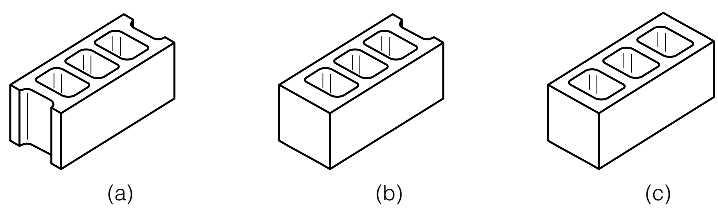

FIGURE 8.5 Concrete masonry units: (a) stretcher, (b) single-corner, and (c) double-corner.

8.1.2 Clay Bricks

Clay bricks are small, rectangular blocks made of fired clay. Clays for brick making vary widely in composition from one place to another. Clays are composed mainly of silica (grains of sand), alumina, lime, iron, manganese, sulfur, and phosphates, with different proportions. Bricks are manufactured by grinding or crushing the clay in mills and mixing it with water to make it plastic. The plastic clay is then molded, textured, dried, and finally fired. Bricks are manufactured with different colors, such as dark red, purple, brown, gray, pink, or dull brown, depending on the firing temperature of the clay during manufacturing. The firing temperature for brick manufacturing varies from 900°C to 1200°C (1650°F to 2200°F). Clay bricks have an average density of 2 Mg/m^3 (125 pcf).

Bricks are used for different purposes, including building, facing and aesthetics, floor making, and paving. *Building bricks* (*common bricks*) are used as a structural material and typically are strong and durable. *Facing bricks* are used for facing and aesthetic purposes and are available in different sizes, colors, and textures. *Floor bricks* are used on finished floor surfaces and are generally smooth and dense and have high resistance to abrasion. Finally, *paving bricks* are used as a paving material for roads, sidewalks, patios, driveways, and interior floors. Paving bricks are available in different colors, such as red, gray, or brown, and typically they are abrasion resistant and could be vitrified.

Absorption is one of the important properties that determine the durability of bricks. Highly absorptive bricks can cause efflorescence and other problems in the masonry. According to ASTM C67 absorption by 24-hour submersion, absorption by 5-hour boiling, and saturation coefficient are calculated as:

$$\text{Absorption by 24-hour submersion}(\%) = \frac{(W_{s24} - W_d)}{W_d} \times 100 \tag{8.5}$$

$$\text{Absorption by 5-hour boiling}(\%) = \frac{(W_{b5} - W_d)}{W_d} \times 100 \tag{8.6}$$

$$\text{Saturation coefficient} = \frac{(W_{s24} - W_d)}{(W_{b5} - W_d)} \tag{8.7}$$

where

W_d = dry weight of specimen,
W_{s24} = saturated weight after 24-hour submersion in cold water, and
W_{b5} = saturated weight after 5-hour submersion in boiling water.

Clay bricks are very durable, fire resistant, and require very little maintenance. They have moderate insulating properties, which make brick houses cooler in summer and warmer in winter, compared with houses built with other construction materials. Clay bricks are also noncombustible and poor conductors.

The compressive strength of clay bricks is an important mechanical property that controls their load-carrying capacity and durability. The compressive strength of clay bricks is dependent on the composition of the clay, method of brick manufacturing, and the degree of firing. The compressive strength is determined by capping and testing a half unit "flatwise" (load applied in the direction of the height of the unit) and is calculated by dividing the load at failure by the cross-sectional area (ASTM C67). In determining the compressive strength, either the net or gross cross-sectional area is used. Net cross-sectional area is used only if the net cross-section is less than 75% of the gross cross section. A quarter of a brick can be tested if the capacity of the testing machine is not large enough to test a half brick. Other mechanical properties of bricks include modulus of rupture, tensile strength, and modulus of elasticity. Most clay bricks have modulus of rupture between 3.5 MPa and 26.2 MPa (500 psi and 3800 psi). The tensile strength is typically between 30% to 49% of the modulus of rupture. The modulus of elasticity ranges between 10.3 GPa and 34.5 GPa (1.5×10^6 psi and 5×10^6 psi).

