Guide for Design and Construction with Autoclaved Aerated Concrete Panels

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Reported by ACI Committee 526

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This guide is intended for use by architects, engineers, contractors, building officials, and manufacturers. Its purpose is to present, in a single source, information that can help those individuals design, specify, and construct with factory-reinforced panels of autoclaved aerated concrete (AAC). In this guide, introductory information on AAC is first presented, followed by a description of its manufacture, guidance on structural design using reinforced panels, and guidance on construction with such panels. The body of this guide ends with an extensive background chapter on the material characteristics of AAC and the structural behavior and design of AAC elements.

Keywords: autoclaved aerated concrete; design; sustainability; shear wall.

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CHAPTER 1—INTRODUCTION

1.1—Introduction

Autoclaved aerated concrete (AAC) is produced as masonry type units where it can be reinforced in the field similar to conventional concrete masonry or as factory-produced panels with reinforcement installed in the factory. Reinforcement for factory-installed panels can be supplemented with reinforcing steel as the panels are assembled in the field. Because design and construction provisions already exist for AAC masonry made from masonry-type units without factory-installed reinforcement, this guide touches only briefly on AAC masonry. Provisions for the design and construction of AAC masonry can be found in TMS 402/602. This guide addresses design, specification, and construction needs for factory-reinforced panels, for which comparable design and construction provisions do not yet exist.

This guide is also intended to be used as a starting point for the development of mandatory-language design provisions, under the mandate of ACI Committee 318 or other committee so designated by ACI. To facilitate that process, the design provisions proposed in this guide, though written in nonmandatory language as required by ACI, are arranged to follow the format of ACI 318.

Fig. 1.3—Macroscopic cellular (void) structure of AAC.

1.2—Historical background of AAC

AAC was first produced commercially in Sweden in 1923. Since that time, its production and use have spread to more than 40 countries in North America, Central and South America, Europe, the Middle East, Asia, and Australia. This wide experience has produced many case studies of use in different climates and under different building codes.

In the United States, modern uses of AAC began in 1990, for residential and commercial projects in the southeastern states. United States production of plain and reinforced AAC started in 1995 in the Southeast and has since spread to other parts of the country.

1.3—Scope and objectives of this guide

AAC, a form of cellular concrete, is a low-density cementitious product of calcium silicate hydrates in which the low density is obtained by the formation of macroscopic air bubbles, mainly by chemical reactions within the mass during the liquid or plastic phase. The air bubbles are uniformly distributed and are retained in the matrix on setting, hardening, and subsequent curing with high-pressure steam in an autoclave, to produce a homogeneous structure of macroscopic voids, or cells (Fig. 1.3). AAC is broken down into classes defined by the unit weight and compressive strength. Material specifications for this product are prescribed in ASTM C1693.

This guide is limited to AAC with a density of 50 lb/ft^3 (800 kg/m^3) or less.

The specific objectives of this guide are to:

a) Review the basic characteristics of AAC
b) Provide a brief history of structural applications of AAC
c) Review the fabrication of AAC panels
d) Recommend structural design procedures for factory-reinforced AAC panels
e) Recommend construction details for use with factory-reinforced AAC panels

The structural design procedures and construction details recommended herein are intended to result in AAC panels with reliable structural capacity, durability, appearance, and overall serviceability.

This guide is limited to AAC with a density of 50 lb/ft^3 (800 kg/m^3) or less. It is written for structural designers and addresses design using factory-reinforced AAC panels. Design of AAC masonry is also addressed in ACI 530/530.1.

The specific objectives of this guide are to:

a) Review the basic characteristics of AAC

b) Provide a brief history of structural applications of AAC

c) Review the fabrication of AAC panels

d) Recommend structural design procedures for factory-reinforced AAC panels

e) Recommend construction details for use with factory-reinforced AAC panels

The structural design procedures and construction details recommended herein are intended to result in AAC panels with reliable structural capacity, durability, appearance, and overall serviceability.

