New Masonry Product for the US Designer Emerges – Autoclaved Aerated Concrete

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Abstract

Masonry is one of mankind's oldest building materials serving admirably in construction of shelters, buildings, and monuments for centuries. We marvel at the structures that stand after thousands of years. A testament to that system is the continued use of conventional brick, block and stone in all type and sizes of construction facilities in the USA. The last few years has seen an emergence in the USA of a new addition to the masonry system – Autoclaved Aerated Concrete Masonry.

Autoclaved aerated concrete masonry units are manufactured from Portland cement, quartz sand, water, lime, gypsum and a gas forming agent. The units are steam cured under pressure in an autoclave transforming the material into a hard calcium silicate. The units are large, solid, rectangular prisms which are laid into masonry assemblages using thin-bed mortar.

This paper covers all aspects of this masonry product from production to construction to applications to rational design provisions.

History of Autoclaved Aerated Concrete

The development of Autoclaved Aerated Concrete began at the Technical College in Stockholm, Sweden in 1923. After World War I, Sweden was hit by a dramatic energy crisis and the government responded with legislation for thermal insulation standards for building materials.

The Swedish architect, Johan Axel Eriksson, succeeded in steam curing a mixture of slate, lime, and a small fraction of aluminum powder, creating a new building material called Autoclaved Aerated Concrete (AAC). This process was patented in 1924.

Karl August Carlen, a Swedish building material producer, acquired the license to manufacture AAC from the inventor, Johan Axel Eriksson, in 1928 and started a new production facility in 1929 near the city of Yxhult, Sweden.

This new building material combined the advantages of wood and cement products. It could be cut, drilled, and nailed like wood while maintaining high strength, excellent durability, thermal insulation, sound insulation, and fire resistance. Subsequently, it gained rapid acceptance in Europe and throughout the world.

As this new building product enjoyed major success in Europe other companies started producing Autoclaved Aerated Concrete products under various registered trade names. Major producers throughout the world include companies such as Aercon, Babb, Celcon, Durox, Hebel, Siporex, Svanholm and Ytong. Today there are in excess of 300 manufacturing facilities for AAC around the world, on all continents. A dramatic increase in the demand for new AAC has been observed today, particularly in the view of the energy efficiency and environmental advantages of the product.

Natural disasters such as hurricanes, fires, tornadoes, and earthquakes have, in recent years, triggered the development of new building codes and the search for alternative building products and methods. The devastating results of Hurricane Hugo in 1989 and Hurricane Andrew in 1992 have led to the development of a new building code published in 1993, Standard for Hurricane Resistant Residential Construction. Likewise, the general building code requirements for masonry structures have been substantially improved (ACI 530 / ASCE 7 / TMS 402) which has led to more durable and safer masonry construction in the United States.

Production of Autoclaved Aerated Concrete

A mixture of finely ground sand, cement, unslaked lime (quicklime), anhydrite or gypsum, and a small amount of aluminum powder or paste (aerating agent) are mixed with water to form a slurry.

The slurry is then poured into a steel mold to about two-thirds of the mold's volume. A reaction then takes place in an alkaline environment between the aluminum and water to produce hydrogen gas, H_2. Small air bubbles develop, and as the slurry stiffens, the expanding air bubbles produce a cake-like product which fills the volume of the mold.

When producing reinforced elements such as floor, wall, and roof panels, corrosion protected steel reinforcement is placed into the mold before or shortly after casting.

During what is called the rising process, heat is developed by the cake due to the slaking reaction of the quicklime. This accelerates the setting reaction of the cement, and the "cake" will develop sufficient green strength for handling after approximately two to four hours.

The cake is then sliced horizontally and vertically into the shape of blocks or panels by means of cutting devices such as high tension wires and profiling knives. The sliced cake is then transported into an autoclave where high temperature saturated steam initiates the curing process of the Aerated Concrete material. Typical pressures range from 1.1 to 1.3 MPa (160 to 190 psi) and temperatures range from 190 to 205°C (380 to 400°F).

