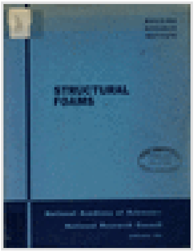

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Milton C. Coon Jr.
MILTON C. COON, Jr.
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Abstracts of Conference Papers

FOAMED GLASS
Walter Lovett, Pittsburgh Corning Corp.

Early development of foamed glass is discussed, and the processes by which it was made. A house built almost entirely of foamed glass in Canada is described, with the steps involved in its construction and erection, as well as the performance of the building as indicated by test results over the past ten years. Foamed glass units currently used for acoustical absorption are described and their performance detailed, and other uses of this material in building are mentioned.

* * * * * * * *

FOAM AND GAS CONCRETES
Rudolph C. Valore, Jr., Sika Chemical Corp.

Commercial production and application of foam and gas concretes are described, both in terms of their use in this country and abroad. Various ingredients used to produce cellular concretes are detailed in terms of the properties of the finished product. Aggregates for autoclaved cellular concrete are analyzed, as well as means of acceleration of hardening, and comparative water ratios. Preparation of cellular concretes is discussed in detail. Processes used in making foamed cellular concrete are described, with a comparison of cell structures produced by various methods. Moist curing of cellular concretes, steam curing at atmospheric pressures, density and compressive strength are presented in contrast with compressive strength of autoclaved cellular concrete. Flexural and tensile strength are described, as is bond strength, elasticity, absorption and capillarity, and resistance to freezing and thawing. Drying and shrinkage of cellular concretes are evaluated, as well as thermal expansion, thermal conductivity, fire resistance and acoustic properties.

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FOAMED METALS
Johan Bjorksten, W.S. Fiedler and L.F. Yntema, Bjorksten Research Laboratories

Current progress in experimental work with foam metals is discussed, with stress laid on the fact that most of the work to date has been on aluminum and its alloys. Processes of foaming and the variables employed are detailed. Interesting and important characteristics of foamed metal are pointed out, including its workability, mechanical strength, density and insulating properties. Uses for such products are suggested.

* * * * * * * *

URETHANE FOAMS IN STRUCTURES
R.H. Harding, Union Carbide Chemicals Co.

The general versatility of urethane foams is mentioned as an introduction to the analysis of the material and the processes involved in its production. Various types of foam machines are described and illustrated in terms of their effect on the finished product. It is pointed out that rigid urethane foams combine a unique array of properties, including exceptional strength per unit weight, low weight per unit volume, flame retardance, dimensional stability, resistance to passage of heat and moisture, ready fabrication in field or factory, and inherent adhesion to most clean surfaces. Some architectural applications of the material are discussed.

* * * * * * * * *

FOAMED POLYSTYRENE IN THIN SHELL CONSTRUCTION

E.E. Ziegler, The Dow Chemical Co.

Economic and aesthetic factors concerned in the rising use of foamed polystyrene construction are noted, plus the fact that extruded polystyrene foam has been widely accepted as a material for thermal insulation over the past 15 years, and as a core for sandwich panels. The use of this foam in the form of boards to provide form liners in the on-site casting of concrete roofs is described, with note taken of the fact that, once the concrete is set and the form boards removed, the exposed foam surface serves as insulation and vapor barrier, and is also susceptible to various types of interior finish. Another use is pointed out, wherein this type of material permits on-site construction of insulated sandwich panels. It is stated that use of foamed polystyrene in roof construction can obviate the necessity for the use of extensive supports necessary in the casting of reinforced concrete. Offset-wire generation of the desired shape is described and some examples given of its successful use with foamed polystyrene.

FOAMED INORGANIC MATERIALS

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Foamed Glass

By Walter Lovett,* Manager, Technical Service Department,
Pittsburgh Corning Corporation

The first foamed glass was developed in this country in 1938 and was first placed on the market in 1942. Several factors contributed to the production of this material, but the most important were:

1) An idea that there was a need for a waterproof, noncombustible, inorganic material of low density and low thermal conductivity to serve industry as an insulant.
2) The Navy's need for a material which would stand up well in salt water, be buoyant enough to float anti-submarine nets, and also withstand the action of enemy bullets.

Since the United States was at war during 1942, the larger part of the development of foamed glass was pointed toward the production of a buoyant item. From foamed glass, cubes were formed approximately 8' on a side, protected on the outside by heavy planking. They were floated out into the mouths of harbors and rivers by the thousands, and there used to hold up steel anti-submarine nets. During the war years, the vast quantity of foamed glass produced was used for this purpose; however, some was also made available for use as an insulant for roofs, and as cold storage and wall insulation for humidity-controlled buildings such as exist in the textile industry.

The material is made by grinding a bora-silica type glass to about the consistency of portland cement. This fine glass powder, with a small addition of other ingredients, is placed in stainless steel pans and heated to about 1750°F, which causes the material to foam. The material is then put through an annealing lear (oven) to relieve any internal stresses, and then is cut into blocks of various thicknesses.

The primary use of foamed glass is for insulation, but it has been and is being used as a structural load-bearing material. For example, when the Central Mortgage and Housing Corporation of Canada was studying the need for low-cost housing, they first made a study of materials other than the conventional wood frame and the prefabricated wall system, which both involve numerous, time-consuming operations to fabricate and erect.

Central Mortgage and Housing's requirements for an acceptable wall material were that the material must be strong, rigid and possess resistance to heat transfer, moisture transfer and fire, and preferably that it be homogeneous and easily mass-produced. After studying various materials, it was decided that foamed glass was the closest approach to the desired material. Having chosen the wall material, it was decided to build an experimental house in the industrial community of Ajax, Ontario. A basementless house was chosen for this investigation consisting of two bedrooms, bathroom, combination dining and living room, kitchen and utility room.

The house was erected in the spring of 1949. The wall and interior partitions were prefabricated using 2" x 12" x 18" thick foamed glass blocks bonded together with hot asphalt

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*WALTER LOVETT, Member, American Society for Testing Materials, Building Research Institute; B.S. and M.S. in civil engineering, University of Pittsburgh; Registered Professional Engineer; formerly assistant professor of civil engineering, University of Pittsburgh.

to form a 4" thick panel. The joints between the blocks were staggered to assure an overlap. Window and door openings were made in the panels as they were fabricated. The edges of the panels were vertical construction joints to be made during erection and were coated with a thermoplastic adhesive which can be reactivated after it has hardened by applying heat.

Before erection, the surfaces of all partitions and exterior panels were covered with cloth set in ordinary oil base paint, over which one coat of paint was applied. Second coats of paint were added on the inside and outside walls for aesthetic reasons, and a decorative finish was applied to the interior walls.

The exposed edges of the panels were protected by wooden crating during transportation and stock piling.

The panels were erected by setting them on the concrete slab in a slow-setting adhesive compound. Aligning the vertical edges close together, a specially designed heater was inserted between the edges in order to reactivate the thermoplastic coating. To prevent heat from escaping, a vertical wood strip was placed over the joint. When the adhesive was reactivated, the heater and wood backing strip were removed, and the one panel was shoved manually against the other.

After all the wall panels were in place, the prefabricated plywood roof sections were hoisted into place and adhered to the top edges of the exterior and interior walls.

A look at the performance record of this foamed glass house reveals that it has been economical to heat since the 4" wall has a 0.09 coefficient of thermal transmission. Also, the homogeneous foamed glass reduced the air infiltration to a minimum. In the coldest months, the tenant uses slightly over 80 gallons of oil. The greatest heat loss is at the perimeter of the concrete slab.