Chapter 2 presents standard notation and definitions. Material and thermal characteristics and an introduction to manufacturing are presented in Chapter 3. A general design overview is presented in Chapter 4. In Chapter 5, handling and erection of panels are addressed. Chapter 6 presents the detailed technical justification for the proposed design provisions. References are presented in Chapter 7. Appendix A provides design examples. In Appendix B, typical design details are used to introduce the reader to specific configurations of the AAC structural elements whose design and construction are addressed by this document.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A = area of wall, in.^{2} (mm^2)

A_s = effective cross-sectional area of horizontal reinforcement in AAC panel, in.^{2} (mm^2)

d = distance from centroid of tension steel to fiber at maximum compressive strain (taken as $0.8\ell_w$ for a shear wall), in. (mm)

d_{cross} = diameter of cross wire in reinforced AAC panel, in. (mm)

d_{long} = diameter of longitudinal wire in reinforced AAC panel, in. (mm)

E_{AAC} = modulus of elasticity of AAC, psi (MPa)

f_{AAC} = tested compressive strength of AAC, psi (MPa)

f'_{AAC} = specified compressive strength of AAC, psi (MPa)

f_{bond} = tensile bond strength of AAC, psi (kPa)

f_c = tested compressive strength of concrete, psi (MPa)

f_g' = specified compressive strength of grout, psi (MPa)

f_r = modulus of rupture of concrete, psi (kPa)

f_{rAAC} = modulus of rupture of AAC, psi (kPa)

f_s = stress developed in horizontal reinforcement of reinforced AAC panel, psi (MPa)

f_t = splitting tensile strength of concrete, psi (MPa)

f_{tAAC} = splitting tensile strength of AAC, psi (MPa)

f_y = specified yield strength of steel reinforcement, psi (MPa)

h_{crack} = height of flexural crack in a shear wall at flexure-shear cracking, in. (mm)

h_{wall} = height of shear wall, in. (mm)

L = length of a beam or floor slab including the support width, in. (mm)

ℓ_{cross} = length of transverse steel in AAC panel, in. (mm)

ℓ_n = clear span of a beam or floor slab, in. (mm)

ℓ_w = plan length of shear wall, in. (mm)

M = moment at the base of shear wall, kip-in. (kN-m)

n_{cross} = number of cross wires

n_{long} = number of longitudinal wires

P = axial force acting on wall, kip (kN)

R-value = thermal resistance of a wall system, h-ft^2°F/Btu (m^{2}K/W)

S = section modulus, in.3 (mm3)

S_{cross} = center-to-center spacing of cross wires (transverse steel) in reinforced AAC panel, in. (mm)

s_h = spacing of longitudinal wires in reinforced AAC panel, in. (mm)

t = specified thickness of shear wall, in. (mm)

U-value = thermal conductivity of a wall system, Btu/h-ft^2°F (W/m^{2}K)

V = shear at the base of shear wall, kip (kN)

V_{AAC} = shear strength provided by autoclaved aerated concrete, kip (kN)

V_c = shear strength provided by concrete, kip (kN)

V_{cr} = base shear at flexural cracking capacity, kip (kN)

V_{ds} = strength of an AAC shear wall as governed by crushing of diagonal strut, kip (kN)

V_n = nominal shear strength of a reinforced concrete section, kip (kN)

V_s = shear strength provided by the shear reinforcement, kip (kN)

V_{ss} = sliding shear capacity of AAC shear wall, kip (kN)

w = horizontal projection of the width of the diagonal strut, in. (mm)

ε_{cs} = drying shrinkage of AAC

μ = coefficient of friction

ρ_{1693} = density of AAC as defined by ASTM C1693

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource. Definitions provided herein complement that source.

autoclaved aerated concrete—cementitious product based on calcium silicate hydrates in which low density is attained by the inclusion of an agent resulting in macroscopic voids and is subjected to high-pressure steam curing.

corrosion-inhibiting coating—acrylic synthetic resin material manufactured specifically for coating smooth wire reinforcement embedded in factory-produced AAC panels; embedded wire cages are generally coated by dipping in the liquid coating after the cages are welded.

thin-bed mortar—mortar for use in construction of AAC unit masonry whose joints should not be less than 1/16 in. (1.5 mm).