Building bricks are graded according to properties related to durability and resistance to weathering, such as compressive strength, water absorption, and saturation coefficient (ASTM C62). Table 8.3 shows the three available grades and their requirements: SW, MW, and NW, standing for severe weathering, moderate weathering, and negligible weathering, respectively. Grade SW bricks are intended for use in areas subjected to frost action, especially at or below ground level. Grade NW bricks are recommended for use in areas with no frost action and in dry locations, even where subfreezing temperatures are expected. Grade NW bricks can be used in interior construction, where no freezing occurs. Note that higher compressive strengths, lower water absorptions, and lower saturation coefficients are required as the weathering condition gets more severe, so as to reduce the effect of freezing and thawing and wetting and drying.

TABLE 8.3 Physical Requirements for Building Bricks (ASTM C62) (Copyright ASTM, reprinted with permission).

	Min. Compressive Strength, Gross Area, MPa (psi)		Max. Water Absorption by 5-hour Boiling, %		Max. Saturation Coefficient	
Grade	Average of Five Bricks	Individual	Average of Five Bricks	Individual	Average of Five Bricks	Individual
SW[1]	20.7 (3000)	17.2 (2500)	17.0	20.0	0.78	0.80
MW[2]	17.2 (2500)	15.2 (2200)	22.0	25.0	0.88	0.90
NW[3]	10.3 (1500)	8.6 (1250)	No limit	No limit	No limit	No limit

[1] Severe weathering
[2] Moderate weathering
[3] Negligible weathering

Sample Problem 8.3

The 5-hour boiling test was performed on a medium weathering clay brick according to ASTM C67 and produced the following masses:

dry mass of specimen = 1.788 kg

saturated mass after 5-hour submersion in boiling water = 2.262 kg

Calculate percent absorption by 5-hour boiling and check whether the brick satisfies the ASTM requirements.

Solution

$$\text{Absorption by 5-hour boiling} = \frac{2.262 - 1.788}{1.788} \times 100 = 26.5\%$$

From Table 8.3, the maximum allowable absorption by 5-hour boiling = 25.0%. Therefore, the brick does not satisfy the ASTM requirements.

Facing bricks (ASTM C216) are manufactured in two durability grades for severe weathering (SW) and moderate weathering (MW). Each durability grade is manufactured in three appearance types: FBS, FBX, and FBA. These three types stand for *face brick standard, face brick extra,* and *face brick architecture.* Type FBS bricks are used for general exposed masonry construction. Type FBX bricks are used for general exterior and interior masonry construction, where a high degree of precision and a low permissible variation in size are required. The FBA type bricks are manufactured to produce characteristic architectural effects resulting from nonuniformity in size and texture of the individual units.

Similar to concrete masonry units, bricks are designated by their nominal dimensions. The *nominal dimension* of the brick is greater than its *specified* (or *modular*) dimension by the thickness of the mortar joint, which is about 10 mm (3/8 in.) and could go up to 12.5 mm (1/2 in.). The *actual size* of the brick depends on the nominal size and the amount of shrinking that occurs during the firing process, which ranges from 4% to 15%.

Clay bricks are specified by their nominal width times nominal height times nominal length. For example, a 4 × 2-2/3 × 8 brick has nominal width of 100 mm (4 in.), height of 70 mm (2-2/3 in.), and length of 200 mm (8 in.). Clay bricks are available in nominal widths ranging from 75 mm to 300 mm (3 in. to 12 in.), heights from 50 mm to 200 mm (2 in. to 8 in.), and lengths up to 400 mm (16 in.). Bricks can be classified as either modular or nonmodular, where modular bricks have widths and lengths of multiples of 100 mm (4 in.).

8.2 Mortar

Mortar is a mixture of portland cement, lime, sand, and water. Adding a small percentage of lime to the cement mortar makes the mortar "fat" or "rich," which increases its workability. Mortar can be classified as lime mortar or cement mortar. *Lime mortar* is made of lime, sand, and water, whereas *cement* (or *cement–lime*) *mortar* is made of lime mortar mixed with portland cement (Portland Cement Association 1987).

