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A Review of Autoclaved Aerated Concrete Products

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A REVIEW OF AUTOCLAVED AERATED CONCRETE PRODUCTS

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ABSTRACT

This report is a review of the properties and performance of
autoclaved aerated concrete. The material has a relatively low
thermal conductivity combined with loadbearing capacity for use
in structural and non-structural applications. This feature may
make its use attractive for energy-conserving applications. For
this reason, the review was conducted at the request of the U.S.
Department of Energy.

The review addressed an overview of the manufacturing process,
uses of autoclaved aerated concrete in building constructions,
properties, energy considerations, the availability of code-related
documents, and standards. Uses include block and panel construction
in both loadbearing and non-loadbearing applications for walls,
floors, and roofs. Many properties are reviewed including
density, fire resistance, moisture expansion and shrinkage,
strength, structure, and thermal conductivity. With regard to
energy considerations, the review points out that, for energy-
efficient applications under severe climatic conditions, the
autoclaved aerated concrete unit alone may be insufficient to
provide the targeted minimum value of thermal resistance. In
these cases, autoclaved aerated concrete has to be used together
with additional thermal insulation. In contrast, autoclaved
aerated concrete alone may satisfy insulation needs in areas
having mild climates.

Key words: aerated; autoclaved; cellular; concrete; insulating
                concrete; lightweight; manufacture; properties;
                review; standards; uses.

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1. INTRODUCTION

Autoclaved aerated concrete (AAC) is a construction material that is factory-made and available to the user in blocks and precast units for walls, floors, and roofs. Blocks for laying in mortar or glue are produced without any reinforcement [1][1]. It has gained widespread use in many areas of the world including Europe, South America, the Middle East, and the Far East. In brief, autoclaved aerated concrete is a porous lightweight concrete whose cellular structure is generally obtained through an in situ gas-producing chemical reaction of a sand and cement slurry. It generally contains no coarse material. Subsequent autoclaving of the material at high temperature and pressure imparts strength, dimensional stability, and other properties of the hardened final product. The autoclaved aerated concrete building material is obtained as the result of a reaction between the binder containing calcium oxide and a silica component cured in an autoclave [2], and a cellular structure producing ingredient. Autoclaved aerated concrete, is at times, referred to as "aerated concrete," "gasbeton," and "autoclaved lightweight concrete (ALC)."

Autoclaved aerated concrete is a type of cellular concrete. Another type, using preformed foam and cast in place, is commonly used in the United States for floor and roof fills. The important properties of autoclaved aerated concrete are present to a large degree in cellular concretes which have not been autoclaved [3].

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[1]Figures in brackets indicate references listed in Section 9.

An often reported advantage [4-7] of autoclaved aerated concrete is the combination of relatively low thermal conductivity, and loadbearing capacity for use in structural applications. Other advantages include relatively low density, high strength-to-weight ratio, nailability, fire resistance, good thermal resistance, and high sound insulation value [8,9]. Its low density permits use of large building units, which is a reported advantage in prefabrication.

The thermal conductivity properties offer potential to conserve energy by reducing building heating and cooling fuel consumption. The potential for energy conservation through the use of an alternative material of construction is of interest to the U.S. Department of Energy (DOE). Consequently, DOE requested the U.S. National Bureau of Standards (NBS) to undertake a study reviewing the properties and use of autoclaved aerated concrete. This report presents the results of the study. The study also provided an occasion to review opportunities for needed research.

1.1 Background

Autoclaved aerated concrete was first introduced commercially over 50 years ago [6,10]. Bessey [4,11,12] has described its early development and use in some detail. Initial development of the products including autoclave curing occurred in the 1920s in Scandanavia, with commercial use commencing in the early 1930s. However, little growth was experienced in commercial applications

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until the mid-1940s and the end of World War II. At this time, its use began to spread in some areas of Europe, in connection with post war building efforts. In subsequent years, expansion continued to many regions of the world. For example, the material was first used in the United Kingdom in about 1950 and by 1965 nine factories were operating under the direction of four different companies [4]. Use in the expansion years of the fifties did not result in U.S. production [13]. In the mid-1960s, autoclaved aerated concrete represented a major portion of all structural materials used in some countries; for example, 20-40 percent in USSR, Germany, Holland, and Sweden [4]. A 1987 estimate placed the amount of autoclaved aerated concrete used annually worldwide at about 8.1×10^8 ft^3 (23×10^6 m^3)[2]. Table 1 provides recent estimates of the annual production of the material for some countries. In 1987, autoclaved aerated concrete was produced in 35 countries[2].

Figure 1 depicts those countries where autoclaved aerated concrete was produced as of 1983 [6]. A notable feature in Figure 1 is the lack of use of autoclaved aerated concrete in Canada and the United States. Reasons for this lack of use have received little documentation in the archival literature. Most of the reasons for lack of use, uncovered during the present study, are anecdotal, coming from individuals who are familiar with the production and use of the material. In general, the

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[2]Gunnar Bave, Siporex, personal communication.

lack of use is attributed to factors associated with production costs and to tradition in the use of conventional building materials. For example, the costs of building a plant to manufacture hollow core concrete blocks may be 20 to 25 percent of the large initial investment to construct an autoclaved aerated concrete plant. In 1968, Bessey [12], writing in his paper on the worldwide development of autoclaved aerated concrete, indicated that the spread of the use of the material into the United States and Canada was marginal. He described the reasons for lack of growth as follows:

"The factors involved are many. Except in dense urban areas, timber still plays a large part in the construction industry in these countries. The concrete block industry is well organized and efficient, and the lightweight-aggregate block is highly competitive in cost and is generally of good quality. An aerated concrete plant must be of good size and have a market which will utilize it at nearly full capacity in order to be economic, for the capital costs and fixed overheads together constitute a high proportion of costs."

Bessey [11] also indicated that general factors affecting global development of autoclaved aerated concrete were partly climatic, partly economic, and partly psychological. Specific factors which he has discussed on this point include: the local building regulations or codes affecting building construction, availability

of raw materials, climatic conditions, fuel and energy requirements, and costs due to production, transportation, erection and maintenance [4,12].

It is interesting to note Bessey [12] indicated that, at the time he was writing (1968), two factories in Canada and one in the U.S. had achieved some minor degree of success. He did not state where these factories were located. The plants referred to by Bessey are not in operation today (Figure 1).

During the period 1955 to 1972 an autoclaved aerated concrete factory operated in Montreal, Canada. Some 54×10^4 ft^3 (15×10^3 m^3) of its reinforced products were imported and used on a variety of building projects in the United States[3].

Renewed interest in autoclaved aerated concrete use has recently occurred. For example, a news item indicated that a 42,000 ft^2 (3900 m^2) facility was completed in 1986 in Florida [14]. The building had autoclaved aerated concrete precast wall and roof panels which were imported from Sweden. The columns and beams consisted of conventional, precast, prestressed concrete. It was reported that the autoclaved aerated concrete components were imported at a relatively high shipping cost. In contrast, labor costs were reportedly saved due to the relative ease and reduction

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[3]Samuel Aroni, University of California at Los Angeles, personal communication.

of time associated with the installation of the lightweight
autoclaved aerated concrete precast planks. The product was not
covered by the building code and therefore a special permit was
needed before the material could be used in Orange County,
Florida [14].

1.2   Objectives

The objectives of this report are:

 (1) to describe the process used in the manufacture of
   autoclaved aerated concrete,

 (2) to present an overview on the use and properties of
   autoclaved aerated concrete products, and

 (3) to provide a listing of standards and related documents
   developed for autoclaved aerated concrete.

1.3   Scope of the Study

The present study was limited to reviewing existing information.
No laboratory or field tests were conducted. The major sources
of information were: (1) the archival chemical and engineering
literature; (2) worldwide building research organizations in
Canada and Europe (including England, Denmark, France, Norway, and
Sweden); (3) discussions with researchers knowledgeable with
autoclaved aerated concrete technology; and (4) literature from
and discussions with representatives of manufacturers of autoclaved
aerated concrete products.

As a construction material which has achieved worldwide use, the body of technical information on autoclaved aerated concrete including research reports, standards, design criteria, codes of practice, and related documents is extensive. A bibliography of archival literature having 492 citations was published in 1983 [15]. The bibliography is included in a Proceedings of an International Symposium entitled "Autoclaved Aerated Concrete, Moisture and Properties" [16]. In 1954, Valore [13,17] gave a review of methods of preparation and physical properties of moist-cured and high-pressure steam-cured cellular concretes, ranging in density from 10 - 100 lbm/ft^3 (160 - 1600 kg/m^3). The review covered three decades beginning in the mid-1920s.

It is noted that at least one process for aerating and autoclaving a lightweight aggregate structural concrete has been described in the literature [18]. This lightweight aggregate concrete has a higher density and greater strength than autoclaved aerated concrete. The scope of the present study precluded a review of this material and other lightweight aggregate concretes.

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2. MANUFACTURE OF AUTOCLAVED AERATED CONCRETE

The manufacture of autoclaved aerated concrete products has been described in the archival literature [1,19-24] and in manufacturers' publications. Although the processes used by different manufacturers are proprietary and have differences between them, the overall procedures of each are considered comparable. The manufacture of autoclaved aerated concrete products is carried out in factories where quality control measures can be implemented regarding materials and handling, as well as the individual steps involved in the overall process.

Production is a continuous process which may be envisioned as having four stages, as shown in Figure 2. The four stages are depicted as: (1) raw materials, (2) molding and cutting, (3) autoclaving, and (4) stocking and shipping.

Raw Materials. The major raw materials are, in many processes, sand and portland cement. In place of sand, other siliceous materials such as sandstone, shale ash, fly ash, and mixtures are often used. For example, fly ash has been substituted for ground sand to the extent of 100 percent[4]. Lime or cement/lime mixtures are at times used instead of portland cement. The raw materials are used as fine powders which are normally obtained through grinding. Grinding may be done either through a wet or dry procedure.

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[4]Poul Nerenst, H + H Industri, personal communication.

Accurately proportioned quantities of the raw materials form the mix. In many cases, a slurry of the siliceous component is made in heated water whose temperature is controlled. The slurry is placed in a mixer into which the cement and/or lime are added. Admixtures such as surfactants and compounds for controlling the rate of cure may also be added.

Generation of the cellular structure is normally done through the addition of aluminum powder as the mixing procedure is ending. The aluminum powder in the alkaline medium (due to the cement or lime) produces hydrogen gas which, in turn, generates the cells. The addition of the aluminum powder is controlled so that gassing does not begin during mixing, but during the molding stage. For example, one control technique uses aluminum powder surfaced with a layer to delay the reaction with the alkalies. Other methods for producing the cellular structure are the introduction of a preformed foam into the mix, or the incorporation of air by whipping [1].

Molding and Cutting. The mixture (from stage 1) is put into steel molds where the production of hydrogen begins and the mass expands, creating the aerated cellular structure. The expanded mass is allowed to set to a soft cake under controlled temperature and humidity conditions. The reaction time for expansion and setting is 30 minutes to a few hours (about 1

to 4) depending upon the raw materials. After setting, the cake is cut into the dimensions of the final product (e.g., block or panel units) using highly strung wires (piano wires) or multiple circular saws.