CHAPTER 3—TYPICAL MATERIAL AND THERMAL CHARACTERISTICS AND MANUFACTURE OF AAC

3.1—Materials used in manufacturing of AAC

Materials for AAC vary with the method of manufacture and the raw materials available at the location of manufacture and are specified in ASTM C1693 and C1694. They include some or all of the following:
a) Fine silica sand (ASTM C33/C33M, C144, or C332)
b) Class F fly ash (ASTM C618) with up to 12 percent loss on ignition (LOI)
c) Hydraulic cements (ASTM C150/C150M, C595/C595M, or C1157/C1157M)
d) Calcined lime (ASTM C110)
e) Gypsum (ASTM C22/C22M)
f) Expansive agent, such as finely ground aluminum powder or paste
g) Mixing water (clean and free of deleterious substances)
h) Reinforcement (ASTM A82), welded to form cages, with corrosion-inhibiting coating

3.2—Typical mechanical and thermal characteristics of AAC

In Table 3.2, typical mechanical and thermal characteristics of AAC are compared with those of conventional concrete, including conventional concrete made with lightweight aggregates. AAC typically has one-sixth to one-third the density and strength of conventional concrete, making it suitable for cladding and infill panels and for load bearing-wall components of low- to medium-rise structures.

The thermal conductivity of AAC is 13 to 16 times smaller than that of conventional concrete, making it energy-efficient. Its fire resistance is slightly longer than that of conventional concrete of the same thickness, making it useful in applications where fire resistance is important. In addition, the fire resistance of AAC is superior to traditional wood construction.

AAC has excellent acoustical properties. Because of its characteristic high internal porosity, AAC has very high sound absorption. Because of its lower density, AAC is not as resistant to sound transmission as conventional concrete of the same thickness. When typical element thicknesses are used, however, AAC has excellent resistance to sound transmission.

Table 3.2—Typical physical characteristics of AAC

Characteristic	AAC	Conventional concrete
Density,* lb/ft^3 (kg/m^3)	25 to 50 (400 to 800)	90 to 150 (1442 to 2400)
Compressive strength f_c, psi (MPa)	290 to 1100 (2.0 to 7.6)	2500 to 10,000 (17.2 to 69)
Moisture content at after autoclaving	30 percent	—
Moisture content in use	5 to 15 percent	—
Coefficient of thermal expansion, /°F (/°C)	4.5×10^{-6} (8.1×10^{-6})	5×10^{-6} (9×10^{-6})
Coefficient of creep, per psi (per MPa)	5×10^{-7} (0.72×10^{-4})	2.5×10^{-7} (0.36×10^{-4})
Drying shrinkage (ε_{cs} by ASTM C1693)	200 με	300 to 600 με
Thermal conductivity, Btu-in./ft^2-h-°F	0.7 to 1.3	10 to 20
Fire resistance, h (by ASTM E119)	≤ 4	≤ 4

*Throughout this guide, density is defined consistently with ASTM C1693 because AAC is defined by ASTM C1693. In ASTM C1693, what is referred to as density is actually a unit weight, with units of lb/ft3 (U.S. customary) and units of kgf/m3 (old metric). This definition is not strictly correct, nor is it consistent with ACI policy for SI units. It is maintained here for consistency with ASTM C1693.