In the curing process, the finely ground sand reacts with lime and water to form a specific calcium silicate hydrate crystalline structure known as Tobermorite ($C_5S_6H_5$), a naturally occurring mineral. The final result after approximately 12 hours is the finished building material which is ready for packaging, delivery, and installation. No further curing of the material takes place after the autoclaving process.

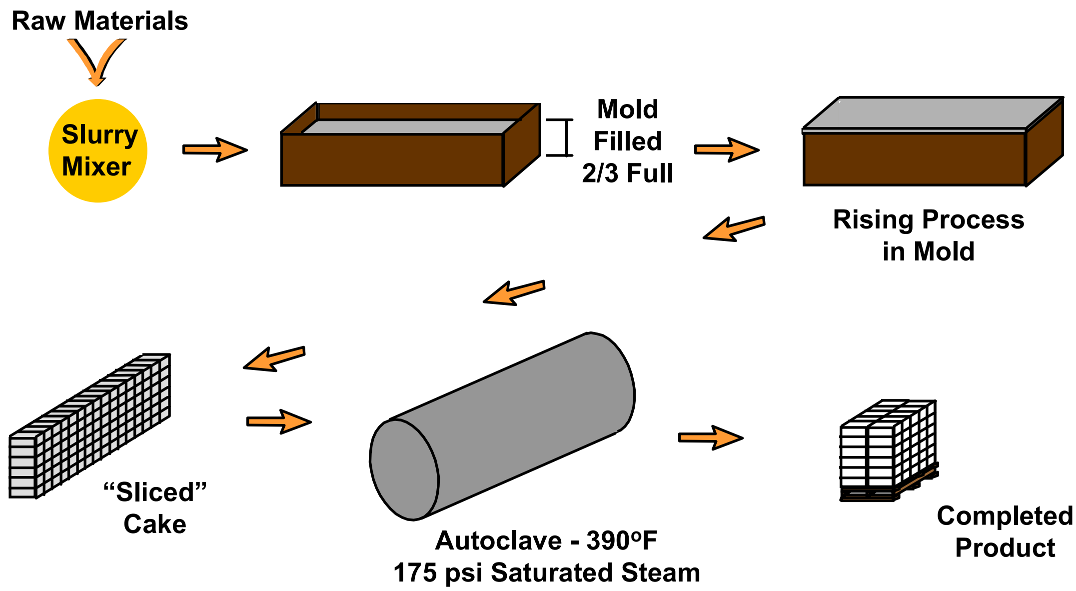

Figure 1. AAC Production

Compressive Strength and Density of Autoclaved Aerated Concrete

AAC products are produced in densities ranging from 400 - 800 kg/m^3 (25 to 50 lbs/ft^3) with compressive strengths ranging from 2 - 6 MPa (290 - 870 psi). The compressive strength and flexural strength requirements are sufficient to build load-bearing, multi-story buildings typically up to six stories.

Strength Class	Minimum Compressive Strength MPa (psi)	Nominal Dry Bulk Density kg/m^3 (pcf)	Density Limits kg/m^3 (pcf)
AAC-2	2.0 (290)	400 (25) 500 (31)	350 (22) – 450 (28) 450 (28) – 550 (34)
AAC-4	4.0 (580)	500 (31) 600 (37) 700 (44) 800 (50)	450 (28) – 550 (34) 550 (34) – 650 (41) 650 (41) – 750 (47) 750 (47) – 850 (53)
AAC-6	6.0 (870)	600 (37) 700 (44) 800 (50)	550 (34) – 650 (41) 650 (41) – 750 (47) 750 (47) – 850 (53)

Table 1. AAC Compressive Strengths and Densities

Product Dimensions of Autoclaved Aerated Concrete

Blocks are produced in various nominal lengths with 24 inches being the most common and thicknesses of 4, 6, 8, 10, and 12 inches. The typical nominal height for blocks is 8 inches, however, 16 and 24 inches can also be produced. Larger blocks placed with the use of a small crane can also be produced, usually approximately 24 inches tall and 40 inches long. Various manufacturers produce slightly different dimensions due to working either in U.S. customary units (inches) or metric. All dimensions should be considered as nominal, as they may vary slightly from one manufacturer to another.

The finished product dimensions are highly accurate, usually within 1/16” of the specified dimensions.