If the final product is to be used for structural applications, steel reinforcement is placed in the mold before casting the autoclaved aerated concrete. The factory procedure allows accurate placement of the reinforcement in the molds so that the set cake may be cut into the intended dimensions without damage. The steel reinforcement is protected from corrosion, normally by coating [25]. For example, one process uses a coating based on portland cement, latex, and finely ground sand. Another process uses a bituminous compound.

Autoclaving. The third stage of the process is the autoclaving whereby the aerated concrete cures to its final strength and dimensions. Autoclaving changes the physical-chemical nature of the hydrated cement materials and produces a material with lower drying shrinkage [26]. The conditions for autoclaving vary somewhat for different proprietary products. In general, the temperature is about 356°F (180°C) at a pressure of about 10 - 12 atmospheres (1.0 - 1.2 MPa). The time varies depending on the size and density of the products, and may range from about 10 to 20 hours. Storage of the uncured cake, even through moist and warm,

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for more than 2 or 3 days prior to autoclaving may be detrimental [27].

Stocking and Shipping.   After the cured units are removed from the autoclave, quality assurance tests are normally conducted.   Also, if desired, additional shaping through milling or related means may be carried out and a surface finish may also be applied.   After autoclaving and cooling the units are ready for use without storage.   If not needed immediately after production, the units are stored at the factory site and then delivered to the job site for installation.

3. USES OF AUTOCLAVED AERATED CONCRETE

The factory-made autoclaved aerated concrete units delivered to the job site are of different types and have many uses. The types of units most commonly produced are blocks and precast panels for floors, walls, and roofs. Less often, complete modular room units are produced in the factory from wall, floor, and roof panels. The blocks and panels are used in both loadbearing and non-loadbearing constructions for both residential and commercial/industrial buildings. As a consequence, autoclaved aerated units are found in single and multi-story constructions oriented both horizontally and vertically. Larger units are reinforced with steel bars or welded mats to resist damage due to superimposed loads and from transportation and handling [8]. It also has been used as an extra layer of insulation for other components of the building envelope [28].

Blocks and panel units are manufactured to very close dimensional tolerances [29]. For example, the French Standard (NF P 14-306) for autoclaved aerated concrete blocks for walls requires that the dimensional tolerance of the length be ± 0.1 in. (± 3 mm) for a minimum block length of 30 in. (760 mm). Close dimensional tolerence is important with regard to modular construction to assure that individual units fit together properly. Consequently, the sizes of the factory-produced units are generally based on a modular system of standard products. One reference points out that the modular construction concept provides for simple and

fast construction, comparatively low costs, and good architectural possibilities [30]. Any deviation from the standard sizes of units could lead to extra costs. As an example of construction efficiency, Nettleton [31] has indicated that a team of eight persons erected, on a prepared foundation, all wall, floor, and roof units for a block of 12 flats in 18 working days. The units were basically 2 ft (0.6 m) wide and of varying lengths up to 16 ft (5 m).

Construction time is shortened and building costs reduced by increasing the size of panels [32]. The use of large panels results in a reduction in the number of joints and less manual labor is involved on site.

3.1 Blocks

A general application of autoclaved aerated concrete has been in the form of masonry block. Blocks are available in standard sizes and generally do not contain reinforcement [21]. They have been widely used for side cladding and as "in filling" for external walls, as well as for external and internal loadbearing walls in low and multi-story construction. In early constructions, blocks were laid using mortar joints. In later uses, construction techniques expanded to include use of thin glue joints (0.08 - 0.1 in. or 2 - 3 mm) in place of mortar joints [33]. This technique was possible because of the dimensional precision of the blocks.

Since autoclaved aerated concrete blocks are of relatively low weight, they are often somewhat larger than concrete masonry units manufactured in the United States. Due to the cutting process during manufacture, the blocks may have an architectural surface (often referred to as a wire cut or scratched surface) [34]. This surface allows the use of the blocks without a decorative rendering or parging. External surfaces of autoclaved aerated concrete should be protected from exposure to water.

3.2 Panels

As previously mentioned, autoclaved aerated concrete panels are manufactured in various sizes and are used in vertical and horizontal applications in building construction. Vertical wall panels are available in "story-height" increments, and have been used in loadbearing applications up to three or four stories high [1,10]. Wall panels are also laid up horizontally. These panels normally do not carry any load other than their own dead weight.

Another common use of autoclaved aerated concrete is for roof and floor slabs. These panels have span lengths of 20 - 25 ft (6 - 7.6 m) [10]. During erection, the slabs are commonly placed, direct from a truck, on loadbearing walls or a structural frame without use of a mortar bed. Bituminous roofing membranes have been applied directly to assembled roof panels [1,34]. Regarding this practice, it has been reported that the autoclaved aerated concrete panels fit closely together and serve as thermal

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insulation [34]. The design of the roof should consider movement between adjacent panels to prevent splitting of the roofing membrane [1,35]. In the conduct of the study, reports addressing the performance of roofing membranes applied directly to autoclaved aerated concrete panels were not found in the literature.

Autoclaved aerated concrete panels are also accepted in several countries for basement walls below ground level [1]. For this application, precautions must be taken to allow moisture present during manufacturing to dry from the walls. One method involves the application of impermeable protection on the outside of the wall below ground level.

In concluding the remarks on autoclaved aerated concrete in panel construction, it is pointed out that this practice in the 1960s involved the use of large-sized panels. For example, in 1965, Bave [36] described European panels having widths up to 5 ft (1.5 m) and lengths up to 26 ft (8 m). With thickness up to 10 in. (25 cm), large panels might weigh about 2 tons (1800 kg). In Russia, where considerable autoclaved aerated concrete is used for both industrial and residential buildings, the panels were even larger, with spans up to 40 ft (12 m) [37]. However, as far back as the late 60s, it was recognized that excessively large panels could have a serious drawback, with cracking sometimes occurring during manufacture or in-service [32]. Recently, in 1980, Bave [38] noted that the trend of using large panels, as

occurred of the sixties seems to be broken, at least in the
countries in Western Europe. The demand for large panels
decreased due to architectural preferences and cost considerations.
At present, the use of large panels is mainly in industrial
constructions.

3.3 Limitations

Although autoclaved aerated concrete has been a long-accepted
construction material, the literature is not without reference to
limitations in its use. For example, used in modular units, any
deviation from standard sizes could lead to extra costs [30].

Some limitations have been reported by Tietz [39], including:
the material chips easily; the face tends to get damaged easily,
e.g., from scaffolding; dowels are required between units; the
external face is hygroscopic and needs a protective coating which
can breathe and should be protected from standing water, bottom
units should be protected from splash back; units absorb enormous
quantities of paint; anchorage of units needs careful planning to
prevent pullout, especially for dynamic loads; the face is weak
and any tough surface may pull away due to the interface pulling
off the parent material. Finally, it should be mentioned that
caution should be exercised in transporting and handling the
units to avoid damage [30,40].

3.4   Design Considerations

3.4.1   The European Experience

A manual entitled, "Autoclaved Aerated Concrete-Design and
Technology" was produced by the Euro-International Committee for
Concrete (CEB) [1]. As indicated in the Preface, the manual is "a
source of information on the technology of this material and
methods of construction associated with it, but it is not
directly referable to the Code," (i.e., the CEB-International
Federation for Prestressing (FIP) Model Code for Concrete). The
manual addresses the manufacture and properties of aerated
concrete, design considerations, and economic considerations.
Many typical construction details and application photographs are
presented.

The manual indicates that codes and practices in some countries
give advice on calculation methods for allowable stresses in
autoclaved aerated concrete structural members [1]. It also
advises to check the design principles for autoclaved aerated
concrete structural units with full-scale tests. Results of
testing of autoclaved aerated concrete under dynamic repeated
loads indicate that the fields of application of this material
must be chosen carefully [41].

Briesemann [42] in his paper concerning criteria for the design
of structural elements of autoclaved aerated concrete indicated
that knowledge relating to their design is not yet complete. He

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stated that structural elements of this material have been used in buildings for over 50 years and they have proved to be satisfactory in practice. With regard to reinforced structural elements, there is a lack of knowledge about the effects of loads applied to only part of the surface of a component and about the design for simultaneous loading by shear and torsional forces. Briesemann stated further that known design rules have not been verified by scientific experiments like those for reinforced concrete structures and may allow for excessively large safety coefficients. This applies, for example, to the coefficient of creep (ratio of the creep deformation to the elastic deformation) of masonry constructions of autoclaved aerated concrete blocks [42].

3.4.2 The U.S. Experience

As previously noted, autoclaved aerated concrete precast units are not presently produced in the United States and Canada. The American Concrete Institute (ACI) publication entitled, "Guide for Low Density Precast concrete Floor, Roof, and Wall Units," outlines practices of design and fabrication of low density, 50 lbm/ft^3 (800 kg/m^3) and under, precast reinforced concrete floor, roof, and wall units which will result in members of adequate load capacity, durability, appearance, and over-all serviceability for the function intended [43]. Both cellular and low density aggregate precast concrete are included in the guide. Units covered by the guide should be protected from the free entry of water. The guide gives allowable design stresses for concrete

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and reinforcement and provisions for anchorage of tensile steel reinforcement. Other provisions are given such as corrosion protection for reinforcement, permissible span deflections, and test of individual flexural units. The compressive strength of the low density concrete used in precast units should have a minimum compressive strength of 300 lbf/in^2 (2.1 MPa). The design allowable stresses in the concrete should conform to the requirements of ACI 318 [44], except for shear stress permitted in an unreinforced web and the compressive stress allowed in low density precast concrete load bearing walls. Dunn [26] discussed some provisions of the ACI guide [43] with regard to precast autoclaved aerated concrete units and he also discussed some physical properties of these units.

The Council of American Building Officials (CABO) and the U.S. Department of Housing and Urban Development (HUD) have issued a report [45] and a Materials Release [46], respectively, for the use of a proprietary autoclaved aerated concrete. The CABO report defines allowable uses for roof, floor, curtain wall, and partition panels and blocks. The HUD Materials Release is for a thin-joint block wall system.

3.4.3 Moisture Considerations

Autoclaved aerated concrete contains moisture from the manufacturing process. The moisture content at the time of delivery to the building site may be 20 - 35 percent by weight (10 - 18 percent

by volume) [1]. The moisture dries out gradually in normally one to two years and reaches equilibrium in external constructions of about 4 - 6 percent by weight (2 - 3 percent by volume) [1]. Moisture may also accumulate in the material during construction and after the building is completed (e.g., from rain and condensation). It is necessary to assure that the design provides for drying out of the initial moisture as well as maintaining low moisture content in the building under service conditions. One literature reference indicated that, if the inside humidity is 60 percent or less, the use of autoclaved aerated concrete is practically unlimited [22]. Higher humidity requires measures to limit vapor diffusion. In general, autoclaved aerated concrete in equilibrium with a normal environment (65 percent R.H. and 68°F or 20°C) tends to have a moisture content of about 3 percent by volume [47].