3.3—Thermal considerations

One of AAC's more desirable properties is that it provides excellent thermal characteristics for energy-saving construction through a unique combination of relatively high thermal resistance and thermal mass in a single continuous material layer. This material characteristic also helps to reduce air infiltration and mitigate thermal bridging, which often plagues multi-layer envelope assemblies with comparable properties. AAC is typically produced in the density range of 25 to 50 lb/ft^3 (400 to 800 kg/m^3) and provides an R-value per inch (millimeter) thickness range of 1.3 to 0.7 h-ft^2°F/Btu-in. (9.0 to 4.9 mK/W), respectively, varying inversely with density (Kosny et al. 2012). At a typical density of 35 lb/ft^3 (560 kg/m^3), the R-value may be taken conservatively as 1.1 h-ft^2°F/Btu-in. (7.6 mK/W) (Behrens and Tanner 2008). R-values per unit thickness quantify the steady-state thermal properties and are the inverse of thermal conductivity k. U-values are the thermal conductivity divided by wall thickness to represent a system's conductivity.

AAC's merits are demonstrated through its dynamic heat transfer performance, within the context of its ability to maintain a constant indoor temperature, despite diurnal temperature swings of the exterior environment. This is accomplished by the high material thermal resistance, which reduces the rate of heat conduction flux Btu/h-ft^2 (W/m^2), as well as the relatively high heat thermal mass, a material property that is derived from the material specific heat, density, and thickness (Aroni 1990). Increasing any of the three latter properties increases the heat capacitance proportionally. Unlike thermal resistance, increasing heat thermal mass does not directly increase the steady-state material resistance to heat flow. Rather, it acts to dampen or delay the transient conduction through the material by requiring that a larger amount of heat from the exterior (source) is used in heating up the material (envelope) before it can increase the interior (sink) surface temperature. Because the amount of heat transferred through the material is proportional to the difference between the surface temperatures, this effectively results in a reduced amount of heat transfer. The result is dynamic mass benefit, where an AAC block wall was dynamically tested by fluctuating the temperature on one surface while measuring the temperature on the other. The

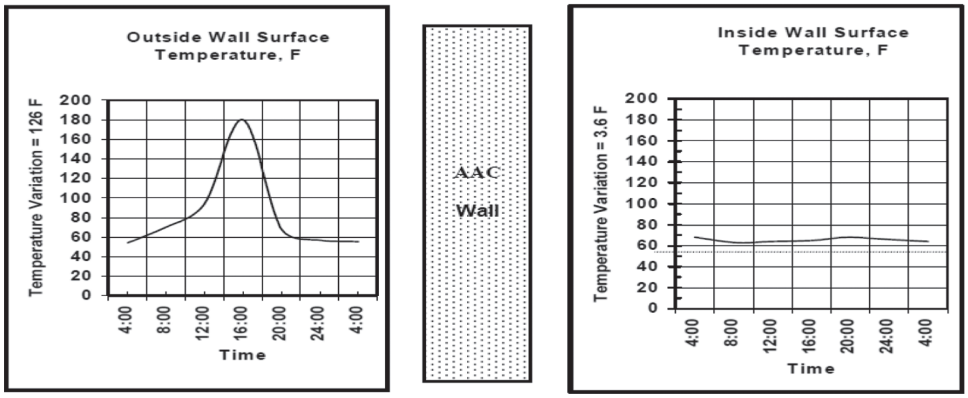

Fig. 3.3—Time-lag thermal mass benefit (Kosny 2000; Kosny et al. 2001). (Note: 1.8°F = 1°C.)

mass dampening effect on heat transfer is clearly visible by both the reduced amplitude and the hourly delay of the inside versus outside temperature peaks, as illustrated in Fig. 3.3 (Kosny 2000; Kosny et al. 2001).