Mortar is used for the following functions:

- bonding masonry units together
- serving as a seating material for the units
- leveling and seating the units
- providing aesthetic quality of the structure

Lime mortar gains strength slowly with a typical compressive strength of 0.7 MPa to 2.8 MPa (100 psi to 400 psi). Cement mortar is manufactured in four types: M, S, N, and O. Type M has the lowest amount of hydrated lime, whereas type O has the highest amount. The compressive strength of mortar is tested using 50-mm cubes according to ASTM C109. The minimum average compressive strengths of types M, S, N, and O at 28 days are 17.2 MPa, 12.4 MPa, 5.2 MPa, and 2.4 MPa (2500 psi, 1800 psi, 750 psi, and 350 psi) (ASTM C270).

Mortar starts to bind masonry units when it sets. During construction, bricks and blocks should be rubbed and pressed down in order to force the mortar into the pores of the masonry units to produce maximum adhesion. It should be noted, however, that mortar is the weakest part of the masonry wall. Therefore, thin mortar layers generally produce stronger walls than do thick layers.

Unlike concrete, the compressive strength is not the most important property of mortar. Since mortar is used as an adhesive and sealant, it is very important that it forms a complete, strong, and durable bond with the masonry units and with the rebars that might be used to reinforce masonry walls. The ability to bond individual units is measured by the *tensile bond strength* of mortar (ASTM C952), which is related to the force required to separate the units. The tensile bond strength affects the shear and flexural strength of masonry. The tensile bond strength is usually between 0.14 MPa and 0.55 MPa (20 psi to 80 psi) and is affected by the amount of lime in the mix.

Other properties that affect the performance of mortar are workability, tensile strength, compressive strength, resistance to freeze and thaw, and water retentivity. The water retentivity is a measure, according to ASTM C91, of the rate at which water is lost to the masonry units.

8.3 Grout

Grout is a high-slump concrete consisting of portland cement, sand, fine gravel, water, and sometimes lime. Grout is used to fill the cores or voids in hollow masonry units for the purpose of (1) bonding the masonry units, (2) bonding the reinforcing steel to the masonry, (3) increasing the bearing area, (4) increasing fire resistance, and (5) improving the overturning resistance by increasing the weight. The compressive strength of grout is usually about 14 MPa (2000 psi) at 28 days.

8.4 Plaster

Plaster is a fluid mixture of portland cement, lime, sand, and water, which is used for finishing either masonry walls or framed (wood) walls. Plaster is used for either exterior or interior walls. Stucco is plaster used to cover exterior walls. The average compressive strength of plaster is about 13.8 MPa (2000 psi) at 28 days.

SUMMARY

Masonry is one of the oldest building technologies, dating back to use of sun-dried adobe blocks in ancient times. Modern masonry units are produced to high standards in the manufacturing process. While the strength of the masonry units is important for quality control, the strength of masonry construction is generally limited by the ability to bond the units together with mortar. The ability of masonry units to resist environmental degradation is an important quality consideration. This ability is closely related to the absorption of the masonry units.

QUESTIONS AND PROBLEMS

8.1 Define solid and hollow masonry units according to ASTM C90.

8.2 What are the advantages of masonry walls over framed (wood) walls?

8.3 A concrete masonry unit is tested for compressive strength and produces the following results:

Failure load = 593 kN
Gross area = 0.074 m^2
Gross volume = 0.014 m^3
Net volume = 0.006 m^3

Is the unit categorized as solid or hollow? Why? What is the compressive strength? Does the compressive strength satisfy the ASTM requirements for load bearing units shown in Table 8.2?

8.4 A half-block concrete masonry unit is tested for compressive strength. The outside dimensions of the specimen are 7.5 in. × 7.5 in. × 7.5 in. The cross section is a hollow square with a wall thickness of 1 inch. The load is applied perpendicular to the hollow cross section and the maximum load is 46,216 lb.
a. Determine the gross area compressive strength.
b. Determine the net area compressive strength.

8.5 A concrete masonry unit has actual gross dimensions of 7-5/8″ × 7-5/8″ × 7-5/8″. The unit is tested in a compression machine with the following results:

Failure Load = 110 kips
Net volume of 366.2 in^3

a. Is the unit categorized as solid or hollow?
b. Calculate the gross area compressive strength.
c. Calculate the net area compressive strength.