As indicated in the ACI Guide 515.1R-79, concrete masonry walls above grade should normally be painted on the exterior for dampproofing purposes [48]. Because of the higher porosity and moisture absorption of autoclaved aerated concrete, as compared to dense concrete, a surface treatment should be considered for exterior surfaces of autoclaved aerated concrete masonry and wall panels. The external treatments that are currently used are mortar for masonry walls and paints for wall panels [1]. The paint used should be nearly impermeable to water but should have some permeability to water vapor so that, if moisture should

become trapped or condensed within the wall, it can slowly escape to the exterior. Protections for masonry have included one to three coats of mortar (not exceeding 0.8 in. or 20 mm) for external application, and for internal use, a thin application of resin or gypsum plaster, lime mortar, or paint [1,49].

For decorative purposes, ceramic tiles, colored sand or granite, marble chips, broken glass, and other materials can be used on wall panels [37]. External walls may also have a prefinished surface [50].

4. PROPERTIES OF AUTOCLAVED AERATED CONCRETE

The physical and mechanical properties of autoclaved aerated concrete may be made to vary over a considerable range, depending on the quantities of the raw materials used, the mix design, and curing conditions [17,18]. It is important to note that many properties of cellular concrete can be given as functions of bulk density and thickness [24,51]. This section of the report presents a brief summary of the most often reported properties of autoclaved aerated concrete. A summary table of property values has not been provided because of their wide variation between products due to factors such as density, structure, thickness, moisture, raw materials, and production conditions. The properties summarized herein are based essentially on the list given in the CEB Manual [1]:

- o Capillarity
- o Coefficient of Thermal Expansion
- o Cracking
- o Creep
- o Density
- o Deterioration Resistance
- o Fire Resistance
- o Frost Resistance
- o Moisture Expansion and Shrinkage
- o Moisture Migration
- o Permeability
- o Shaping and Working

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o   Specific Heat

o   Solubility in Water

o   Sound Absorption

o   Strength (compressive, tensile, shear and bond, modulus
     of elasticity)

o   Structure

o   Temperature Resistance

o   Thermal Conductivity

4.1 Capillarity

Capillarity is important for wetting and drying out the materials.
The capillary suction is slow in aerated concrete compared with some
other porous materials such as clay bricks [1]. Capillary
suction takes place almost exclusively through the micropores in
the cell walls and is negligible for the macropores [1].

4.2 Coefficient of Thermal Expansion

The coefficient of linear thermal expansion for autoclaved
aerated concrete is 4.5×10^{-6} per °F (8×10^{-6} per °C) compared
to 6.8×10^{-6} per °F (12×10^{-6} per °C) for mild steel reinforce-
ment [6,21,28]. Dense concrete and steel have about the same
value of coefficient of linear thermal expansion.

4.3 Cracking

One of the major concerns with autoclaved aerated concrete is
that of cracking, both externally and internally [28]. Cracking

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may be caused by shrinkage, creep, temperature, moisture effects,
or by deformation and settlement of foundations. It is not
always possible to separate the causes and effects of cracking.
The repair of cracks in occupied houses and apartments can be
difficult and expensive. In a study by Cividini [52], it was
reported that prestress of autoclaved aerated concrete slabs, due
to differential drying and cooling after autoclaving, may in some
cases increase crack resistance to such an extent that the slab
cross-section may remain without cracks during its service life.

4.4 Creep

For all autoclaved materials, creep is low in relation to the
elastic deformation [18]. Factors affecting creep of autoclaved
aerated concrete are stress level, moisture content, ambient
temperature and relative humidity. A creep coefficient (creep
strain divided by the momentary deformation) is indicated as 0.8
to 1.2 for autoclaved aerated concrete having a density of 31 lbm/ft^3
(500 kg/m^3) [1]. According to Kruml [53], factors influencing the
quantitative value of creep have not been sufficiently defined
and evaluated. For this reason, he noted that the creep coefficient
often differs in the literature. Also, creep is indicated to be
proportional to the applied stress up to a stress of approximately
50 percent of the strength of the autoclaved aerated concrete [1].

In creep studies by Nielson [54] using unreinforced beams, he
reported creep coefficients, after one year for dry material at

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43% R.H., that ranged from 0.2 to 0.3. For water-saturated material, the creep coefficients ranged from 0.2 to 0.6. These values are somewhat less than those found for normal concrete.

In a study by Houst, Alou, and Wittmann [55], larger creep deformations for moist specimens were reported than for dry ones.

4.5 Density

Density of autoclaved aerated concrete generally refers to oven-dry material. At the time that the material is delivered to the building site, the practical density is higher because of the moisture content and presence of any reinforcement. The density of autoclaved aerated concrete is normally reported in the range of 19 - 62 lbm/ft^3 (300 - 1000 kg/m^3), with 31 lbm/ft^3 (500 kg/m^3) or more being the most common density for load-bearing products and reinforced flexural members [1,56]. Bave [38] reported in 1980 that a density of 22 lbm/ft^3 (350 kg/m^3) is now used for structural units of autoclaved aerated concrete such as loadbearing walls, floors, and roofs. The dry density of the solid material (without pores or air cells) is 150 lbm/ft^3 (2500 kg/m^3).

4.6 Deterioration Resistance

Autoclaved aerated concrete, because of its porosity and relatively low alkalinity (pH = 9 - 10.5), does not provide the same corrosion protection of reinforcement as that provided by dense concrete [1].

Thus, it is recommended that reinforcement should be protected against corrosion by adequate surface treatment [1]. In areas of relative humidity less than 50 percent at equilibrium moisture content, corrosion of reinforcement is reported likely to be negligible [1].

There also may be a risk of corrosion of nails and steel anchors because of the initial moisture content of the material, or moisture from condensation or rain penetration [1]. Acids in the form of liquid and gases penetrate aerated concrete more easily than dense concrete and their deteriorating effect is more rapid than for dense concrete. Autoclaved aerated concrete should therefore be protected from acidic liquids or fumes. The porous structure of autoclaved aerated concrete allows air to penetrate the material readily and, depending on the availability of carbon dioxide and atmospheric humidity, a decrease in alkalinity of the material occurs [25]. During autoclave treatment in high pressure steam, a reaction takes place between the calcium hydroxide and finely ground silicate aggregate components to form calcium silicate hydrates. Because of this reaction, the lime availability is greatly reduced and the calcium hydroxide content of the concrete is lowered. Thus, it was found that 10 in. (24 cm) thick autoclaved aerated concrete members had been carbonated throughout after only two years of service [25]. The CEB Manual [1] indicates that carbonation of autoclaved aerated concrete is generally not of concern if the carbon dioxide content of the air

is as normally expected (0.03 percent). For carbon dioxide
concentrations above about 0.2 percent, carbonation of the
calcium silicate hydrate of fresh, moist autoclaved aerated
concrete can proceed rapidly and may lead to shrinkage cracking
[1]. Manufacturer's recommendations should be followed if
autoclaved aerated concrete is to be exposed to carbon dioxide
concentration above about 0.2 percent.

One literature reference has noted that autoclaved aerated
concrete is resistant to insects, termites, and fungi [21].

4.7 Fire Resistance

Autoclaved aerated concrete is non-combustible [1]. Because of
its low thermal conductivity, heat migration takes place at a
much lower rate than in dense concrete. Consequently, the fire
ratings for autoclaved aerated concrete units issued in some
countries in Europe indicate that this material provides for very
good fire resistance compared to other building materials [1,28].
One reference [21] indicated that, for the same thickness, the
use of cellular concrete in place of normal concrete has been
reported to increase the fire resistance by 30 to 40 percent. In
comparison, another reference [8] stated that a 4.0 in. (10 cm) thick
aerated concrete slab gives fire resistance of 2 hours against
one hour for an 4.4 in. (11 cm) thick brick wall or a 4.0 in.
(10 cm) thick normal concrete slab. As another example of the
fire rating of autoclaved aerated concrete, the Fire Offices

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Committee in the U.K. recognizes that a 6.0 in. (15 cm) thick
loadbearing fire break of the material will give six hours fire
resistance [3]. The fire rating of loadbearing roof and floor
flexural units depends upon density and the thickness of the
cover of the reinforcement. Autoclaved aerated concrete may be
used as a cladding to protect other materials such as steel
members or to increase the fire rating of normal concrete walls
[1].

In the early 1960s, the U.S. National Bureau of Standards
conducted fire tests of lightweight, cellular precast concrete
(reportedly of the in situ gas-forming type) panels for floors
and roofs [57]. It was found that fire endurances were up to 2
hours for 6 in. (15 cm) thick slabs tested under load, and up to
4 hours for other slabs not loaded. It was also found that,
within the narrow density range of 35 - 50 lbm/ft^3 (560 - 800
kg/m^3), slabs made of higher density cellular concrete provided
longer fire endurance than those of lower density, both in terms
of heat transfer through the slab and in terms of continued
structural stability. The use of greater cover for the reinforcing
bars, in the range of 3/4 to 1-1/4 in. (19 to 32 mm), even
without increasing the total thickness of the cellular concrete,
will result in longer fire endurance.

4.8   Frost Resistance

The extensive use of aerated concrete in countries with cold
climates indicates that the material has resistance to frost.
Nevertheless, a risk of frost damage exists if the moisture
content in any part of the construction unit exceeds the critical
moisture content of the autoclaved aerated concrete.   The
critical moisture content can be considered as the moisture
content of the material at which, upon freezing and thawing, a
loss in strength properties or damage occurs.   The critical
moisture is, for example, about 40 percent by volume for aerated
concrete manufactured in Sweden with a density of 31 lbm/ft^3
(500 kg/m^3) [1].   However, the moisture content is usually
highest during construction, rarely exceeding 15 - 20 percent by
volume, before drying out takes place [1].   Under extreme
conditions, higher moisture contents may occur close to the
surface of the unit which increases the risk of frost damage.
Edlind [28] reported that heavier autoclaved aerated concretes
are satisfactory with regard to frost resistance but at densities
below about 31 lbm/ft^3 (500 kg/m^3) liability to frost damage
increases.

From tests of 30 cycles of freezing for 5 hours and thawing for 3
hours, Purins [58] concluded that the critical moisture content
was between 50 - 70 percent by volume and is dependent on the bulk
density.   Critical moisture content was 50 percent by volume for
density of 25 lbm/ft^3 (400 kg/m^3) and 65 - 70 percent by volume for

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density of 40 lbm/ft^3 (650 kg/m^3). Tensile strength after the tests decreased considerably, from 60 - 70 lbf/in^2 (0.41 - 0.48 MPa) to 4 - 20 lbf/in^2 (0.03 - 0.14 MPa). This decrease was attributed to internal damage occurring during the test, although reportably not visible from the outside [58].