In addition to its resistance to heat transfer, this material has very good resistance to moisture penetration. Some small penetration occurred at the joints of panels. At these points, caulking compounds were applied which remedied the situation.

The house has weathered the elements for ten years and has proven structurally sound against high wind, including "Hurricane Hazel." The cost of the experimental unit was $14,117. This included all material, labor, trial installations and development work. It was estimated that the potential cost of the same unit produced on a mass-production basis and erected by an experienced crew would run about $7,600 using 1949 costs.

The newest use of foamed glass is in the acoustical absorption field. Foamed glass, as originally manufactured, is a completely closed-cell material. In order to give the material sound-absorbing properties, foamed glass with open cells has been developed. A unit is now being produced which measures 13-1/2" x 13-1/2" x 2-1/2" having four 2-1/2" square x 1/2" thick pads on the back for mounting, to leave a 1/2" air space behind each unit. This unit is designed to be used as a "patch absorber."

These foamed glass units (Fig. 1) are incombustible, rigid, and dimensionally stable. They will not shrink, warp or change dimension with changes of temperature or humidity. The units are especially designed as a sound-conditioning material to provide the architect or designer with a product whose prime function is sound absorption, diffusion and control. By the proper placement and spacing of these units in a room, the reverberation time and diffusion of the sound waves may be closely controlled.

Let us look at how the foamed glass sound absorbers are adapted in a room to provide good listening conditions. For example, if we decided that a particular room is to have a certain desired reverberation time, and calculated that "x" amount of Sabins of absorption is required, knowing the number of Sabins required, we divide this figure by two which gives the number of absorbers required, since each foamed glass unit absorbs an average of 2.0 Sabins over the speech frequency range.

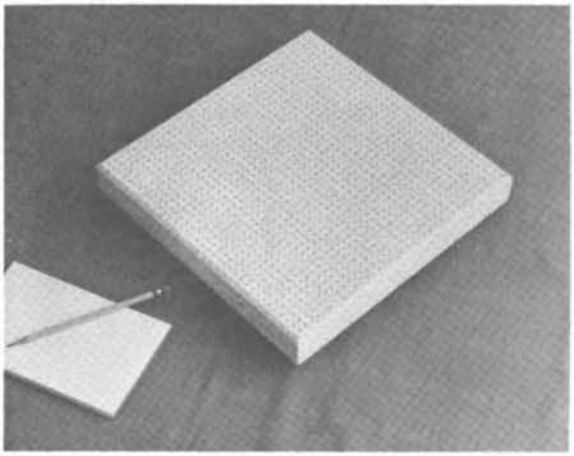

Figure 1.

Figure 2.

Figure 3.

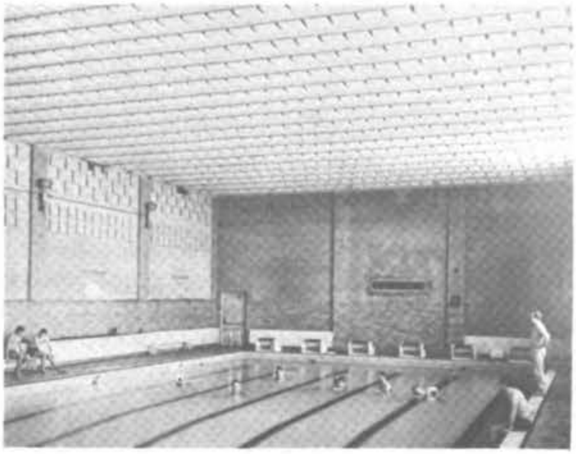

Figure 4.

For good acoustics, the sound reflection must be diffused and must not give a directional impression. To accomplish this, the absorbing units should be distributed on the surfaces of a room and not concentrated on one surface or in large areas. This can be done by the "spot-and-patch" technique. This consists of spacing absorbers to provide contrasting reflection and absorption surfaces. With foamed glass unit absorbers, this is easily done because of the independent unit design that allows spaced or cluster mounting on wall and ceiling areas.

In general, the upper areas of the wall and perimeter areas of ceilings in from the wall are used for mounting the units. In classrooms or auditoriums, the units are placed in larger numbers around and toward the listening (audience) end. At the speaking end, the units are few or nonexistent, for reflective reinforcement. In areas of general noise (cafeterias, swimming pools, etc.) the units are placed uniformly around wall and ceiling areas. Figure 2 shows foamed glass absorbers being placed on the wall. Figure 3 shows a classroom treatment, and Figure 4 shows the units on the walls and ceiling of a swimming pool.

Another use of foamed glass has been in the construction of cold storage warehouses. Blocks of foamed glass have been erected and fastened to the steel framework forming the outside wall where they also serve as insulation. Foamed glass blocks have also been placed between or over bulb purlins to form the structural roof deck. Figure 5 shows foamed glass being erected against the outside framework of a large freezer.

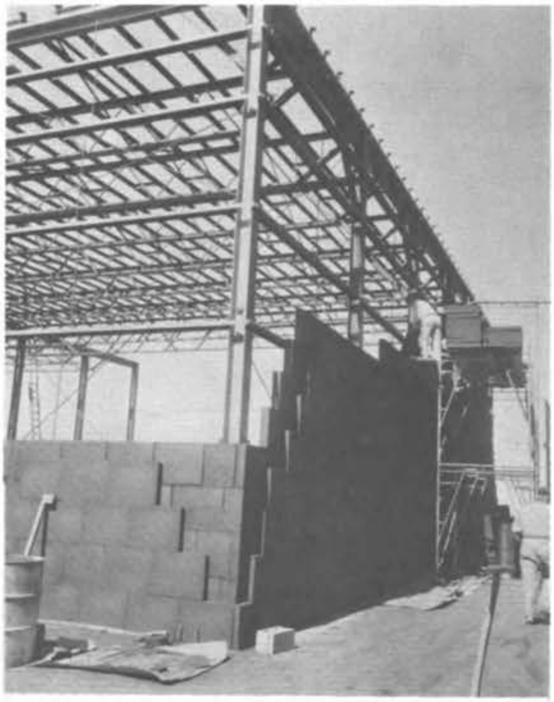

Figure 5

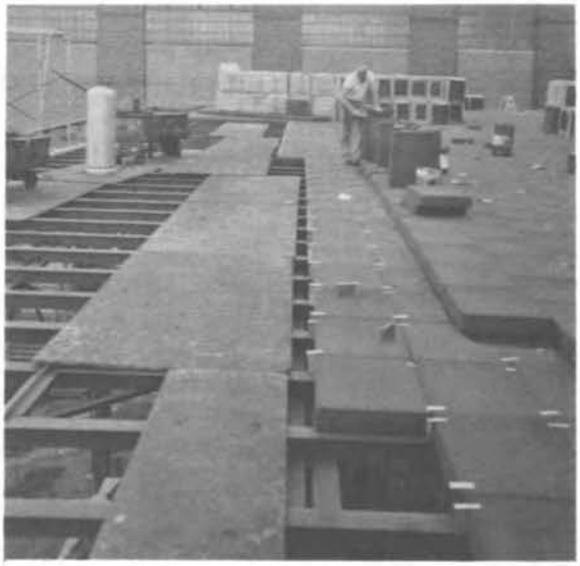

Figure 6

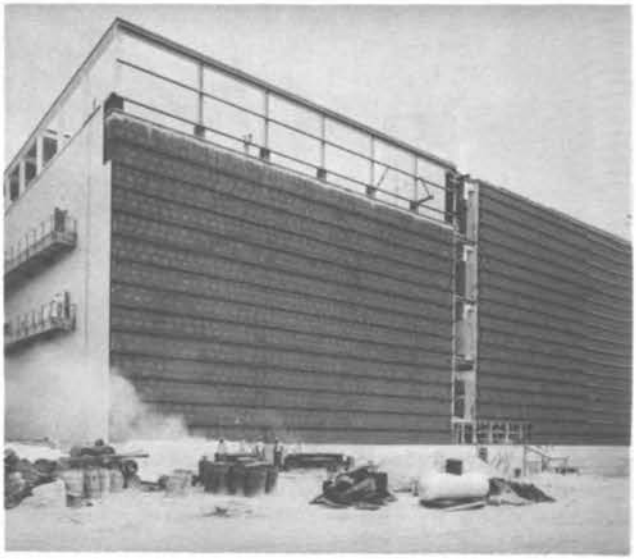

Figure 7.