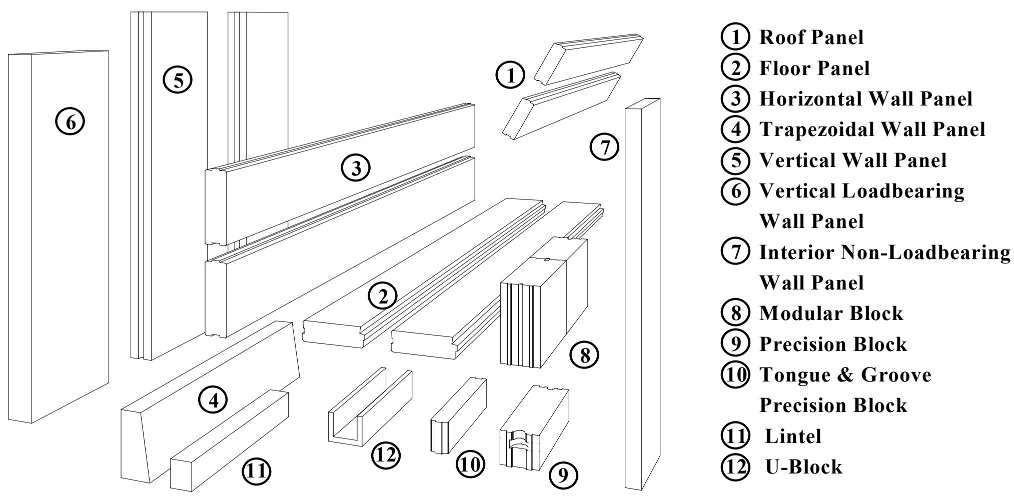

Figure 2. AAC Products - Typical Shapes

Thermal Insulation of Autoclaved Aerated Concrete

Thermal mass damping and time lag are characteristics of materials with significant mass. These characteristics are illustrated in the figure below. Time lag is the time it takes for the temperature on the exterior wall surface (outdoors) to travel to the interior wall surface (indoors). For 8 inch thick AAC walls, a typical time lag would be approximately 6 hours. The damping effect reduces the maximum and minimum temperatures on the interior wall surface (indoors) due to the thermal mass and insulation of the wall material.

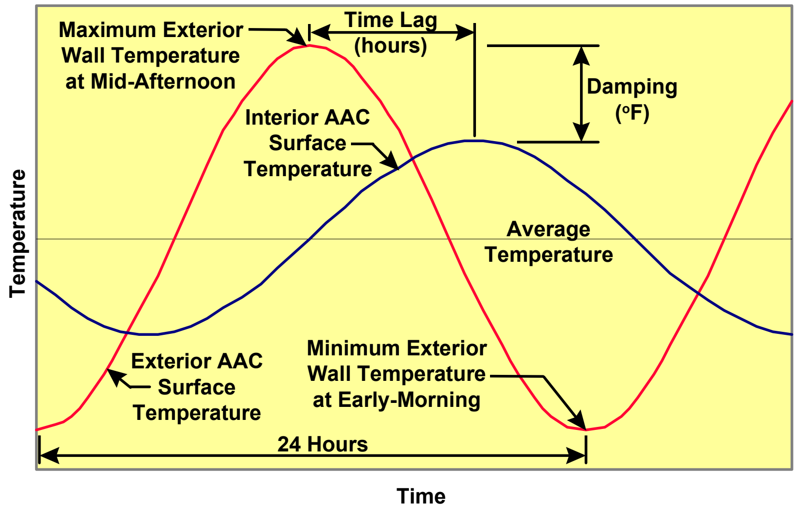

Figure 3. Thermal Mass Damping / Lag

Utilizing a combination of high porosity and thermal mass, AAC represents one of the most energy efficient building materials currently on the market, resulting in major cost savings for heating and air conditioning. This combination gives AAC the ability to moderate the interior climate of a home from the extreme exterior conditions by damping the external thermal peaks and valleys. Therefore, the transmission of the exterior thermal conditions into the interior is substantially reduced.