Although traditional concrete possesses excellent structural qualities, it is a relatively poor insulator. In traditional concrete masonry unit (CMU) construction, some type of supplemental insulation, either through insulated cores or continuous exterior or interior insulation, is required for most climates to provide adequate thermal resistance. The Kosny et al. (2012) study demonstrated that 10 to 12 in. (250 to 300 mm) of AAC block provided roughly equivalent thermal performance to a traditional CMU wall with 2.5 in. (64 mm) of continuous expanded polystyrene insulation board. The same study demonstrated that AAC block significantly outperformed CMU block with insulated cores. This is mostly due to the thermal bridging effect of the CMU block webs, which is not present with solid AAC block.

The dynamic benefit for massive systems (DBMS) value was introduced as a multiplier for the steady-state assembly R-value in a study performed by Oakridge National Laboratory. The DBMS value quantifies and presents an effective R-value for an 8 in. (200 mm) thick AAC wall when whole-building energy analysis considers the dynamic envelope behavior that accounts for AACs heat capacitance versus nonmassive systems such as wood frames (Kosny 2000). DBMS is used to define an effective comparison to the performance of wood-frame systems and is specific to a particular climate. Values ranged between approximately 1.5 in climates with lower diurnal temperature swings (Minneapolis, Miami) to approximately 2.5 in climates with high diurnal temperature swings (Phoenix) where thermal mass benefit is more effectively leveraged. Values are compared to a reference value of 1 for wood-frame walls for all climates. This trend is consistent with the action of thermal mass; the dampening of short-term fluctuations is most effective because the period of the temperature reversal being shorter than the time to reach steady-state allows for an internal reversal of the direction of heat flow prior to conduction reaching its peak. This means that diurnal temperature swings are dampened more effectively, than seasonal temperature fluctuations. The mass benefit is magnified by the amplitude of the swing. Large daytime-nighttime swings common in desert climates are better suited for thermal mass construction, where short, intense peaks that are dampened by mass would otherwise quickly transmit a large envelope peak through a lightweight construction.

This broader concept of mass benefit has been known and employed since ancient times, as exemplified in the massive adobe structures of the American Southwest and similar construction in desert climates throughout the world. An additional dynamic thermal mass benefit can be found by shifting the peak wall conduction load to a nonpeak hour. If this does not coincide with other cooling loads such as solar gains, lighting, and occupants, the benefits of thermal mass are further magnified. Kosny et al. (2001) performed a similar study for traditional CMU block and demonstrated that the combination of thermal resistance (R-value) and thermal mass intrinsic to AAC is critical. While AAC saw dynamic benefits in all climates as shown by the preceding study, traditional CMU block saw benefit only in Phoenix, which, despite its higher thermal mass, was not as good as AAC. Furthermore, CMU performed worse than wood frame in all other climates, unlike AAC, which outperformed wood frame in all cases.

ASHRAE 90.1 requires that designers demonstrate that an envelope assembly is compliant. The industry-favored approach is a prescriptive compliance path that provides required assembly U-values and insulation R-values based on climate zone that should be met. An overall assembly U-value should be met or continuous insulation should be provided to a certain value, which increases (or decreases in the case of U-value) with climate zone number. Climate Zone 1 is located in the southern most United States and Climate Zone 8 in the extreme northern United States. Buildings are further subdivided by construction type with four categories: mass; metal panel building; steel frame; and wood frame/all others. ASHRAE 90.1 provides a benefit for mass construction by increasing assembly U-values and decreasing insulation requirements for mass construction, which allows for less thermal resistance than nonmassive construction. This mass benefit is most pronounced in cooling dominated southern climate zones such as Zones 1 and 2, where the ratio of mass to non-mass assembly U-value