In a similar study, Roulet [59] reported on the resistance to frost action of three different densities of autoclaved aerated concrete. The densities were 19, 25, and 31 lbm/ft^3 (300, 400, and 500 kg/m^3). The frost expansion upon cooling to -4°F (-20°C) and their length during thawing was measured. With dry samples, there was linear thermal expansion. For samples with low water content (degree of saturation of 20 - 40 percent by weight), they exhibited contraction on freezing, and after thawing no significant permanent expansion was measurable. Specimens having a critical water content (60 - 70 percent by weight), which is low compared to the total porosity or the zero pressure capillary water content, exhibited a large expansion while freezing to about -4°F (-20°C). After thawing, the sample with critical water content showed a permanent expansion. If the samples were nearly saturated with water, they became very brittle after one freeze-thaw cycle. Roulet [59] also reported that samples with a high degree of saturation upon freezing became brittle and cracked. However, scanning electron micrographs gave no evidence of a structure change due to freezing.

In a related study, tests carried out on factors such as loss of weight on freezing, tensile strength after freezing, and changes in length and volume after repeated cycles indicated that the critical degree of saturation was about 35 - 40 percent of pore saturation [60]. Pore saturation denotes that the total pore volume is filled with moisture. The dynamic modulus of elasticity was determined for each cycle for samples in the thawed condition. Damage occurred at a degree of pore saturation of 38 - 45 percent [60]. However, a measure of the critical degree of moisture was also obtained by studying the moisture-dependent deformation of samples. It varied to some extent due to the quality of the material and seemed to be in the range of 50 - 60 percent [60].

4.9 Moisture Expansion and Shrinkage

Autoclaved aerated concrete is similar to dense concrete in that it expands on wetting and shrinks on drying [28]. Drying shrinkage varies with density and method of manufacture. Values of drying shrinkage range from 0.1 to 0.5 percent when measured from saturated condition to a condition of equilibrium at 45 percent R.H. [28]. The low drying shrinkage of an autoclaved product as compared to that for air-cured cellular concrete, has been attributed to chemical reactions that take place during autoclaving [21].

The test results for shrinkage may vary considerably with different materials and methods of tests. In practice, the

shrinkage between delivery moisture content and equilibrium moisture content is of interest [1]. Excessive drying below equilibrium at 43 percent relative humidity results in an increase in shrinkage of the material. An example of shrinkage was given for materials where the moisture content was reduced from about 75 percent to 3 percent by mass. The materials were tested from water-saturated condition to equilibrium at 43 percent R.H. and 68°F (20°C). The shrinkage for this case was 0.03 percent [1]. The density of the materials was not reported.

4.10 Moisture Migration

Autoclaved aerated concrete, due to its higher porosity, has higher moisture absorption than dense concrete. Moisture may migrate through capillarity, or through diffusion or both. For normal moisture content conditions, the moisture migration is mainly by diffusion and with increasing moisture content, it is due more to capillarity [1]. Moisture migration is due almost entirely to capillarity when the moisture content is above 40 percent by mass (20 percent by volume). The moisture migration is also influenced by the pore structure, the dimensions of the unit, the thermal conductivity of the material, temperature, vapor pressure, and movements of the air to which the surfaces of the construction units are exposed.

4.11 Permeability

The permeability of autoclaved aerated concrete to air varies with the moisture content of the material. It decreases with an increase in moisture content in the pores [6]. Nevertheless, the CEB Manual [1] has indicated that the permeability of dry material at normal pressure differences, such as caused by wind, is very low and may be considered negligible. It is noted that significant penetration can take place through improperly formed joints and other connections in the building.

The water vapor permeability by diffusion also decreases with an increase in the moisture content of the material. The diffusion factor of aerated concrete (ratio between the diffusion of water vapor through a layer of air to that through a layer of material of the same thickness) has been determined to be 5 - 7 under air dry conditions for material having a density of 31 - 38 lbm/ft^3 (500 - 600 kg/m^3) [1].

4.12 Shaping and Working

During construction, autoclaved aerated concrete can be easily cut, nailed, drilled, milled, or shaped to accomodate building needs such as utilities, or other construction requirements [1,28,61]. In most cases, ordinary woodworking tools can be used. Reinforced flexural members should not be cut on the construction site without authorization of the manufacture since anchorage of reinforcement may be affected [1].

Attachment of other buildings units, materials, or accessories to autoclaved aerated concrete is more critical than those in denser materials such as brick or normal concrete, since ultimate failure loads (pullout) are lower [62].

4.13 Specific Heat

Specific heat of a material is the heat required to raise the temperature of unit mass of the material one degree. It is a measure of the capacity of a material to store heat. For autoclaved aerated concrete the value of specific heat is about 0.24 - 0.26 Btu/lbm°F (1.0 - 1.1 kJ/kg°C) for material of normal moisture content (2 - 3 percent by volume or 4 - 6 percent by weight) [1].

4.14 Solubility in Water

The strength-related components of autoclaved aerated concrete have only very low solubilities in water. However, depending on the raw material and mix proportions the product may contain small quantities of soluble salts which, under certain climatic conditions such as those resulting in slow evaporation, may crystallize on the surface to form efflorescence [1].

4.15 Sound Absorption

Autoclaved aerated concrete is considered to provide good sound insulation, having sound absorption properties somewhat better than that for smooth dense concrete [1,21,28]. The sound

absorption coefficient of untreated autoclaved aerated concrete was reported to be 0.00, 0.15, 0.25, 0.20, 0.20, and 0.20 for frequencies (H_z) of 125, 250, 500, 1000, 2000, and 4000 respectively [1]. If the aerated concrete is painted or coated, its sound insulation effectiveness is reduced. In general, for solid construction, sound transmission depends on the mass of the structure. Cavity wall construction gives greater sound reduction than solid construction for the same total mass [20].

4.16 Strength

Considerable data have been generated regarding the strength of autoclaved aerated concrete including compression, tension, shear and bond strength, and modulus of elasticity. Strength tends to increase with an increase in density, while thermal resistance tends to increase with a decrease in density [28]. According to Shrivastava [21], there is a straight line relationship between strength and density. Grimer and Brewer [63] tested four aerated concretes of varying density, 33 - 43 lbm/ft^3 (530 - 690 kg/m^3), and found that there was a slight systematic increase in strength with depth. The strength increases were accompanied by increase in specific gravity. The moisture content of autoclaved aerated concrete also has an influence on its strength. Svanholm [64] reported that strength decreases with an increase in moisture content. This was found for compressive and tensile strength and modulus of elasticity.

4.16.1 Compressive Strength

The compressive strength of autoclaved aerated concrete increases with an increase in density [1,8]. The average value of compressive strength measured using cubes for a dry density of 25 lbm/ft^3 (400 kg/m^3) was reported to be about 290 lbf/in^2 (2 MPa), and for a dry density of 44 lbm/ft^3 (700 kg/m^3), it was reported to be about 870 lbf/in^2 (6 MPa) [1]. Another report showed that for a density range of 31 - 44 lbm/ft^3 (500 - 700 kg/m^3), the compressive strength was 290 - 580 lbf/in^2 (2 - 4 MPa) [8]. The relationship between the cube compressive strength and the density of autoclaved aerated concrete is shown in Figure 3 [1].

Examples of values of compressive strength and modulus of elasticity for three densities of dry autoclaved aerated concrete (Table 2) were given by Edlind [28]. He noted that the compressive strength depends on test conditions such as test specimen size, its planeness or type of capping material, and its moisture content. The compressive strength decreases with an increase in moisture content of the material. The relationship between the compressive strength and the moisture content of autoclaved aerated concrete is shown in Figure 4 [1]. With moisture contents of 5 and 10 percent, the compressive strength is reduced about 20 and 25 percent, respectively. In another study by Dworjadkin and Malinowski [65], it was reported that the compressive strength of an autoclaved aerated concrete with maximum water

saturation (40 - 42 percent by volume) was 40 - 50 percent less than that of the air-dried material.

Compressive strength has, in at least one case, been found to decrease with time of exposure. For example, block samples exposed outdoors up to one year were tested by Grimer and Brewer [66] who found changes in strength (as indicated by compressive strength, as well as splitting strength, and modulus of rupture) with time. The decrease ranged from 10 - 15 percent for these properties.

4.16.2 Tensile Strength

The tensile strength of autoclaved aerated concrete is normally 1/4 to 1/6 of the compressive strength [1]. Edlind [28] reported the tensile strength to be about 20 percent of the compressive strength. A moisture gradient within the test specimen has a large effect on the tensile strength test result. The measurement of this property is even more sensitive to test conditions than the measurement of the compressive strength.

The tensile strength in bending is normally somewhat higher than when measured in direct tension. A moisture gradient in the specimen also affects this property.

Grimer and Brewer [66] reported that the modulus of rupture of specimens uncovered and stored outdoors changed considerably (up

to 50 percent decrease) from one month to one year. For specimens covered and also exposed outdoors, no significant change in strength occurred as compared to specimens stored indoors.

The modulus of rupture for a density range of 31 - 47 lbm/ft^3 (500 - 750 kg/m^3) was about 100 - 190 lbf/in^2 (0.7 - 1.3 MPa) [8]. Cracking in reinforced flexural members was observed to occur between 1.5 and 2.0 times the working load, under which condition the tensile stress can approach 50 percent of the compressive strength of the material.

4.16.3 Shear and Bond Strength

The shear rupture strength, based on pure punching shear, can be assumed to be 25 - 30 percent of the compressive strength [1]. The value for pure shear can be taken as that for direct tension, if information about shear strength is not available. The shear strength was also reported to be about 1/8 of the compressive strength and to range from 36 - 72 lbf/in^2 (0.25 - 0.5 MPa) [8].

In tests reported by Regan [67], the nominal shear stresses in reinforced autoclaved aerated concrete beams at the cracking stage were in the range 51 - 58 lbf/in^2 (0.35 - 0.4 MPa). This corresponds to the upper limit of values obtained from unreinforced (shear) slabs. The test results suggest that once shear cracking occurs in an autoclaved aerated concrete member, the truss action of the stirrups has to support the full shear with practically no

separate contribution from the concrete. The increases in strength produced by vertical and transverse stirrups were modest, about 17 percent of the strength of comparable unreinforced beams. However, the use of inclined stirrups was much more effective and increased the ultimate load by almost 50 percent [67].

Based on a statistical evaluation of previously published test results, Briesemann [68] developed semi-empirical methods of calculating the ultimate shearing strength of autoclaved aerated concrete slabs without web reinforcement, as well as the loads resulting in diagonal cracks and shear failure in beams with shear reinforcement. This design method was reported as being useful for components of autoclaved aerated concrete because the test specimens and the components used in practice were identical. The best agreement between the calculated methods and test results was achieved with a linear equation for slabs without shear reinforcement and with a quadratic equation for beams without shear reinforcement.

The bond of reinforcement in autoclaved aerated concrete is normally a fairly plastic phenomenon with the peak stress attained at a slip of about 0.0004 in. (0.01 mm) and maintained for movements up to about 0.008 in. (0.2 mm) [67]. Because of the relatively low bond strength, the reinforcement in autoclaved aerated concrete members often relies on welded cross-bars or stirrups which transfer load by bearing [8,26,43,67].