Fire Resistance of Autoclaved Aerated Concrete

AAC offers one of the greatest fire resistance building materials currently on the market. Fire resistance tests carried out by Underwriters Laboratories have shown fire ratings of 4 hours for 6 inch and thicker block walls.

The fire resistance classifications for AAC were established using a single component system instead of the composite systems required by many fire resistant designs. Therefore, AAC is one of the most effective building materials available for firewall applications.

Autoclaved Aerated Concrete offers the combination of all the properties desired of any building material. The high strength-to-weight ratio, durability, fire resistance and thermal insulation properties make it the ultimate in building materials available on the market today.

Construction and Applications of Autoclaved Aerated Concrete

Autoclaved Aerated Concrete products are equally suitable for residential construction, multi-story buildings, commercial, and industrial applications. It has been used for most types of building construction throughout the world.

Hotels, schools, dormitories, commercial and office buildings are popular types of buildings that utilize AAC throughout their structures. By using a structural product that incorporates the thermal energy efficiency as well as the inherent high fire safety properties, a very cost-effective alternative to conventional construction is achieved. Warehouses also find the thermal and fire resistance properties an added benefit to the fast construction of AAC.

AAC masonry can be utilized in either load or non-load bearing applications. The walls can be reinforced with deformed reinforcing bars in grouted cells, much like conventional masonry construction in order to strengthen the wall for lateral loads from wind or seismic activity. Pilasters can also be built into the walls for added structural resistance.

Structural systems of AAC elements typically fall into 2 general categories; namely reinforced panel elements (roof, wall, floor) and unreinforced / reinforced masonry. Both categories have been successfully used outside the US for many years. Applications in USA have been lacking due to a dearth of U S research data and national code provisions. This situation is changing

Proposed Design Provisions for Reinforced AAC Panels

To be used in conjunction with the concrete code ACI 318, a new document under ACI balloting, ACI 523.5R is a guide that gives specific directions to proposed design provisions for reinforced AAC panels. Those directions include the design equations associated with using reinforced AAC panels under typical structural applications including flexure, axial compression, shear, bearing, bond and development, and seismic conditions. The proposed design provisions are non mandatory and are a synthesis of design recommendations from the Autoclaved Aerated Concrete Products Association and from results of research conducted at the University of Alabama at Birmingham and the University of Texas at Austin.

Proposed Design Provisions for AAC Masonry

Material, construction, and structural provisions for application of unreinforced and reinforced AAC masonry are currently under ballot by the Masonry Standards Joint Committee (ACI 530). Basis for these provisions are the results of research conducted at the University of Alabama at Birmingham and the University of Texas at Austin. Anticipated approval will result in AAC provisions being incorporated in the next edition of the MSJC Code and Specifications (2005). Some highlights of these provisions include:

1) Minimum strength design provisions for both unreinforced and reinforced AAC masonry. The required strength based on strength design load combination of the legally adopted code or by ASCE7-02 is limited to the design strength of the AAC masonry. The design strength is the nominal strength (expected strength) multiplied by strength reduction factor Ø to give a reliable strength capacity. The reduction factors account for uncertainty in

construction material properties, calculated versus actual member strength and modes of failure. As expected, higher reduction factors are associated with reinforced masonry.

2) AAC masonry compressive strength equals or exceeds 290 psi.
3) Grout compressive strength equals or exceeds 2000 psi with an upper limit of 5000 psi.
4) AAC masonry splitting tensile strength

$$f_{t\,AAC} = 2.4\sqrt{f'_{AAC}}$$

5) AAC masonry modulus of rupture

$$f_{r\,AAC} = 2 f_{t\,AAC}$$

6) AAC masonry direct shear strength

$$f_v = 0.15 f'_{AAC}$$

7) Coefficient of friction between AAC and AAC is 0.75.
   Coefficient of friction between AAC and mortar is 1.0
8) Reinforcement yield limited to a maximum 60,000 psi and a maximum bar size of #9
9) Member strength computed using section properties based on a minimum net cross sectional area of the member, based on specified dimensions.

Reinforced AAC Masonry Design Provisions

These provisions govern masonry design where reinforcement is used to resist the tensile forces.