Figure 6 shows foamed glass being used on a large brewery. Foamed glass walls built in this manner are usually 7" to 8" thick and are erected in two layers, with horizontal and vertical joints staggered to prevent any thermal short circuit. The outside of the wall is usually finished with stucco or metal siding. If metal siding is used, horizontal wood sleepers are imbedded in the outer layer of foamed glass to facilitate fastening of the metal.

One might question how this construction stands up structurally. Wind load tests have been run on a 10'-0" x 20'-0" x 8" thick foamed glass wall panel. Before excessive deflection took place, the wind velocity exceeded 78 mph. The panel tested did not have an outside finish, which would add to the structural strength. Also, the foamed glass is rigid, having an ultimate compressive strength of 100 lbs. per sq. in., and the material is not affected by moisture or changes of humidity, which insures against sagging or buckling of the wall.

Foam and Gas Concretes

By Rudolph C. Valore, Jr.,* Director of Research,
Sika Chemical Corporation

INTRODUCTION

Low density cellular concrete may be obtained by incorporation of a homogeneous cell structure within a cementitious slurry. Methods of preparation and properties of cellular concretes were described in an earlier paper (1).**

Cellular concretes are divided into two major groups, according to the method of curing. In one group are materials subjected to moist curing (including steam curing at atmospheric pressure) and in the other are those cured in an autoclave (in saturated steam at temperatures near 350°F). This classification differentiates the materials in some degree with respect to composition, physical properties, and uses.

Within each type, cellular concretes may be graded according to density. Materials weighing as little as 15 to 20 lbs. per cu. ft. when dry may have only sufficient strength to hold their shape and may be used as thermal insulation or fill. Densities of load-bearing cellular concretes may range from 30 to 100 lbs. per cu. ft.; compressive strengths in this density may range from several hundred to several thousand psi.

History

Lach (2) and Graf (3) cite relevant patents and other literature. Kudriashev (4) gives a history of Russian autoclaved cellular concretes. Whitaker (5) has reviewed literature on cellular and other lightweight concretes.

A patent of Aylsworth and Dyer (6) in 1914 covered the use of aluminum and other powdered metals and calcium hydroxide as chemical gas-forming agents in cementitious mixtures. Patents of Adolf and Pohl (7) cover the use of hydrogen peroxide and sodium or calcium hypochlorite for similar purposes.

Bayer (8) was granted patents beginning in 1923 on the preparation of cellular concretes by "foaming" processes, including the blending of prefoamed air-foams into cementitious slurries; curing in high-pressure steam was recommended. Significant developments since 1936 in air-foams used to combat gasoline fires are chronicled in the patents on hydrolyzed protein foaming agents listed by Clark (9). The air-foams are useful in producing "pre-foamed" concrete.

Ippach and Bieligk (10) were granted a French patent in 1923 on "cellular" concrete made with excess water instead of a gassing or foaming agent.

Patents granted Eriksson (11) since 1923 cover the use of aluminum powder in moist-cured and autoclaved concretes containing lime and burned oil shale. Patents of Lindman (12) and Sahlberg (13) cover the use of fly ash and finely divided silica, respectively, in cellular concretes.

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*RUDOLPH C. VALORE, Jr., Member American Concrete Institute, American Society for Testing Materials, Highway Research Board; A.B., North Dakota State Teachers College, A.M., New York University; formerly associated with Texas Industries, Inc., and with National Bureau of Standards.

**Raised figures in parentheses refer to list of references at end of paper.

Commercial Production and Applications

Moist-cured or atmospheric-pressure steam-cured cellular concrete finds its largest use in nonstructural applications in which it serves as thermal insulation or fill. It may be cast in place over steel decking for roof insulation. The low strength is sufficient in this application and the moderate to extensive shrinkage cracking, controlled by the decking itself or light reinforcement, is not highly objectionable. The cured and dried insulating concrete is finally covered with conventional roof-waterproofing membranes. Underground steam lines laid in trenches are insulated by placing cellular concrete around them. The strength requirement is virtually nil and shrinkage cracking of no consequence. Cellular concrete for roof insulation may have strength in compression of 100 to 300 psi and densities of 20 to 30 lbs. per cu. ft.; for underground steam lines densities of 15 to 20 lbs. per cu. ft. and strength as low as 50 psi are satisfactory.

Some efforts have been made to use nonautoclaved cellular concrete in production of precast short-span reinforced plank. Shrinkage cracking is often excessive in this application and low strength, while it does not vitiate such semi-structural applications, renders handling of elements difficult without extensive damage.

It can be stated generally that in most applications of all types of precast cellular concrete the strength requirements may be influenced as much by the necessity for transporting and handling elements without extensive chipping and cracking as by structural requirements.

Commercial production of autoclaved cellular concrete has attained a high level in Sweden. One of the Swedish products (14) is made from limestone and oil shale which are burned together; this "shale-lime" is ground to a fine powder and then mixed with aluminum powder, other chemicals, and water. Large molds are partially filled with the thin slurry. As the gas generation nears completion the material overflows the molds; after initial set, excess material is struck off (to be re-used in a following batch), the sides of the molds are removed, and the large masses of material are cut into blocks or slabs. These units are then cured in autoclaves (Figs. 1 through 6).

Another Swedish cellular concrete (15) is made by a similar process with portland cement, ground silica sand, and aluminum powder. The materials used most widely in building-block form have a density of about 35 to 45 lbs. per cu. ft. and compressive strengths claimed are 800 and 1,000 psi.

Swedish construction with cellular concretes employs some innovations. In one application, a suitably braced wall of low-density block is the exterior form for ordinary concrete which forms the structural part of the wall. The external "insulation-form" is later stuccoed. It is claimed that the increased proportion of the total heat capacity contained within the external insulation reduces temperature fluctuations in a building, due to changes in weather. A variety of special shapes is manufactured. Reinforced roof planks, beams, and lintels are widely used; unreinforced panels are also made. These autoclaved cellular concretes can be sawn easily with a carpenter's saw and are said to be nailable.

Virtually all Swedish concrete masonry above grade is cellular concrete. Almost all cellular concrete masonry exterior walls are stuccoed to provide protection from frost action and to improve appearance.

Much of the Swedish production is in the form of reinforced members. Plank up to 20' in length and 8" or 10" thick contain both tensile and compressive reinforcement. The relatively low strength concrete simply becomes a "holder" for the reinforcing steel from which it derives its load-carrying capacity. Roofs of industrial buildings and apartments are constructed of such planks, which may then be caulked and covered with conventional roofing membranes.

Fig. 1 - Swedish factory for making autoclaved cement-silica cellular concrete showing multi-level form cars with uncured material cut into slabs and blocks.