Regan [67] suggests from pullout tests a limiting value of bond stress for coated plain (smooth round) bars of 180 lbf/in^2 (1.25 MPa) based on the perimeter of the bar not including the coating. The bond strength of plain bars embedded in autoclaved aerated concrete may differ depending on the type of protective coating used. Other pullout tests [26] on small diameter plain bars coated with a cement-latex coating embedded in autoclaved aerated concrete having a compressive strength of 500 lbf/in (3.4 MPa) yielded bond stresses of 150 - 200 lbf/in^2 (1.0 - 1.4 MPa) at a slip of 0.001 in. (0.03 mm) at the free end. Dunn [26] stated that these values are generally greater than those calculated at design load, and actual load tests on precast units confirm that while the bond is adequate for design loads, slip can occur at about 1.25 times design load. Because of this, Dunn [26] further states that welded anchor bars or cross-bars as required in the ACI Guide for Low Density Precast Floor, Roof, and Wall Units [43] are needed to provide an adequate factor of safety.

4.16.4 Modulus of Elasticity

The modulus of elasticity is about one tenth that of dense concrete [24]. It has been given as a function of the density and compressive strength of the material. As an example, the modulus of elasticity for autoclaved aerated concrete having a density range of 31 - 44 lbm/ft^3 (500 - 700 kg/m^3) was reported to be 200 - 400 x 10^3 lbf/in^2 (1.4 - 2.8 x 10^3 MPa) [8]. The moisture content also affects the modulus value. The modulus

decreases with an increase in moisture content, similar to the
way it affects the compressive strength. Moisture effects can be
taken into account by using the compressive strength value for
the wet material according to the formula below. The formula has
been reported to correspond well with test values of some autoclaved
aerated concrete produced in Sweden having a density range of 25
- 44 lbm/ft^3 (400-700 kg/m^3) and a range in moisture contents of
3 - 10 percent by volume [1].

$$E_O = k\gamma_{dry} \sqrt{f_c}$$

where:

E_O is the tangent modulus, MPa

γ_{dry} is the dry density, kg/m^3

f_c is the compressive strength, MPa, for wet material

k is an empirical constant, the value reported to vary

between 1.5 and 2.0 [1]

It was noted [1] that this formula can be used by the designer to
estimate elastic deformations of unreinforced material even
though values obtained from this formula may differ from test
results for other autoclaved aerated concrete products.

4.17 Structure

The structure of autoclaved aerated concrete is characterized by
pores or cells which are formed by the hydrogen gas, air, and
water during the molding and expanding phases of production [1].

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The micro-cellular structure of autoclaved aerated concrete is shown in Figure 5.

Scanning electron microscopy (SEM) micrographs of the cell structure of the hardened material, which is generally considered to be uniform, have been reported [1,58,59,69,70]. The pore structure is important with regard to physical properties of the material such as strength, thermal conductivity, capillarity, and frost resistance. Depending on the pore size and their physical characteristics, they can be divided into micropores and macropores. An example of the distribution of pore sizes in autoclaved aerated concrete is given in Figure 6 [1]. Larsson and Purins [60] reported pore size for various kinds of autoclaved aerated concrete investigated in freezing tests. The macropores were determined to have radii of between 64,000 and 550,000 Å and micropores to have radii of between 40 and 64,000 Å. They also reported that the pore size distribution was different for the various autoclaved aerated concretes investigated. Micropores may be considered to be capillary active, and the distribution of cell sizes within the micropore range is important with regard to properties such as freezing and moisture migration [1]. The macropores are usually almost spherical in shape; however, for cases where they are more oval in shape, it may be assumed that the physical characteristics of the autoclaved aerated concrete may differ somewhat in the directions of the major and minor axes

[1]. If the cells are irregularly shaped rather than being spherical, excessive reduction in strength occurs [21].

In a study by Schwiete and Ludwig [71], the porosities of some autoclaved aerated concrete specimens were found to be about 70 - 80 percent. They considered the concept of effective porosity to assess the micropore content of the specimens. They reported that the effective porosities ranged from 4 - 13 percent. Moisture contents of the specimens were about 2 percent by volume and the bulk densities were 44 lbm/in^2 (700 kg/m^3).

Purins [58] conducted an examination of pore structure and he reported no entirely closed pores in autoclaved aerated concrete. His evidence was electron micrographs of the material with magnifications of up to 26,000. He observed that the structure was capillary, both at the bottom and in the walls of the pores, and concluded that no closed pores existed in the material.

4.18 <u>Temperature Resistance</u>

Shrinkage cracking will result if autoclaved aerated concrete is exposed to dry air at a high temperature for a long time, and excessive drying eventually takes place. For this reason, structural aerated concrete should not be used in constructions that are continuously exposed to dry air at a temperature above 122 - 158°F (50 - 70°C) without protection against excessive drying [1]. For non-structural applications, aerated concrete can be exposed

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to much higher temperatures, up to 1300°F (700°C), if appropriate
precautions are taken against excessive drying. The CEB Manual
[1] indicates that, for such high temperature use, manufacturers'
design considerations must be strictly followed. The melting
point of aerated concrete is 1800 - 2200°F (1000 - 1200°C),
depending on the materials used [1].

4.19   Thermal Conductivity

The relatively low thermal conductivity of any cellular concrete
is due to air-filled pores [26]. The thermal conductivity, k
value, of aerated concrete depends primarily on its density.
Other factors such as moisture content, temperature level, pore
structure, and raw materials also effect the thermal conductivity
[1]. The relationship between the thermal conductivity and the
density of dry specimens of autoclaved aerated concrete is given
in Figure 7 [1]. Based on dry density, the average value of
thermal conductivity for a density of 25 lbm/ft^3 (400 kg/m^3) was
reported to be about 0.55 Btu·in./ft^2·h·°F (0.08 W/mK), and for a
density of 50 lbm/ft^3 (800 kg/m^3), it was reported to be about 1.5
Btu·in./ft^2·h·°F (0.21 W/mK) [1,10]. It was reported by Leitch
[3] that k-values associated with autoclaved aerated concrete, as
with unautoclaved materials, go as low 0.55 Btu·in./ft^2·h·°F
(0.08 W/mK).

As expected, thermal conductivity increases with an increase in
moisture content [1,10,64,72,73]. Data in the CEB Manual [1] indicate

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that this relationship is linear for moisture contents up to 20 percent by weight. As an illustration of the relationship, the average value of thermal conductivity for a material with a dry density of 31 lbm/ft^3 (500 kg/m^3) was shown to be about 0.76 Btu·in. /ft^2·h·°F (0.11 W/mK) at zero moisture content, whereas it was shown to be 1.1 Btu·in./ft^2·h·°F (0.15 W/mK) at 10 percent moisture content by weight [1]. It was interesting to note, that moisture factors (ratio of thermal conductivity of moist material to that of dry material), determined experimentally by Loudon [72], correlated better with moisture content by weight than moisture content by volume.

For lightweight concretes in general, Valore [74] suggested a single moisture factor that consists of a 6 percent increase in thermal conductivity for each one percent of moisture, by weight, relative to oven dry density. A constant moisture content of 4 percent, by volume, was proposed for lightweight concrete walls having a density of 25 lbm/ft^3 (400 kg/m^3), protected from rain penetration.

5. ENERGY CONSIDERATIONS

As stated in the introduction to this report, a major advantage influencing the use of autoclaved aerated concrete products has been the relatively low thermal conductivity combined with load-carrying capacity. This factor has been noted by numerous authors who have reported on the properties and performance of autoclaved aerated concretes [e.g., 1,5-7,10,19,21,24,28,38].

Bave [6,10,38] has summarized the development and growth in use of autoclaved aerated concrete, particularly noting the factors affecting energy conservation. The use of this material originated in northern European countries where thermal insulation has been a long time concern due to cold climates and a dependency on imported fuel. Subsequently, its use expanded to warm climates where its low thermal conductivity offered advantages for energy savings in cooling buildings. Bave [6] has indicated that autoclaved aerated concrete, in many geographic locations, satisfies both thermal and loadbearing requirements while offering an overall energy saving. He did not indicate the details of these requirements.

In addition to energy considerations associated with use of a low thermal conductivity material, Bave [6,10] also pointed out qualitatively other factors regarding energy savings in the use of autoclaved aerated concrete. These factors included raw materials, the production process, and transportation and

erection of the manufactured units. As an example, he stated
that the relatively low weight of aerated concrete building units
allows cuts in the energy consumption due to handling and
erection on site.

Kohler [7] has presented the results of a study on the energy
costs for the production and use of autoclaved aerated concrete
taking into account direct and indirect energy costs. He
compared the energy costs for production of different types of
walls having equivalent thermal and loadbearing properties.
Among his findings, he reported that the separation of the thermal
and loadbearing functions (i.e., composite wall with thermal
insulation and structural element) leads generally to lower
overall energy costs. For example, he found that the energy
costs for a composite autoclaved aerated concrete wall with
expanded polystyrene insulation were about 8 percent less than
those for the equivalent wall comprised only of autoclaved aerated
concrete.

Kohler [7] also modeled the energy performance of complete
buildings whereby the use of autoclaved aerated concrete floors,
walls, and ceilings was compared to the same elements of conventional
materials. A significant finding was that, in the case of
energy-efficient houses, "it was not possible to reach the
insulation requirements by aerated concrete only even by using
very large sections". He indicated that, in these cases,

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autoclaved aerated concrete has to be used together with a material which is specifically a thermal insulation.

In this regard, Kohler's findings may be related to current practice (as recommended by ASHRAE) in the U.S. for opaque walls and roofs of new buildings except low-rise residential. For relatively severe climatic locations having 6500 heating degree days or more, the minimum total thermal resistance (R-value) of walls is about 20; whereas for roofs, it is about 30 [75]. An autoclaved aerated concrete wall, 8 in. (20 cm) thick and having a density of 31 lbm/ft^3 (500 kg/m^3) may have an R-value about 11 [28]. A 6 in. (15 cm) roof slab of similar density material would have an R-value of about 8. Obviously, for both the wall and the roof, additional thermal insulation would be needed to attain an R-value of 20 to 30. In contrast, in areas of the U.S. having mild climates, autoclaved aerated concrete alone may satisfy insulation needs.

Recently Frey and Briesemann [5] studied the factors affecting the primary energy costs to produce autoclaved aerated concrete. They found that, for the plants studied, raw materials production, raw materials transportation, and actual factory production accounted for 60 percent, 5 percent, and 35 percent of the energy costs, respectively. They indicated that the process is currently very energy efficient, and consequently, substantial energy savings cannot be expected in the future. Where reductions are

accomplished, they will be associated with improvements in cementitious binder technology.

6. STANDARDS AND RELATED DOCUMENTS

Since autoclaved aerated concrete has been used extensively
worldwide, standards and related documents have been developed in
many countries. With the exception of the previously mentioned
CABO [45] and HUD [46] documents, no standards and codes have been
developed in the U.S. Recently, RILEM[5] Technical Committee 78-MCA
on Model Code for Aerated Concrete Based on RILEM Testing Methods
[76] has compiled, as a working document, a list of "Standards
and Regulations Concerning Building and Buildings Constructed
with Autoclaved Aerated Concrete." The titles of these documents,
as listed by the RILEM committee, are given in Appendix A. A
summary of the contents of these documents is beyond the scope of
this review. The contents vary among standards, and some treat a
broader range of requirements and use conditions than others. In
general, the standards provide: general information on the
autoclaved aerated concrete product, minimum requirements for
material properties, requirements for the dimensions of specific
products (e.g., blocks), test methods, requirements for quality
control of the production process, and marking.