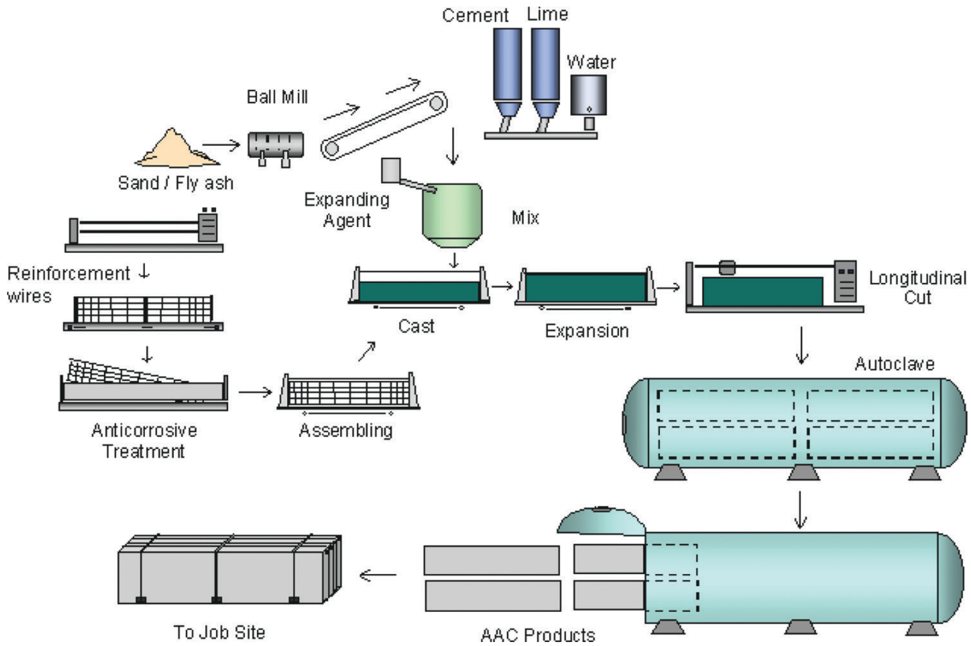

Fig. 3.4—Steps in the manufacture of AAC.

is approximately 6.5:1. As climate zone increases, this ratio decreases until it reaches approximately 1:1 in Climate Zone 7, corresponding to no thermal mass benefit. ASHRAE 90.1 defines a mass wall as a wall with a heat capacity exceeding one of the following two criteria:

a) 7 Btu/ft^2°F (45.2 kJ/m^{2}K)

b) 5 Btu/ft^2°F (32.2 kJ/m^{2}K), provided that the wall has a material unit weight not greater than 120 lb/ft^3 (1922 kg/m^3)

AAC is not specifically listed by ASHRAE 90.1, which includes U-values and heat capacity values for lightweight and normalweight concretes. An area of current research includes both experimental and numerical simulation approaches to provide the necessary performance data to demonstrate AAC code compliance. The goal is to eventually have standardized performance data and parameters incorporated into future codes.

Experimental data have shown AAC with densities ranging from 32 to 35 lb/ft^3 (510 to 560 kg/m^3) is near the lower limit of this mass wall definition at a thickness of approximately 8 in. (200 mm) and greater. Compliance could be estimated using an assembly U-factor of 0.10 (R-10) that would allow AAC to meet the mass-wall thermal criteria for Climate Zones 4 and below (southern United States), but not for 5 and above (Kosny et al. 2012; Ropelewski and Neufeld 1999). Below this thickness, typical AAC might not provide the required heat capacity or U-factor required for prescriptive compliance. Lighter-density AAC also may fall below the required heat capacitance threshold and would, thus, be categorized as other, subjecting it to the more stringent U-factor requirements of traditionally framed wall systems. This would result in a thicker wall assembly if a prescriptive design path were still desired. The other prescriptive path would be to provide the code-required value of continuous insulation, which would unnecessarily penalize AAC because these values are based on the lesser thermal resistance of normalweight concrete.

Another option for designers of AAC structures would be to perform a whole-building simulation against baseline in accordance with ASHRAE 90.1 using energy modeling software. This is a current option for designers of AAC structures to prove energy code compliance. Energy modeling simulation may also be used to assess energy performance for green building programs such as LEED as well as energy cost benefit and life-cycle cost analysis to provide energy data for design decision making and design optimization of AAC structures.