Fig. 2 - Cured autoclaved cellular concrete in Swedish factory showing lintels, beams and slabs.

Fig. 3 - Partially completed factory building with walls of autoclaved cellular concrete.

Fig. 4 - Floors of houses made of autoclaved cellular concrete.

Fig. 5 - Partitions and roof (partially erected) of housing units constructed with autoclaved cellular concrete.

Fig. 6 - Roof construction with autoclaved cellular concrete for factory building.

Cellular concrete planks are also used for floors of houses and, placed vertically or horizontally, for walls and partitions of factories, apartments, houses and other buildings. Interior surfaces are plastered and exterior surfaces are stuccoed or covered with cement base paint.

In its various applications and methods of handling at job sites, precast cellular concrete more closely resembles timber than more conventional members of the concrete family.

Cellular concretes produced in the United States, Russia and elsewhere are made according to "prefoaming" processes. Commercially available foaming agents and equipment for producing cellular concretes by preformed foam processes have been developed in Great Britain (16) and the United States (17, 18).

Ingredients of Cellular Concretes

The cementitious or "binder" ingredient of moist-cured or atmospheric-pressure steam-cured cellular concrete is portland cement. Because the modest strength requirement should be developed in the shortest possible time, rapid-hardening, "high-early-strength" (ASTM Type III) cement is often used. Alternatively, normal (Type I) cement may be used, with or without chemical accelerators.

Moist-cured cellular concretes have been proportioned, 1:0 (neat cement) to 1:4, (bags of cement: cu. ft. of sand or lightweight aggregate).

For precast autoclaved cellular concrete, optimum physical properties result when the binder consists of two or more finely divided components that will react chemically under the influence of elevated temperatures in the presence of water to form strong, dimensionally stable calcium hydrosilicates (19).

Portland cement is "unbalanced" chemically when used as the sole binder in autoclaved products, and therefore does not produce optimum strength, although it does produce superior dimensional stability. Portland cement normally consists of 20 to 25% of SiO_2 and 60 to 68% of CaO, a ratio of lime to silica (by weight) of about 3. This ratio is optimum for producing dicalcium silicate and tricalcium silicate as cementing compounds. Kalousek and Adams (20), and Miranov and Malinina (21) have shown that the major reaction products of lime and silica in autoclaved products are hard and strong crystalline forms of calcium hydrosilicate having a molar ratio of lime to silica of approximately 0.9, or a weight ratio between 0.8 and 0.9. This material appears to be similar to a form of the mineral tobermorite, having a molar ratio of 0.8, according to Kalousek.

The lime-bearing cementitious ingredient may be portland cement, lime (hydrate or quicklime) or a blend of cement and lime.

When portland cement is the sold binder and the mixture contains no aggregate with available reactive silica, strengths after autoclave curing will be considerably lower than after 28 days of moist curing, and may be less than half the strength of autoclaved mixtures containing sufficient available reactive silica to react with all of the lime in the cement.

To assure that there will be sufficient silica to react with all of the lime present, it is usually necessary to supplement the silica in the cement by adding finely ground quartz sand (almost pure silica) or some other finely divided material rich in reactive silica such as fly ash, ground burned shale, clay or slate, ground brick or tile, glass polishing waste, diatomaceous earth, ground pumice or other "pozzolans." The siliceous material is usually added as a partial replacement for cement in the mix, the optimum percentage depending primarily on the chemical composition and fineness of the siliceous material, the amount of available silica in the aggregate (if an aggregate is used) and the chemical composition and fineness of the cement. In the manufacture of autoclaved masonry units, including those containing a siliceous aggregate, it is usually advantageous to replace 25 to 50% of the cement by ground silica having a fineness similar to that of portland cement. If the siliceous ingredient is a "pozzolan," i.e., capable of reacting with lime hydrate at ordinary temperatures, it will probably react during autoclave curing and the quantity required to achieve optimum properties may be substantially greater than when purer forms of silica are used.

For some mixtures subjected to autoclave curing, lime may be used instead of portland cement in the form of high-calcium hydrate (calcium hydroxide over 90%) or quicklime (CaO over 90%). Some of the less pure forms of lime are hydraulic, i.e., they will "set" or harden under water in a manner similar to the behavior of portland cement. Some of the European commercial autoclaved cellular products are made with hydraulic limes. The percentage of magnesia (MgO), however, should not exceed about 3% to avoid disruptive expansion due to hydration of magnesia during autoclaving. Hydraulic limes of composition satisfactory for autoclaving are rare in the United States.

High calcium hydrate and quicklime are not hydraulic, i.e., they will not harden readily in a moist atmosphere or under water. While lime may be used as the sole binder in sand-lime brick or other preformed products, it is essential that the relatively fluid mixes of cellular concrete develop sufficient "set" to prevent disruption of cell structure during temperature rise in the autoclave. The use of a minor proportion of cement with lime is sufficient to provide this necessary stiffening. Quicklime readily hydrates when mixed with water with evolution of considerable heat. For this reason it may be used in combination with and to accelerate the setting of portland cement. The heat evolved during and shortly after mixing, controlled by the amount of quicklime used, and the immobilization of a portion of the mixing water will accelerate the initial setting of the cement and permit early autoclaving. Whether quicklime or the hydrate is used, the essential ingredient is calcium hydroxide which requires, as is the case with the lime present in cement, finely divided silica with which to react during the autoclave curing to form stable calcium hydrosilicate.

From the foregoing it may be concluded that optimum binders for economical production of autoclaved cellular concrete may be blends of lime and cement over a broad range of proportions. Lime may be used as an admixture for cement, or conversely, cement may be used as an admixture for lime.

A sufficient quantity of reactive silica must be present to react all of the lime, for optimum results. Unreacted lime remaining in the cured product causes low strength, because lime itself is not a hard or strong material and is soluble in water. Generally an excess of siliceous material is desirable for economic reasons, to assure ready combination with all of the lime, and because most siliceous materials are hard and strong and excess unreacted silica serves as relatively inert and inexpensive filler or aggregate without seriously lowering strength. This principle is true to a lesser degree, when portland cement is used, but when using lime, the available silica must exceed a critical value. This critical value depends not only on the silica content of the siliceous material but on its fineness as well. Silica in the interior of a coarse particle of silica flour may not react with lime during the limited autoclave curing schedules used commercially. In the manufacture of sand-lime brick only a small proportion of the sand, consisting of the finest particles, and relatively small surface area of the coarser sand particles serve as aggregate, sand-lime ratios in the range of 1:10 to 1:20 being common.

Accordingly, the proportion of siliceous material to cement or lime used in the manufacture of autoclaved cellular concrete is usually well above what might be considered stoichiometric amounts. For mixtures made with cement, ratios of cement to silica flour (of equal fineness) of 1:1 to 1:3 are used; for a good, low-carbon fly ash, ratios of 1:1 to 1:4 may be satisfactory. When lime hydrate is used the proportions of lime to siliceous material may be 1:2.5 to 1:5 and even greater proportions of siliceous material may be used with quicklime.

The physical properties of autoclaved cellular concrete depend in part on the chemical nature of the cement or lime used. The reasons are obvious in the case of lime, but for cements which consist of several major potentially cementitious compounds, conflicting conclusions on the role of cement composition have been given by various investigators. Reasons for such conflict may be found in the fact that cements have changed during the period covered by various studies, and the work done in various countries probably involved studies of dissimilar basic ingredients.