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[5]RILEM is a French acronym for International Union of
Testing and Research Laboratories for Materials and Structures.

7. SUMMARY

This report is a review of the properties and performance of autoclaved aerated concrete. This is a construction material that has gained widespread use in many areas of the world. Little use has occurred in Canada and the United States. It is a lightweight porous concrete whose cellular structure is generally obtained through an in situ gas-producing reaction. Subsequent autoclaving in the factory provides strength, dimensional stability, and other properties of the finished product. These materials combine a relatively low thermal conductivity with a bearing capacity suitable for use in structural applications. This combination of properties might make them attractive for energy-conserving applications. For this reason, the review was conducted at the request of the U.S. Department of Energy.

The review addressed an overview of the manufacturing process, uses of autoclaved aerated concrete in building constructions, properties, energy considerations, the availability of code-related documents, and standards. The literature on these materials is extensive. Uses include block and panel construction in both loadbearing and non-loadbearing applications for walls, floors, and roofs. With regard to energy considerations, the review pointed out that, for energy efficient applications under severe climate conditions, the autoclaved aerated concrete unit alone may be insufficient to provide the targeted minimum value of thermal resistance. In these cases, autoclaved aerated concrete

has to be used together with additional thermal insulation. In contrast, in areas of the U.S. having mild climates, autoclaved aerated concrete alone may satisfy insulation needs.

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COUNTRIES USING
AUTOCLAVED AERATED CONCRETE

Use of AAC
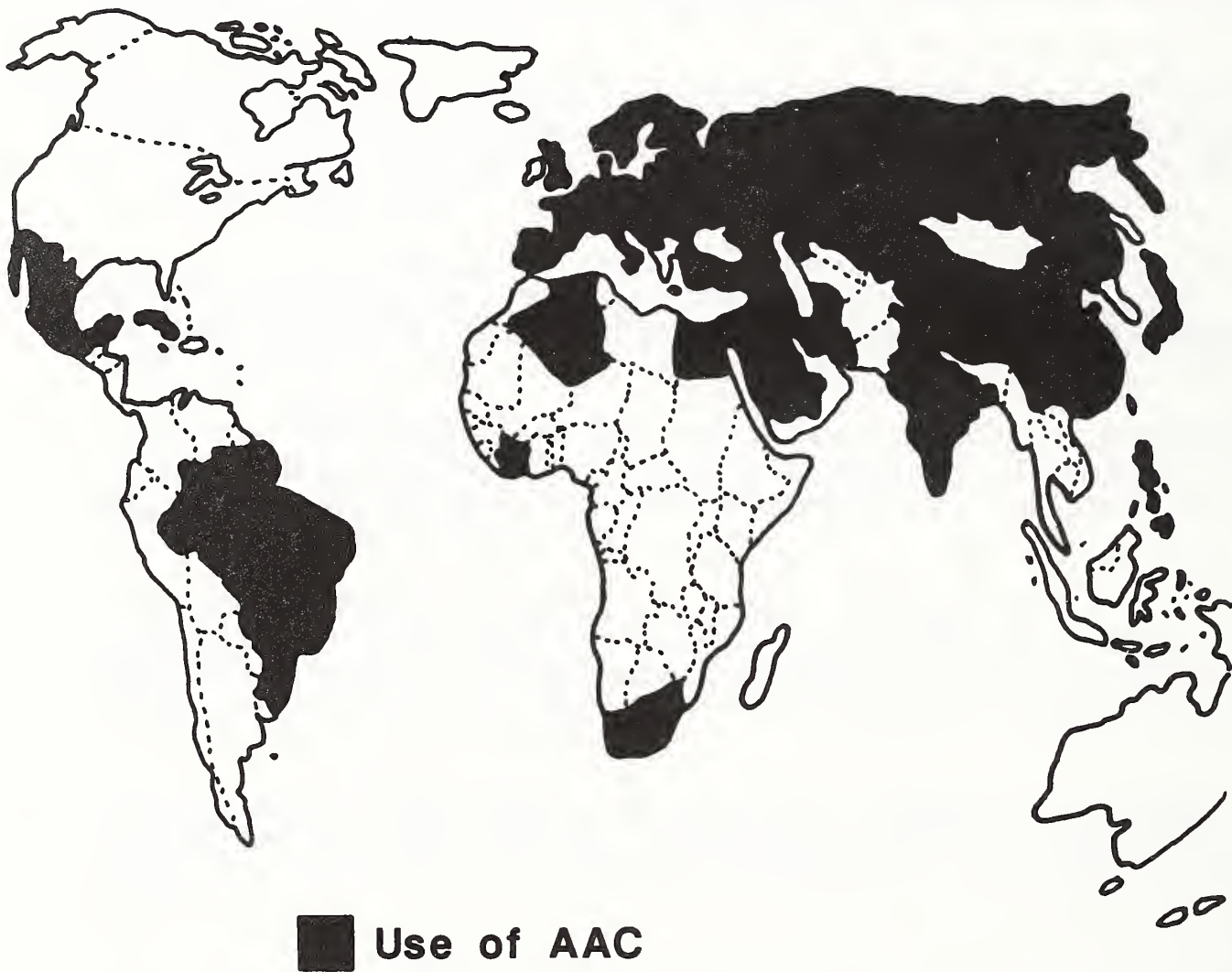
Figure 1.   Countries where Autoclaved Aerated Concrete (AAC) is
            Used, As Described by Bave in 1983 [6].