Basic design assumptions include:

- Strain continuity between reinforcement, grout and masonry – composite action
- Nominal strength based on applicable conditions of equilibrium
- Maximum usable strain, εμ, at extreme masonry compression fiber is 0.003 in/in
- Strain in reinforcement and masonry directly proportional to distance from neutral axis
- Reinforcement stress equals Es times steel strain with an upper limit of fy
- Tensile strength of masonry is neglected in flexural strength calculation, but considered in deflection calculations
- Relationship between masonry compressive stress and masonry strain assumed to be as follows:

  A masonry stress of 0.85 f'_{AAC} shall be assumed uniformly distributed over an equivalent compression zone bounded by edges of cross section and a straight line located parallel to the neutral axis at a distance of a = 0.67 c from the fiber of maximum compressive strain. The distance c from the fiber of maximum strain to the neutral axis shall be measured perpendicular to that axis.

Nominal Strengths for Reinforced AAC Elements

- Nominal Axial Strength – Using basic design assumptions above and modifying for slenderness

For members having an h/r ratio not greater than 99:

$$P_n = 0.80\left[0.85 f'_{AAC}\left(A_n - A_s\right) + f_y A_s\right]\left(1 - \left(\frac{h}{140r}\right)^2\right)$$

For members having an h/r ratio greater than 99:

$$P_n = 0.80\left[0.85 f'_{AAC}\left(A_n - A_s\right) + f_y A_s\right]\left(\frac{70r}{h}\right)^2$$

▪ Nominal Flexural Strength – Using the basic design assumption above the flexural strength equation for a rectangular singly reinforced rectangle section would have the form

$$M_n = \text{Ø}\ 0.85\ f'_{AAC}\ ab\ (d - {}^{a}/_{2})$$

$$M_n = \text{Ø}\ A_s\ f_y\ (d - {}^{a}/_{2})$$

The nominal flexural strength at any section along the member is required to be ≥ to ¼ of the maximum nominal flexural strength at the critical section

▪ Nominal shear strength

$$V_n = V_{AAC} + V_s$$

$\leq 6A_n\sqrt{f'_{AAC}}$ for $M_u/V_u\, d_v < 0.25$

$\leq 4A_n\sqrt{f'_{AAC}}$ for $M_u/V_u\, d_v > 1.00$

Nominal Masonry Shear Strength V_{AAC} as governed by web shear cracking

For running bond masonry with mortared head joints

$$V_{AAC} = 0.95\,\ell_w\, t\sqrt{f'_{AAC}}\sqrt{1 + \frac{P_u}{2.4\sqrt{f'_{AAC}}\,\ell_w\, t}}$$

For running bond masonry with unmortared head joints

$$V_{AAC} = 0.66\,\ell_w\, t\sqrt{f'_{AAC}}\sqrt{1 + \frac{P_u}{2.4\sqrt{f'_{AAC}}\,\ell_w\, t}}$$

For other than running bond

$$V_{AAC} = 0.9\sqrt{f'_{AAC}}\,A_n + 0.05\,P_u$$

Nominal Masonry Shear Strength V_{AAC} as governed by crushing of diagonal compressive strut

$$V_{AAC} = 0.17 f'_{AAC} t \frac{h \cdot l_w^2}{h^2 + (\frac{3}{4} l_w)^2}$$ for walls with $M_u/V_u d_v < 1.5$

Nominal Masonry Shear Strength V_{AAC} as governed by sliding shear

$$V_{AAC} = \mu P_u$$

Nominal Shear Strength of shear reinforcement

$$V_s = \left(\frac{A_v}{s}\right) f_y d_v$$

Nominal Masonry Shear Strength as governed by out-of-plane loading

$$V_{AAC} = 0.8 \sqrt{f'_{AAC}}\, bd$$

Some Issues for Specific Reinforced Elements

▪ Reinforced Beams

1. Factored Axial Force ≤ 0.05 $A_n f'_{AAC}$
2. No more than 2 bar sizes allowed
3. Nominal flexural strength ≥ 1.3 times the nominal cracking moment M_{cr}
4. Shear reinforcement required where $V_\mu > Ø\, V_{AAC}$
   - Minimum A_v = .0007 bdv
   - 1st bar located ≤ dv/4 from end
   - Maximum spacing ≤ ½ beam depth or 48″
5. Grouted Solid
6. Beam depth ≥ 8 in