The two most important cementitious components of portland cement are dicalcium silicate (C_2S abbreviated for $2CaO.SiO_2$) and tricalcium silicate (C_3S for $3CaO.SiO_2$). The alumina compounds, tricalcium aluminate (C_3A for $3CaO.Al_2O_3$) and tetracalcium alumino ferrite (C_4AF for $4CaO.Al_2O_3.Fe_2O_3$) are also important.

The calculated potential cementitious compound composition of a typical Type I cement is as follows, according to Bogue (22):

C_3S	45%
C_2S	27%
C_3A	11%
C_4AF	8%

Miranov and Malinina (21) studied the strength-producing properties of pastes of cements varying over a wide range in composition and of pastes of the four major cementitious ingredients individually, all with and without additions of silica flour, as influenced by moist curing and by autoclave curing at various temperatures and of several durations.

Neat pastes of C_3S and C_2S each develop low strength during autoclave curing, according to Miranov and Malinina, but when finely divided silica flour is added in optimum proportions strengths are increased several fold. The optimum addition of silica for C_3S is twice that for C_2S. C_3A neat paste develops no strength during autoclave curing but modest strengths are obtained when silica admixture is used. C_4AF develops high strength but added silica lowers the strength progressively as the amount added is increased. For silica addition producing optimum strength for C_3A however, the strength of C_4AF with a similar addition is several times greater.

On the basis of studies by Miranov and Malinina, it may be concluded that portland cement for autoclaved cellular concrete should contain the highest practicable quantity of C_3S and the lowest practicable quantity of C_3A. Alumina should preferable be present in the form of C_4AF. The present author has determined that mortars made with a cement having 70% C_3S and no C_3A had strengths after autoclave curing 40 to 80% higher than those obtained with other "typical" cements.

Aggregates

Autoclaved cellular concretes usually contain no aggregates in the usual sense.

When aggregates are used, they are generally dense siliceous sands. Most of Graf's (3) moist-cured cellular concretes made by gas-generating processes contained sands having 10 to 20% passing the No. 100 sieve, and less than 5% passing the No. 200. In Graf's concretes of identical density and cement content, sand gradation had little effect upon compressive strength, except for concrete containing the finest sand, which had a markedly lower strength.

The use of lightweight aggregates as sole means for reducing the weight of concrete is not within the scope of this report. However, we may consider concretes that are hybrid lightweight aggregate-cellular concretes (23). In such cases the cementitious paste contains a high air or gas volume of the order of 30% of the concrete volume or higher, and the purpose of the cell structure is limited to a lowering of density. Such aggregates as expanded perlite, vermiculite, clay, shale, slate or slag can be used in concretes which are rendered cellular in structure by use of foaming agents, preformed air-foams or chemical gas-forming agents. Such combinations provide lower densities than when sand is used as aggregate. The lightweight aggregate is preferably of a "sand" or fine gradation with maximum particle size less than 1/4" or 1/8". The use of preformed air foams with expanded clays and shales not only provides moderately low concrete density, but also produces lower drying shrinkage than when no aggregate is present. Such mixtures can be cured at ordinary temperature or autoclave cured. The finest particles of the clays, shales and slates are usually pozzolanically reactive at ordinary temperature, and reactive with lime or cement in the autoclave because of their high silica contents.

Coarse aggregates are not used when a gas-generating process is employed because, prior to gas generation in sufficient quantity to "thicken" the thin slurry, the larger particles do not remain uniformly suspended.

Acceleration of Hardening

Moist-cured cellular concretes have a low strength potential relative to ordinary dense concrete. Without acceleration, the time required for removal of forms, or for handling precast elements, must be extended beyond requirements of convenience and economy. If hardening is delayed too long the cell structure may become unstable and show a marked decrease in volume. In autoclaved cellular concretes large changes in temperature prior to or during the onset of solidification may disrupt the cell structure. Shortening the period between mixing and autoclaving is desirable.

An effective method of accelerating setting is the use of heat, by using ingredients at a uniform elevated temperature. Foaming agents and preformed foams generally lose their stability at temperatures of 120°F or higher. Specially developed foaming agents are said to be stable up to 150°F, however (18).

In some European commercial applications in which aluminum powder or hydrogen peroxide gas-generating processes are employed, all materials are stored at a uniform elevated temperature prior to and following mixing so that acceleration due to heat is attained without large changes in temperature. Storage temperature in such cases may be 100 to 120°F. The use of mixing water at 150°F was recommended in a process patented in 1927 by Schenck (24).

Chemicals successfully used for accelerating setting and strength development of portland cement concrete may be satisfactory in cellular concretes. When calcium chloride, other salt solutions, or waterglass are used they should be added and mixed into the slurry prior to introducing preformed foam or foaming agent, to avoid loss of air. Sodium hydroxide, triethanolamine, or high alumina cement should not be used in autoclaved materials because autoclaving destroys the cementitious value (25). Calcium chloride has been used in moist-cured and autoclaved cellular concretes with high-early-strength cement (26). A proprietary admixture designed to accelerate hardening of foam concrete was developed recently (27).

Plaster of paris, gypsum and anhydrite have been used to accelerate the early hardening of cellular concretes.

In the hydrogen peroxide-calcium hypochlorite process, calcium chloride is a reaction product. In the aluminum powder process, supplementary alkali in the form of sodium hydroxide is often added (28).

Water Ratios

For autoclaved mixtures containing finely divided siliceous materials the water-solids ratio appears to be of greater significance than the water-cement or water-lime ratios. Water-solids ratios of experimental mixtures reported earlier ranged from 0.45 to 0.85 (1). Lowest values, for silica and low carbon fly ash of cement fineness, varied little with proportions. The highest values, for expanded slate kiln dust (much finer than the cement) and for a fly ash containing 9% of carbon but of the same fineness as the cement, depended to a marked extent on the proportion of siliceous material used.

For cellular concretes in general, it is customary to gage the proper amount of water in a mix by consistency rather than by a predetermined water-cement or water-solids ratio.

Inasmuch as properties of cellular concretes are always compared in relation to dry rather than to wet densities, very wet mixtures are not precluded. In the excess-water process all of the "cells" are micropores remaining after evaporation of excess water, and the water-cement ratio loses completely the connotation it carries in conventional concretes; water-cement or water-lime ratios of 5 to 10, or whatever value is necessary to obtain the desired density, may be used.

PREPARATION OF CELLULAR CONCRETES

The necessarily intimate degree of mixing of the finely divided ingredients of cellular concrete may be accomplished most efficiently by rapid mixing. Small amounts of gas-generating chemicals must be dispersed uniformly in a fluid mixture to produce a homogeneous cell structure. Efficient use of foaming agents in the mix-foam method requires rapid beating or whipping action; in the preformed foam process, rapid mixing produces a homogenous structure of relatively small and stable air cells free from foam inclusions.

Kitchen-type mixers are suitable for small experimental batches and, for larger batches, types used for mixing dough in bakeries are satisfactory. Horizontal drum mixers with rotating paddles, and the types used for mixing plaster or mortar, may be readily adapted for mixing cellular concretes by using a motor which permits continuous variation in paddle speed up to 90 or 100 rpm. "Blenders" with vertical drums and paddles rotating at speeds up to several hundred rpm have been used by others.

Chemical Processes

The most widely used gassing agents are aluminum powder and hydrogen peroxide. In theory, a known quantity of agent reacts with chemicals, added or otherwise present in a cementitious mixture, to generate a known volume of gas. Ideally, the mixture expands a predetermined amount.