STEPS IN MANUFACTURING PROCESS
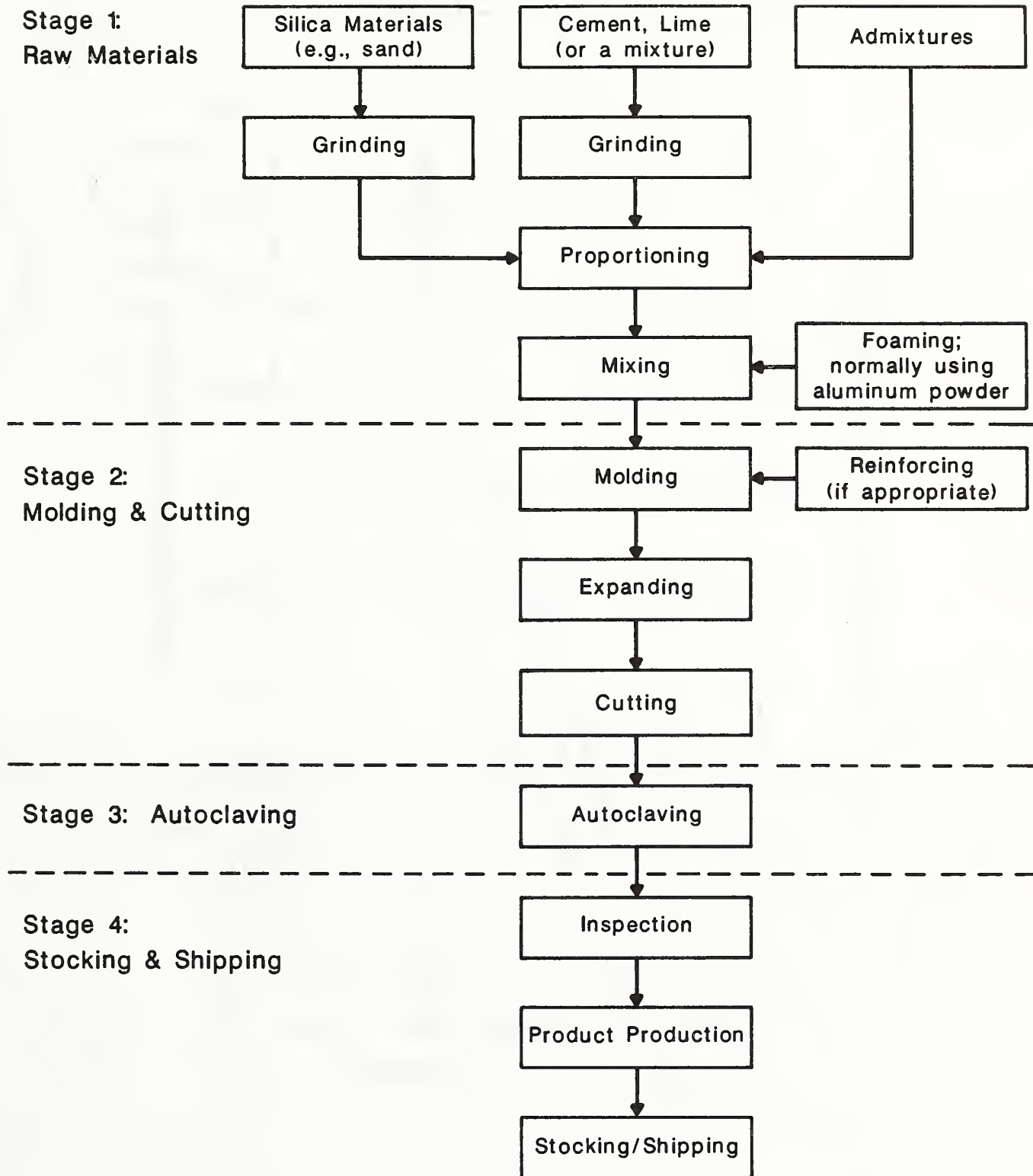
Figure 2.   Production of Autoclaved Aerated Concrete Products.
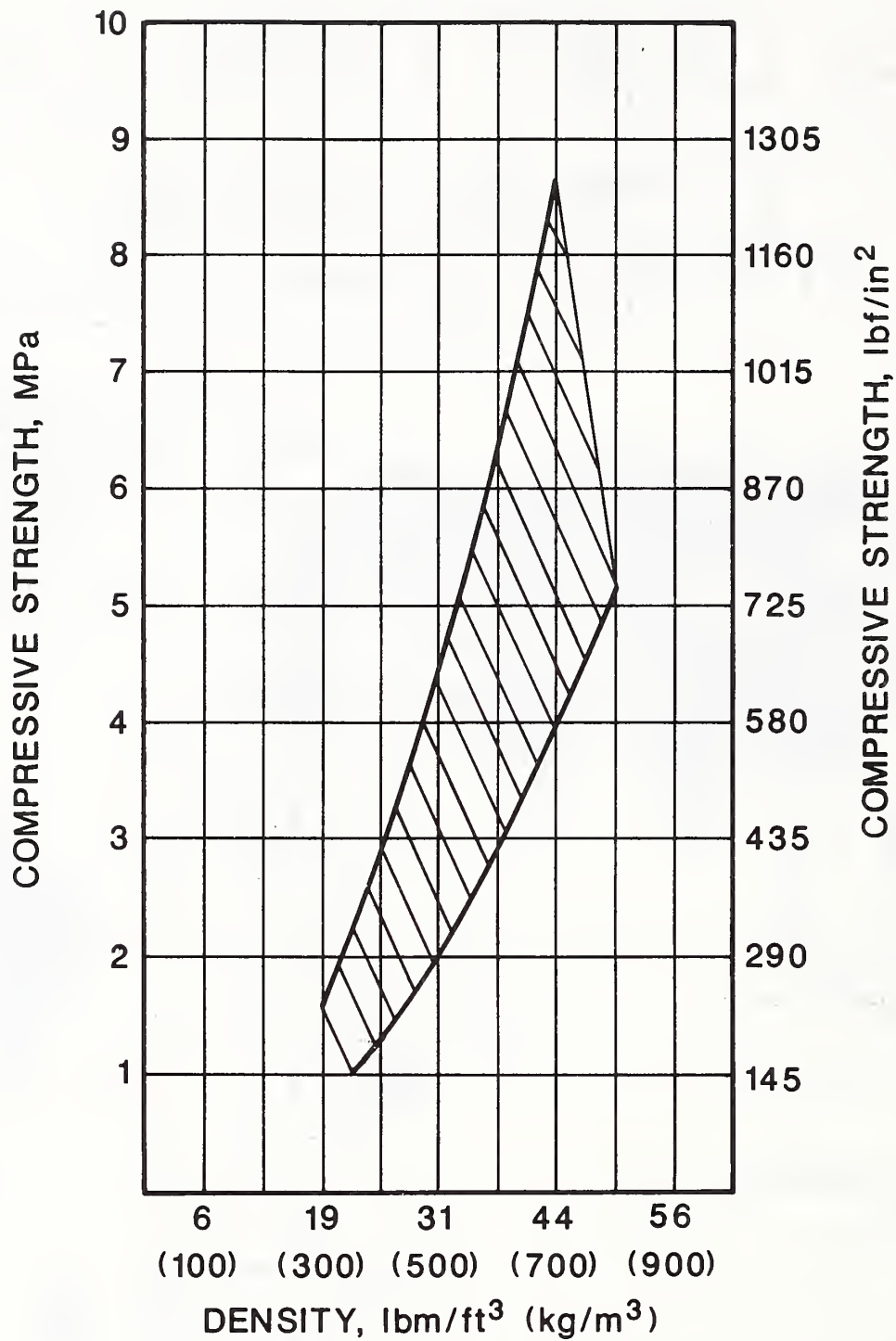
Figure 3. Relationship Between the Cube Compressive Strength and
the Density of Autoclaved Aerated Concrete (From CEB
Manual [1], Courtesy of CEB and the Construction Press).
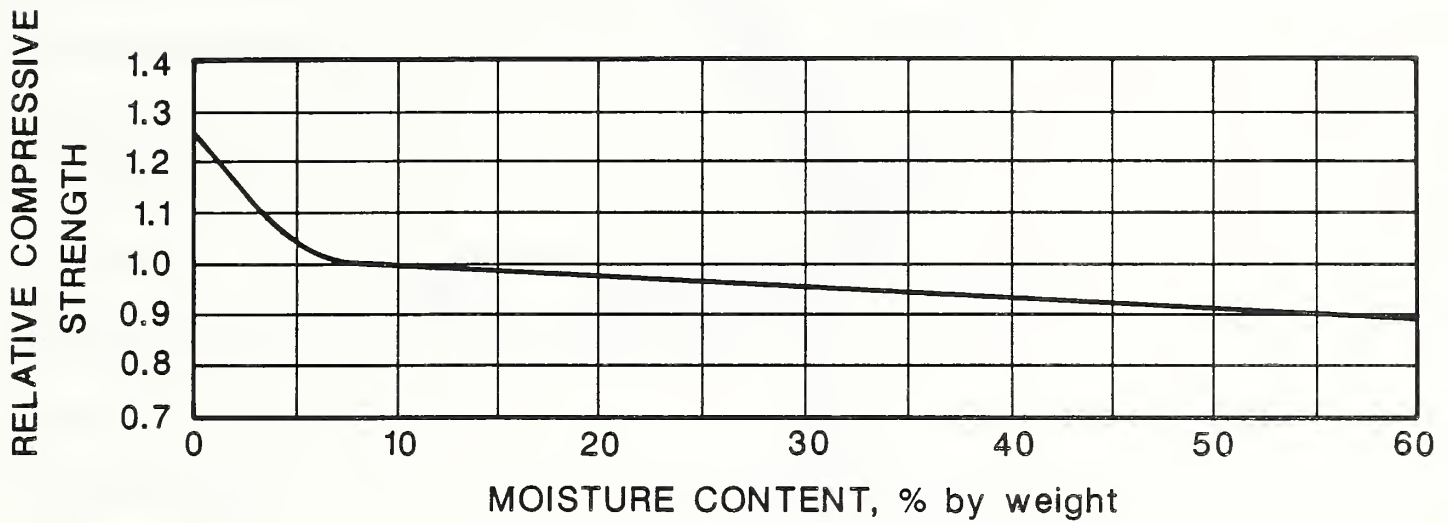
Figure 4. Relationship Between the Compressive Strength and the Moisture Content of Autoclaved Aerated Concrete (From CEB Manual [1], Courtesy of CEB and the Construction Press).
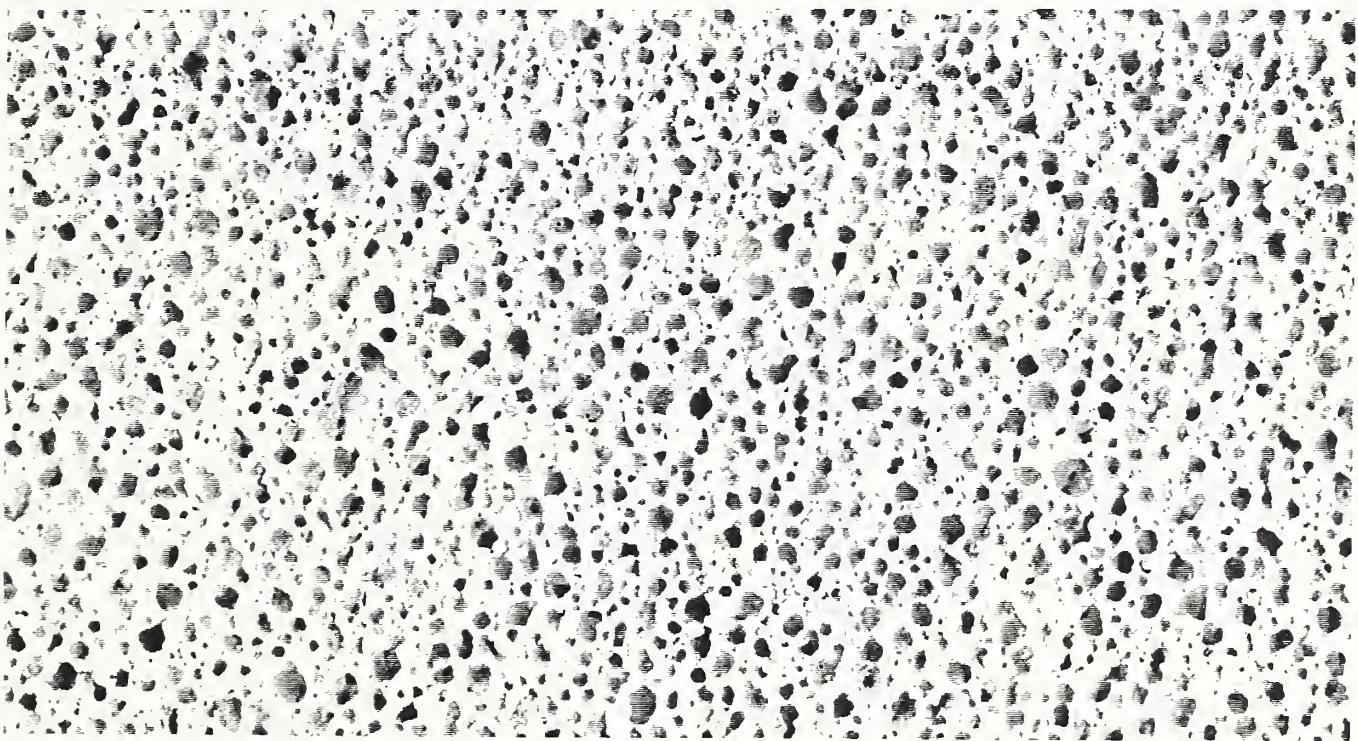
Figure 5. The Micro-Cellular Structure of Autoclaved Aerated Concrete (Magnified to About 3 x Acutal Size).
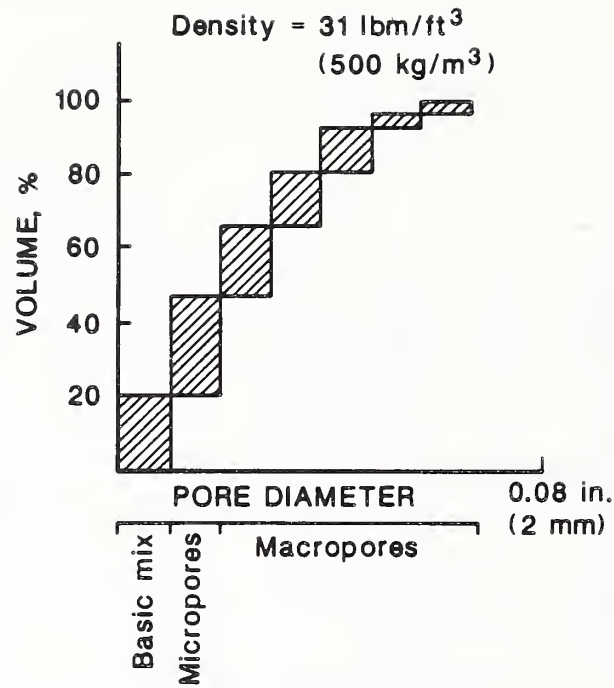
Figure 6.   Example of Distribution of Pore Sizes in Autoclaved
Aerated Concrete (from CEB Manual [1], Courtesy of CEB
and the Construction Press).
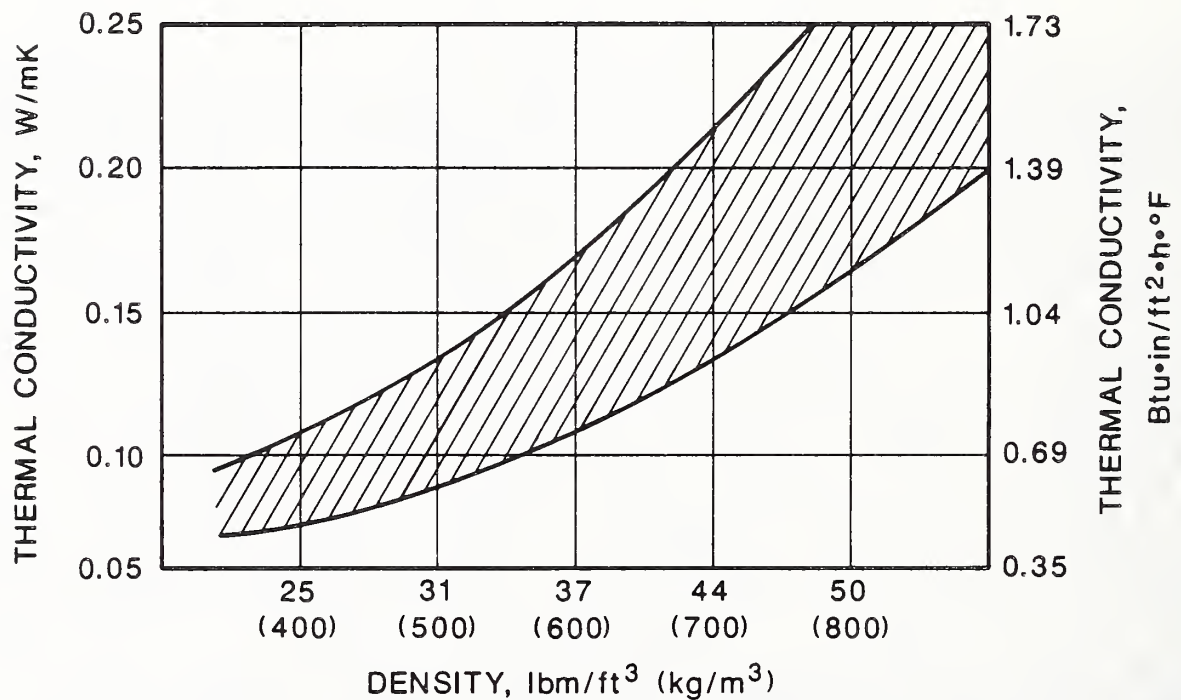
Figure 7.   The Relationship Between the Thermal Conductivity and
the Density of Dry specimens of Autoclaved Aerated
Concrete (from CEB Manual [1], Courtesy of CEB and the
Construction Press).