▪Reinforced Columns

1. Longitudial steel = minimum of 4 bars
2. Max $A_s \leq 0.04\, A_n$
3. Min $A_s \geq 0.0025\, A_n$
4. Lateral ties ≥1/4in diam. with spacing of
   - 16 d_b
   - 48 d_t
   - least cross section dimension

▪Reinforced Walls Designed for out-of-plane loading

Walls with factored axial stress of ≤ 0.05 f'_{AAC}

(1) Factored moment & axial force determined at mid height of wall

$$M_u = \frac{w_u h^2}{8} + P_{uf} \frac{e_u}{2} + P_u \delta_u$$

$$P_u = P_{uw} + P_{uf}$$

(2) Design strength is

$$M_u \leq \phi M_n$$

$$M_n = \left(A_s f_y + P_u\right)\left(d - \frac{a}{2}\right)$$

$$a = \frac{\left(P_u + A_s f_y\right)}{0.85 f'_{AAC} b}$$

(3) Deflection – The horizontal mid height deflection , δ_s under service lateral and service axial loads limited to

$$\delta_s \leq 0.007\, h$$

$$\delta_s = \frac{5 M_{ser} h^2}{48 E_{AAC} I_g}$$

$$\delta_s = \frac{5 M_{cr} h^2}{48 E_{AAC} I_g} + \frac{5\left(M_{ser} - M_{cr}\right)h^2}{48 E_{AAC} I_{cr}}$$

$$M_{cr} = S_n\left(f_{rAAC} + \frac{P}{A_n}\right)$$

▪Reinforced Walls Designed For In-Plane Loads

- Amount of Vertical Reinforcement = one half horizontal reinforcement
- Flexural cracking strength computed as

$$V_{cr} = \frac{S_n}{h} \cdot \left(f_{rAAC} + \frac{P}{A_n}\right)$$

- Nominal flexural & axial strength determined as previously presented
- Nominal shear strength determined as previously presented.

Unreinforced AAC Masonry – AAC masonry is used to resist tensile forces.

- Strength design provisions used
- Stress in reinforcement (if exists) not considered effective
- Designed to remain uncracked

● Design Assumptions:

1. Strength design of element for factored flexure and axial load in accordance with principles of engineering mechanics.
2. Strain in masonry directly proportional to distance from neutral axis.
3. Flexural masonry tension directly proportional to strain.
4. Nominal compressive strength shall not exceed a stress of $0.85 f'_{AAC}$.

Nominal Axial Strength of Unreinforced Elements

(a) For members having an *h/r* ratio not greater than 99:

$$P_n = 0.80\left(0.85 A_n\, f'_{AAC}\left[1-\left(\frac{h}{140r}\right)^2\right]\right)$$

(b) For members having an *h/r* ratio greater than 99:

$$P_n = 0.80\left(0.85 A_n\, f'_{AAC}\left(\frac{70\,r}{h}\right)^2\right)$$

Nominal Masonry Shear Strength

Determine the controlling mode of failure considering web-shear cracking, crushing of diagonal compressive strut, and by sliding shear using equations previously presented.

Flexural Cracking Strength – Computed by

$$V_{cr} = \frac{S_n}{h}\cdot\left(f_{rAAC} + \frac{P}{A_n}\right)$$

Summary and Conclusion

AAC has a long successful history of application outside the U. S.. Limited application in the U. S. has been associated with lack of research data and non-existent code provisions. Recent U. S. research on reinforced AAC panels and unreinforced / reinforced masonry assemblages has provided the validation for development of a rational design methodology for structural design of AAC assemblages.

ACI 532.5R is a guide that gives specific direction to proposed design provisions for reinforced AAC panels.

MSJC 2005 will contain material, construction, and structural provisions for application of unreinforced and reinforced AAC masonry.

Now in the USA there is a new addition to the masonry system of design and construction – Autoclaved Aerated Concrete Masonry.