Aluminum Powder Process–In portland cement mixtures sodium hydroxide may be added with aluminum powder to accelerate the reaction and, by decreasing hydrogen ion concentration of the mixture, permit all aluminum to be consumed in the reaction, according to Caldwell (28).* Caldwell gives the reaction as

$$2\,Al + 2\,Na\,OH + 2\,H_2O = 2\,Na\,Al\,O_2 + 3\,H_2$$

According to this equation, 1 lb. of aluminum liberates about 20 cu. ft. of hydrogen gas under standard conditions of pressure and temperature. For some mixtures, to obtain a dry density of 40 lbs. per cu. ft., expansion should be approximately 100%, and cell volume about 50% of the expanded mixture. The theoretical aluminum requirements, per cu. yd. of concrete, should then be a minimum of about 0.6 to 0.8 lb. This requirement would be influenced, to some extent, by the proportions of solids, and to a greater extent by appreciable variations in water content of the mixture. In practice, however, perfect efficiency is not obtained and the aluminum requirement is usually higher than the theoretical. Under the best conditions, about 1 lb. of aluminum per cu. yd. of concrete is required for a density of 40 lbs. per cu. ft.

Efficiency of aluminum powder may be influenced by the amount of sodium hydroxide

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*The reaction of aluminum and calcium hydroxide is: $2Al + 3\,Ca\,(OH)_2 = Al_2\,(CaO)_3 + 3\,H_2$.

used, which is usually two or three times the weight of the aluminum; by particle size of the aluminum, which is usually finer than 50 microns; by the purity and degree of agglomeration of the aluminum particles; and by means taken to prevent escape of gas from the mixture before hardening. The last-mentioned factor requires an agent to stabilize the gas cells; foaming agents such as saponin or a neutralized resin have been used for this purpose.

Aluminum powder may be mixed dry with the cement; water, stabilizing agent, and aggregate or pozzolan may then be added and mixed for a short period; sodium hydroxide is usually added last, followed by a final short mixing period. Molds are partially filled with the thin slurry, which expands as hydrogen is generated, in from 20 min. to more than an hour. If the cells are not stable, the mixture may collapse after expansion is complete or the mixture may be denser at the bottom than at the top. These difficulties may be overcome if solidification begins shortly after completion of expansion. If the cells are irregular, rather than sperical in shape, due either to agglomeration of aluminum particles or instability of the cells, excessive lowering of final strength occurs. The method is said to require precise control of temperature (29).

Despite various difficulties and the critical nature of required precautions, some products produced by the aluminum powder method are of excellent uniformity, expecially when produced on a large scale with close control of raw materials and manufacturing conditions. The scatter in density values reported by Vinberg (30) for factory-produced materials under optimum conditions indicates that precise control of density is difficult, however.

Hydrogen peroxide process — Reaction between hydrogen peroxide and calcium hypochlorite (bleaching powder) is given by Graf (3) as

$$CaCl(OCl) + H_2O_2 = CaCl_2 + O_2 + H_2O$$

The ratio used of commercial bleaching powder (with 70% of active chlorine) to hydrogen peroxide (30% solution) may be 1.5 or higher. One pound of 30% H_2O_2 evolves approximately 3-1/4 cu. ft. of oxygen, according to the equation. For cellular concretes weighing 40 lbs. per cu. ft. (as considered in the section on the aluminum powder process) about 4 to 5 lbs. of 30% H_2O_2 and 6 to 8 lbs. of bleaching powder with 70% of active chlorine are theoretically required per cu. yd. of concrete. The H_2O_2 process theoretically does not depend upon the chemical nature of the cement-water mixture and presents no problems of agglomeration, particle size, dispersion, or purity, as use of aluminum powder does. Stabilization of cell structure is necessary, however, and saponin, neutralized resin, or other foaming or air-entraining agents may be used for this purpose. Calcium chloride is evolved from the chemical reaction in amounts sufficient to accelerate solidification of the mixtures (almost 2% by weight of cement in 1:2 cement-silica mixtures weighing 40 lbs. per cu. ft. when dry).

Graf (3) has indicated that the oxygen and calcium chloride evolved in the H_2O_2 process cause rusting of steel reinforcement, and recommends that molds of noncorrosive material be used. Graf has also shown that the density may be considerably lower at the top than at the bottom of a specimen, and for this reason the height to which the freshly mixed material may expand should be limited to not more than 16".*

In the hydrogen peroxide process the gas may, if desired, be almost entirely evolved during mixing, or alternatively, most of it may be evolved in the molds. When hypochlorite is added and mixed into a premixed slurry prior to adding the mixing the peroxide, the "mix-expansion" occurs.**

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*Dilnot(29) states that maximum rise is restricted to about 12" when the aluminum powder process is used.

**To provide greater uniformity in mixing, calcium hypochlorite is prepared as an aqueous suspension before use. In mixtures made at the National Bureau of Standards, a suspension of 1 part of hypochlorite (70% of active CL) in 3 parts of water (by weight) was used.

More gradual "mold expansion" occurs when the order of adding and mixing of the chemicals is reversed. Mix-expansion permits measuring the density of the expanded concrete before molding; this cannot be done when aluminum powder is used. A high degree of reproducibility is claimed for the peroxide process. It is claimed that cell size may be controlled by the choice of cell-stabilizing material (31).

FOAMED CELLULAR CONCRETE

Foaming processes used in making cellular concretes are air-entraining in character and some agents used in structural, sand-gravel air-entrained concretes may be used as foaming agents. The term "foaming" connotes relatively high air contents. The following types of foaming agents have been used:

1) Detergents and wetting agents (sodium lauryl sulfate, alkyl aryl sulfonate, and others).
2) Resin soap and vegetable (8) or animal (32) glue.
3) Saponin.
4) Proprietary neutralized resin.
5) Hydrolyzed protein such as keratin ("hoof and horn meal") (9), cattle hooves and fish scales (18), blood and saponin (9), and casein.

Experiences with gas and foam processes indicate that excellent cellular concretes, indistinguishable in physical properties, may be made by both methods.

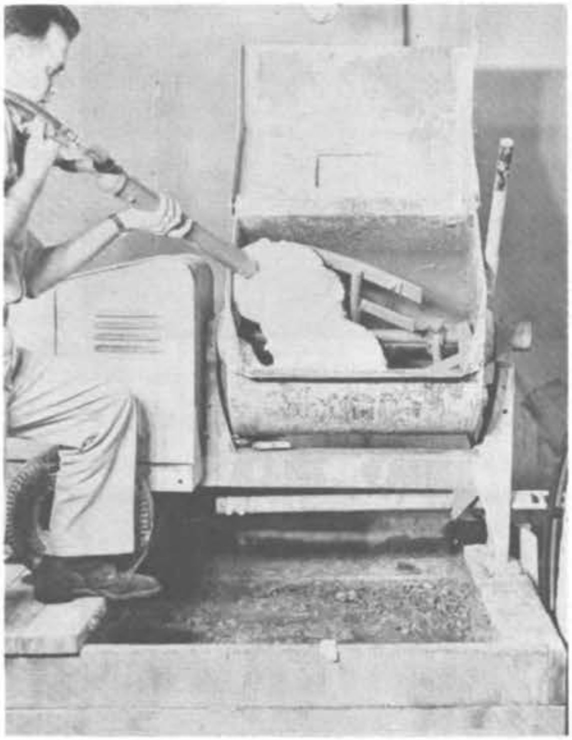
In the mix-foam method, a foaming agent may be added to the mixture after all other ingredients (including an accelerator) have been mixed to a fairly thin slurry; the mixer may then be operated at 80 to 90 rpm for a final 2 or 3 min. Consistency after mixing may be that of an easily pourable but thick cream; more viscous mixtures are susceptible to entrapment of large air voids during mixing or molding. Molds are usually filled to overflowing to compensate for some subsidence due to bleeding of water through the bottoms of the molds. The quantity of foaming agent required to obtain a given density is affected by mixing speed and character of the mix ingredients, and may depend upon the type of mixer used, quantity of materials mixed, mix consistency, nature of the accelerator, mix proportions, length of mixing period, and, most important, the type and brand of foaming agent used.