3.4—Manufacture of AAC

Overall steps in the manufacture of AAC are shown in Fig. 3.4. Because the same basic AAC material can be used for unreinforced AAC units (masonry-type units) as well as reinforced panels, information on both types of units is presented in this chapter. The masonry-type units are addressed only briefly for the sake of completeness. Design and construction provisions for AAC masonry units are not addressed by this document. They are addressed in ACI 530/530.1.

3.4.1 *Preparation, batching, and mixing of raw materials*—Sand is ground to the required fineness in a ball mill, if necessary, and is stored along with other raw materials. The raw materials are then batched and delivered to the mixer. Measured amounts of water and expansive agent are added to the mixer, and the cementitious slurry is mixed.

3.4.2 *Casting, expansion, and initial hydration*—Steel molds are prepared to receive the fresh AAC slurry mixture. If reinforced AAC panels are to be produced, steel reinforcing cages are secured within the molds. After mixing, the slurry is poured into the molds. The expansive agent creates small, finely dispersed voids in the fresh mixture, which increases the volume by approximately 50 percent in the molds within 1 hour.

3.4.3 *Cutting*—Within a few hours after casting, the initial hydration of cementitious compounds in the AAC gives

Fig. 3.4.3a—Fresh AAC after removal of molds.

Fig. 3.4.3b—Cutting AAC into desired shapes.

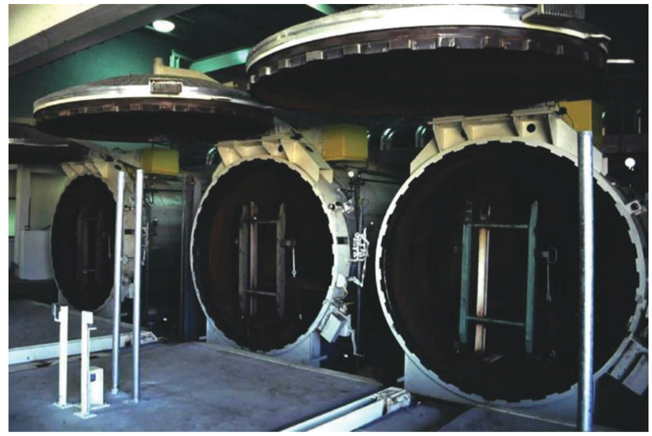

Fig. 3.4.4a—Autoclaving AAC.

Fig. 3.4.4b—Packaging of finished AAC units.

it sufficient strength to hold its shape and support its own weight. The material is removed from the molds (Fig. 3.4.3a) and fed into a cutting machine that uses wires to section the blocks and panels into the required sizes and shapes (Fig. 3.4.3b). After cutting, the units remain in their original positions in the larger AAC block.

3.4.4 *Autoclaving*—After cutting, the aerated concrete product is transported to a large autoclave, where the curing process is completed (Fig. 3.4.4a). Autoclaving is required to achieve the desired structural properties and dimensional stability. The process takes approximately 8 to 12 hours under a pressure of approximately 174 psi (1.20 MPa) and a temperature of approximately 360°F (180°C), depending on the class of material produced. During autoclaving, the wire-cut units remain in their original positions in the AAC block. After autoclaving, the individual units are dimensionally stable and are specified to have a drying shrinkage no more than 0.02 percent (ASTM C1693). They are then separated for packaging (Fig. 3.4.4b).

3.4.5 *Packaging*—AAC units are normally placed on pallets for shipping. Unreinforced units are typically shrink-wrapped whereas reinforced elements are typically banded only, using edge guards to minimize localized damage from the banding.

3.4.6 *AAC strength classes*—AAC is produced in different densities and corresponding compressive strengths, in accordance with ASTM C1693. Densities and corresponding strengths are described in terms of strength classes. In each case, the strength class corresponds to the specified compressive strength in psi (MPa) (Table 3.4.6).