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Table 1.   Estimated 1987 Production of Autoclaved Aerated
           Concrete in Some Countries[1]

Country	ft^3	m^3
Belgium	8.8×10^6	250×10^6
Czechoslovakia	105.9×10^6	3000×10^3
Denmark	10.6×10^6	300×10^3
Finland	7.1×10^6	200×10^3
France	17.6×10^6	500×10^3
Federal Republic of Germany	97.1×10^6	2750×10^3
Japan	105.9×10^6	3000×10^3
Netherlands	10.6×106	300×10^3
Poland	141.3×10^6	4000×10^3
Sweden	8.8×10^6	250×10^3
Soviet Union	187.2×10^6	5300×10^3
United Kingdom	100.6×10^6	2850×10^3
Yugoslavia	35.3×10^6	1000×10^3

[1] Gunnar Bave, Siporex, personal communication

Table 2.   Examples of Values of Compressive Strength and Modulus
           of Elasticity [28]

Density		Compressive Strength		Modulus of Elasticity	
kg/m^3	lbm/ft^3	MPa	lbf/in^2	MPa	lbf/in^2
400	25	1.5	215	1000	142,230
500	31	3.0	430	1400	199,130
650	41	6.5	924	2600	369,810

APPENDIX A. LISTING OF STANDARDS AND RELATED DOCUMENTS

This appendix lists standards and related documents for autoclaved aerated concrete products (Table A1). The listing was assembled from the working document prepared by RILEM Technical Committee 78-MCA on Model Code for Aerated Concrete Based on RILEM Testing Methods [76] as part of its activities to recommend an application practice for autoclaved aerated concrete. As is evident from the listing, some of the titles of the documents are given in their language of origin. In these cases, only the original language was given in the RILEM working document. The ASTM documents included in the listing are not specific for autoclaved aerated concrete.

Table A1.   Standards and Related Documents Associated With
            Autoclaved Aerated Concrete

  Country   Standard

 Belgium   NBN 538 (1962)
                     Blocs en beton pour maconnerie ordinaire

 Denmark   DS 420.1 (1967)
                     Vandrette baerende elementer af armeret autoklaveret
                     letbeton

                     Ds 420.1 (1967) (Supplement)
                     Vandrette baerende elementer af armeret autoklaveret
                     letbeton

                     DS 420.2 (1977)
                     Vertical load bearing elements of lightweight concrete

                     DS 420.3 (1980)
                     Letbeton vandretbaerende elementer

                     DS 438 (1981)
                     Blokmurvaerk

 Federal   DIN 4223 (1958)
 Republic   Bewehrte Dach- und Deckenplatten aus dampfgehartetem
 of Germany   Gas- und Schaumbeton

                     Entfurf DIN 4223 (1978)
                     Bewehrte Bauteile

                     DIN 4164 (1951)
                     Gas- und Schaumbeton - Herstullung, Verwendung und Prufung

                     DIN 4165 (1982)
                     Gasbeton-Blocksteine

                     DIN 4166 (1973)
                     Gasbeton-Bauplatten

                     Zulassungsbescheid Nr. Z 17.1-1387 (1981)
                     Mauerwerk aus Hebel-Plansteinen

                     Zulassungsbescheid Nr. Z 17.1-43 (1975)
                     Geschosshohe tragende Hebel-Wandtafeln aus dampfgehartetem
                     Gasbeton der Festigkeitsklassen G 35 und G 50

                     Zulassungsbescheid Nr. Z 2.1-5.1 (1982)
                     Bewehrte Hebel-Deckenplatten aus dampfgehartetem Gasbeton
                     der Festigkeitsklassen GB 3.3 (GSB 35) und GB 4.4 (GSB 50)

Table A1.   Standards and Related Documents Asociated With
            Autoclaved Aerated Concrete (continued)

   Country   Standard

                        Zulassungsbescheid Nr. Z 2.1-5.2 (1982)
                        Bewehrte Hebel-Dachplatten aus dampfgehartetem Gasbeton
                        der Festigkeitsklassen GB 3.3 (GSB 35) und GB 4.4 (GSB 50)-

                        Zulassungsbescheid Nr. Z 2.1-23 (1982)
                        Bewehrte Hebel-Sturze aus dampfgehartetem Gasbeton
                        GB 4.4 (GSB 50) ohne schragbewehrung

   Finland   RIL 69 (1969)
                        Karkaistun kevytbetonin normit 1969

   France   NF P 14-306 (1978)
                        Blocs en beton cellulaire autoclavé pour murs

                        Avis no 16/75-20 (1976)
                        Avis sur le mur en blocs de beton cellulaire Ytong (Burcht)

                        Avis no 3/77-58 (1978)
                        Avis sur le plancher Siporex (Bernon)

                        Avis no 16/77-29 (1978)
                        Avis sur le procede de maconnerie Sipobloc (Bernon)-
                        Durobloc (Bernon)

   German   TGL 21098 (1972)
   Democratic   Gasbeton - Technische Forderungen
   Republic
                        TGL 21098 (1972)
                        Gasbeton - Prufung

                        TGL 23374 (1971)
                        Wandplatten fur den Skelettbau - Fensterplatten aus
                        Stahlbeton

                        TGL 23374 (1974)
                        Wandplatten fur den Skelettbau - Aussenwandvollplatten aus
                        Gasbeton

                        TGL 23374/02 (1975)
                        Wandplatten fur den Skelettbau - Einschichtige
                        Aussenwandelemente aus Leicht- und Schwerbeton

                        TGL 25553 (1972)
                        Wandbausteine aus Gasbeton

Table A1. Standards and Related Documents Associated With
           Autoclaved Aerated Concrete (continued)

  Country   Standard

Great   BS 6073 (1981)
Britain   Precast concrete masonry units
                 Part 1: Specification for precast concrete masonry units
                 Part 2: Method for specifying precast concrete masonry
                          units

                 CP 110 (1972)
                 Code of practice for the structural use of concrete
                 Part 1: Design, materials and workmanship

                 CP 121 (1973)
                 Code of practice for walling
                 Part 1: Brick and block masonry

                 Regulations D13(b) and D14 (1976)
                 The building regulations

Israel   SI 268 (1979)
                 Ytong blocks

Japan   Standard for structural design of autoclaved lightweight
                 concrete construction - noticed by the Ministry of
                 Construction - 1967

Romania   STAS 8036-81 (1981)
                 Beton cellular autoclavizat - Gazbeton - Conditii tehnice
                 generale

Sweden   PFS 1980:3
                 Autoclaved aerated concrete products - products of
                 autoclaved aerated concrete without coarse aggregate

Switzerland   SIA 177 (1980)
                 Maconnerie

                 SIA 177/1 (1983)
                 Calcul des murs de maconnerie sollicites a la compression

The   Bouwblokken en -stenen van beton (concrete building blocks
Netherlands   and stones)

Turkey   TS 453 (1977)
                 Gazbeton ypi malzeme ve elemantari (gas concrete material
                 and elements for building)

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Table A1.   Standards and Related Documents Associated With
            Autoclaved Aerated Concrete (continued)

  Country   Standard

 USA   ANSI/ASTM C 796-80
                     Foaming agents for use in producing cellular concrete using
                     preformed foam

                     ANSI/ASTM C 869-80
                     Foaming agents used in making preformed foam for cellular
                     concrete

 USSR   GOST 190 10-82 (1982)
                     Blocs en beton et en beton armé pour murs de batiments

                     GOST 25485-82 (1982)
                     Cellular concretes, technical specifications

 Yugoslavia   Civil engineering and architectural documentation IR-9
                     Vol. 337:   Regulations on technical standards for the
                     design and erection of structures made of precast nonrein-
                     forced and reinforced aerated concrete units

                     JUS U.N1.300 (1981)
                     Celijasti beton - proizvodnja, primena i ispitvanje
                     prefabrikovanih elemenata od gasbetona i pjenobetona
                     osnovne odredbe

                     JUS U.N1.302 (1981)
                     Celijasti beton - armirane krovne i mdeukatne ploce od
                     plinebetona i pjenobetona

                     JUS U.N1.304 (1981)
                     Celijasti beton - armirane zidne ploce od plinobetona i
                     pjenobetona

                     JUS U.N1.306 (1981)
                     Celijasti beton - zidni blokovi od plinobetona i pjenobetona

                     JUS U.N1.310 (1981)
                     Celijasti beton - zastita armature od korozije

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This report is a review of the properties and performance of autoclaved aerated concrete. The material has a relatively low thermal conductivity combined with loadbearing capacity for use in structural and non-structural applications. This feature may make its use attractive for energy-conserving applications. For this reason, the review was conducted at the request of the U.S. Department of Energy.

The review addressed an overview of the manufacturing process, uses of autoclaved aerated concrete in building constructions, properties, energy considerations, the availability of code-related documents, and standards. Uses include block and panel construction in both loadbearing and non-loadbearing applications for walls, floors, and roofs. Many properties are reviewed including density, fire resistance, moisture expansion and shrinkage, strength, structure, and thermal conductivity. With regard to energy considerations, the review points out that, for energy-efficient applications under severe climatic conditions, the autoclaved aerated concrete unit alone may be insufficient to provide the targeted minimum value of thermal resistance. In these cases, autoclaved aerated concrete has to be used together with additional thermal insulation. In contrast, autoclaved aerated concrete alone may satisfy insulation needs in areas having mild climates.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)
aerated; autoclaved; cellular; concrete; insulating concrete; lightweight; manufacture; properties; standards; uses.

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