Preformed foam processes were used in making commercial moist-cured materials in Europe prior to 1926 (8). The development of hydrolyzed protein foaming agents and compressed-air foam generators (9) brought several manufacturers of foaming agents used in fire fighting into the cellular concrete field. Development by these firms has evolved simple and economical equipment and techniques for preparing and using air-foam as an "aggregate" in cellular concretes. Under ideal conditions, an amount of "air foam" containing a definite volume of air is blended (Figs. 7, 8 and 9) without change in volume, into a premixed slurry. The foams have densities of 2 to 5 lbs. per cu. ft. and are prepared from 2 to 4% solutions of foaming agents; foam density and concentration of the foaming agent solution depend upon the brand of agent used.

Using the same type of mixer employed in preparing mix-foamed concretes, satisfactory results have been obtained with prefoamed foam.

In commercial applications, foam is "injected" from the foam generator directly into the mixer and the quantity is gaged by duration of delivery. Advantages of the preformed foam method are a much lower foaming agent requirement than in the mix-foam process, and a close relationship between the amount of foaming agent used and the air content of a mix.

Mixing of cellular concrete using the excess-water method has been described by Anderegg (33); this method was used by Hummel and Huttemann (34) and is based upon a previously cited patent of Ippach and Bieligk (10). Excess-water mixtures patented by Swezy and Jones in 1941 (35) consisted of hydrated lime, finely divided slate, or shale, and had water-solids ratios of 1.2 to 8.



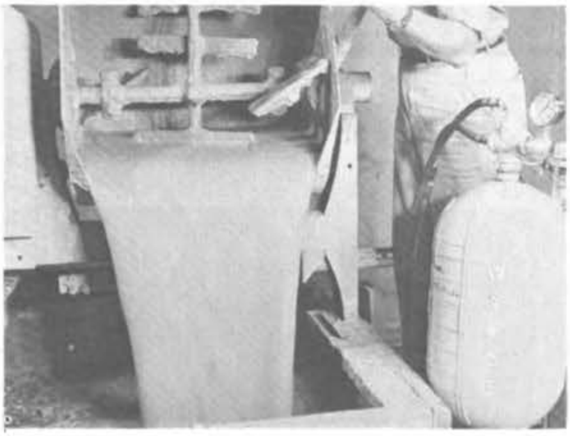


Fig. 7 - (Upper left) Preformed airfoam being injected into mix.

Fig. 8 - (Above) Partially blended airfoam and cementitious slurry.

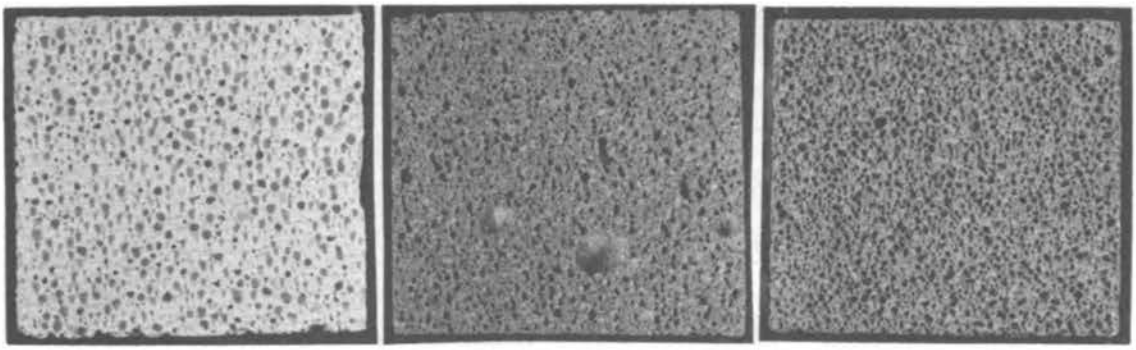
Fig. 9 - (Left) Discharging foam concrete made with preformed airfoam from mix.

The process generally involves the use of lime (quicklime or hydrate) and finely ground silica, slate or shale; asbestos fiber or diatomaceous earth may be added as water-retaining materials. The material is cured in an autoclave. Densities of 30 lbs. per cu. ft. or lower may be obtained. Since low density depends on a fine pore structure left by evaporation of excess water, absorption may be relatively high, despite autoclave curing.

Comparison of Cell Structures Produced by Various Methods

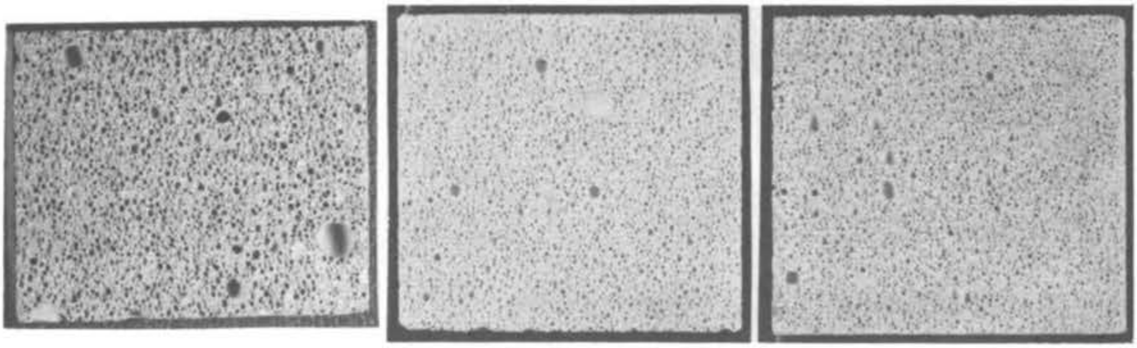
Figures 10 and 11 are photographs of the ground surfaces of various cellular concretes. In Figure 10 (a) is a Swedish cement-silica autoclaved material made with aluminum powder; (b) is a Swedish autoclaved lime-shale material made with aluminum powder; (c) is a moist-cured neat cement made with aluminum powder. Density of these materials was 35 to 45 lbs. per cu. ft. All materials in Figure 11 were autoclaved and were made: (a) by the preformed foam process, and the others by mix-foaming.

Figures 12 and 13 show cell structures of materials made by the hydrogen peroxide and prefoam processes, respectively (x 14).



(a) (b) (c)

Fig. 10 - Commercially produced cellular concretes made by aluminum powder process.



(a) (b) (c)

Fig. 11 - Experimental cellular concretes made by mix-foam and prefoam processes.