8.6 A half-block concrete masonry unit is subjected to compression until failure. The outside dimensions of the specimen are 190 mm × 190 mm × 190 mm. The cross section is a hollow square with a wall thickness of 38 mm. The load is applied perpendicular to the hollow cross section and the maximum load is 217 kN.
a. Determine the gross area compressive strength.
b. Determine the net area compressive strength.

8.7 A symmetrical hollow concrete masonry unit, with a cross-sectional area as shown in Figure P8.7, is tested for compressive strength. The compressive load at failure is 412 KN. What is the compressive strength in MPa?

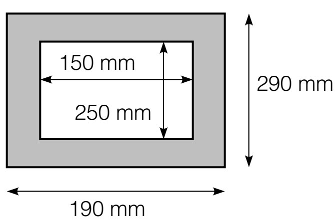

FIGURE P8.7

8.8 A concrete masonry unit has actual gross dimensions of 7-5/8″ × 7-5/8″ × 7-5/8″. The unit is tested in a compression machine with the following results:

Max. Failure Load = 83 kips
Net volume = 312.7 in^3

a. Is the unit categorized as solid or hollow? Why?
b. Calculate the gross area compressive strength.
c. Calculate the net area compressive strength.

8.9 a. Why it is important that, the concrete masonry units meet certain absorption requirements?
b. A portion of a normal-weight concrete masonry unit was tested for absorption and moisture content and produced the following weights:

weight of unit as received = 3.605 lb
saturated weight of unit = 3.939 lb
oven-dry weight of unit = 3.524 lb
immersed weight of unit = 1.684 lb

Calculate the absorption in lb/ft^3 and the moisture content of the unit as a percent of total absorption. Does the absorption meet the ASTM C90 requirement for absorption?

8.10 A portion of a medium-weight concrete masonry unit was tested for absorption and moisture content and produced the following weights:

weight of unit as received = 5435 g
saturated weight of unit = 5776 g
oven-dry weight of unit = 5091 g
immersed weight of unit = 2973 g

Calculate the absorption in kg/m^3 and the moisture content of the unit as a percent of total absorption. Does the absorption meet the ASTM C90 requirement for absorption?

8.11 A portion of a concrete masonry unit was tested for absorption and moisture content according to ASTM C140 procedure and produced the following weights:

weight of unit as received = 7805 g
saturated weight of unit = 8223 g
oven-dry weight of unit = 7684 g
immersed weight of unit = 4027 g

Determine the following:
a. percent absorption
b. moisture content of the unit as a percent of total absorption
c. density
d. weight classification according to ASTM C90 (lightweight, medium weight, or normal weight).

8.12 A concrete masonry unit was tested according to ASTM C140 procedure and produced the following results:

weight of unit as received = 8271 g
saturated weight of unit = 8652 g
oven-dry weight of unit = 7781 g

For this unit, calculate (a) absorption in percent and (b) moisture content as a percent of absorption

8.13 Define the nominal, specified (modular), and actual dimensions of clay bricks.

8.14 State and define the three grades of clay bricks.

8.15 A severe weathering clay brick was tested for absorption and saturation coefficient according to ASTM C67 procedure and produced the following data:

dry weight of specimen = 1.822 kg
saturated weight after 24-hour submersion in cold water = 2.044 kg
saturated weight after 5-hour submersion in boiling water = 2.060 kg.

Calculate absorption by 24-hour submersion, absorption by 5-hour boiling, and saturation coefficient. Does the brick satisfy the ASTM requirements?

8.16 What are the functions of mortar?

8.5 References

Adams, J. T. *The Complete Concrete, Masonry and Brick Handbook*. New York: Arco, 1979.

Portland Cement Association. *Mortars for Masonry Walls*. Skokie, IL: Portland Cement Association, 1987.

Portland Cement Association. *Masonry Information*. Skokie, IL: Portland Cement Association, 1991.

Somayaji, S. *Civil Engineering Materials*. Upper Saddle River, NJ: Prentice Hall, 2001.