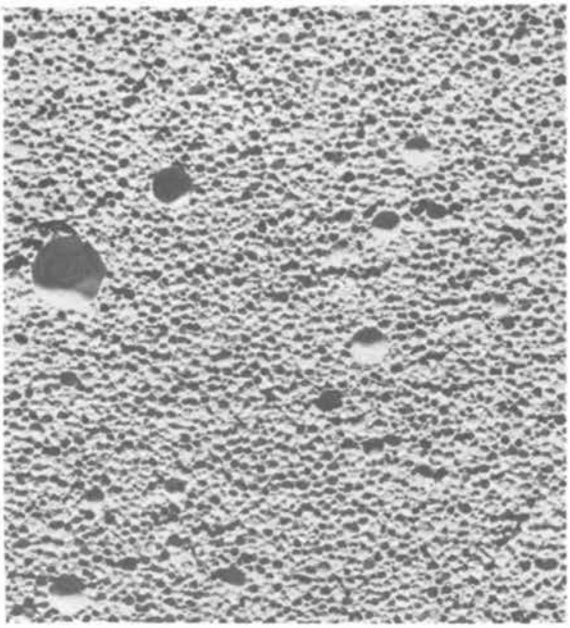


Fig. 12 - Experimental cellular concrete made by hydrogen peroxide process (14X).

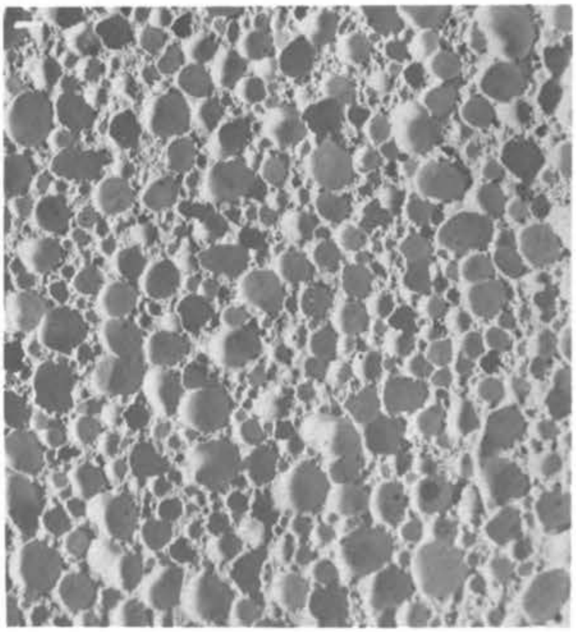


Fig. 13 - Experimental cellular concrete made by prefoam process (14X).

CURING OF CELLULAR CONCRETES

Moist Curing

Insulating and fill concretes are usually given a short period of moist curing (1 to 7 days) and then allowed to air dry, prior to application of a moisture-proofing material. The time required for satisfactory air drying is smallest in the materials of lowest density.

Steam Curing at Atmospheric Pressure

Steam curing at atmospheric pressures at temperatures of 125° to 180°F accelerates the hardening of cellular concretes. Drying shrinkage and moisture movement of concretes after atmospheric-pressure steam curing of various durations, up to 24 hrs., differ little from those properties of similar concretes after moist curing for 28 days at 70°F. Atmospheric-pressure steam curing produces strengths generally near those attained after 3 days of moist curing at 70°F if "nonreactive" (nonpozzolanic) aggregates are used, according to Nurse (36). If the aggregates contain reactive silica, strengths following atmospheric-pressure steam curing may be double those attained with similar concrete after 3 days of moist curing at 70°F.

The variables of importance in high-pressure steam curing are:

1) Age and condition of the mixture at the start of the curing cycle.
2) Rates of change of temperature.
3) Curing temperature.
4) Duration of curing at constant elevated temperature.

It is essential with cellular concretes that large temperature changes occur only after initial solidification. In commercial operations in Europe the waiting period may be from 2 to 24 hrs. and preheating is often employed. Waiting periods of 16 hrs. to as long as 4 months have been reported (1). When the concrete was continuously moist before autoclaving, the length of the waiting period had little effect on physical properties. Intermittent drying during an extended waiting period permanently injured the cellular concrete by producing drying shrinkage cracks even after protracted continuous moist curing.

On the basis of presently available information, a satisfactory range of temperatures for high-pressure steam curing of cellular concrete containing optimum ratios of cement or lime to the siliceous ingredient appears to be 345° to 365°F (or steam pressure of 125 to 150 psi). The length of curing under such conditions should be at least 5 to 6 hrs. in addition to the periods required for gradually increasing and decreasing temperature. Curing cycles employed by various European firms are within these general requirements.

Density

The physical properties of lightweight concretes depend rather sensitively upon density, and values for the properties of cellular concrete should be qualified by their relation to density. Appreciable quantities of water used in preparing cellular concretes are removed as the concretes attain a satisfactorily dry condition.

European practice is to use the density after drying at 220°F for 24 hrs. (or to constant weight) as a basis for evaluating other properties. In view of the fairly close agreement between "oven-dry" and "room-dry" densities as shown in Table I, this practice appears reasonable. The percentage by which density of a hardened cellular concrete exceeds the oven-dry density is termed "free moisture," according to the usage of Bessey and Dilnot (26)

COMPRESSIVE STRENGTH

Effects of free moisture upon compressive strength are indicated in Table II. The first 2 to 3% of moisture reduces strength about one-half as much as the 20 to 50%

TABLE I

Density of Selected Cellular Concretes Under Various Moisture Conditions*

Type of Cell Former	Binder	Cure	Density Oven-Dry (lb./cu. ft.)	Ratio of Density to Oven-Dry Density: From Molds	After Auto-clave cure	24-Hr. Soak	Equilibrium 73°F 50% R.H.
Foam	Cement-silica	Autoclave	40	1.34	1.22	1.36	1.02
Foam	Cement-fly ash	Autoclave	50	1.36 to 1.62	1.22 to 1.30	1.43 to 1.73	1.04
Gas	Cement-silica	Autoclave	44	-	-	1.30	1.04 to 1.07
Foam	Cement-silica	Atmos. steam	54	-	-	1.32	1.02
Foam	Cement (sand aggregate)	Atmos. steam	78	-	-	1.20	1.02
Excess water	Lime-pozzolan	Autoclave	20 to 30	>4.00	-	>4.00	-

*From Reference (1).

TABLE II

Effect of Free Moisture on Compressive Strength of Typical Cellular Concretes*

Type of Cell Former	Binder	Cure	Density Oven-Dry (lb./cu. ft.)	Room-Dry / Oven-Dry: Free H_2O (percent)	Room-Dry / Oven-Dry: Strength Ratio	Saturated / Oven-Dry: Free H_2O (percent)	Saturated / Oven-Dry: Strength Ratio
Foam	Cement (sand aggregate)	Atmos. steam	78	2	0.79	20	0.66
Foam	Cement-silica	Atmos. steam	55	2	0.74	32	0.56
Gas	Cement-silica	Autoclave	44	7	0.85	30	0.70
Foam	Cement-fly ash	Autoclave	40	4	0.87	43	0.75
Foam	Cement-silica	Autoclave	40	2	0.88	36	0.73
Foam	Cement-burned slate	Autoclave	45	2	0.88	66	0.57

*From Reference (1).

reduction caused by saturation, in autoclaved as well as moist-cured materials. Effects of similar magnitude have been shown for cement mortars and sandstone by Stradling (36a) and for sand-lime brick by Bessey (37). Bessey and Dilnot (26) state that comparison of strength test results of dry cellular concrete from different sources "can have little meaning without a close definition of the degree of dryness."

Graf (3) and Koudriashoff (32) have stated that increases in strength of up to 40% occur over long periods of storage after autoclaving. An earlier study, including tests of specimens soon after autoclaving, after oven-drying, and after months of room-drying at ordinary temperature, indicated that in many instances increases observed were due to gradual loss of free moisture (1). Oven-dry specimens gradually decreased in strength during subsequent storage at ordinary temperature, apparently due to increases in free moisture. Atmospheric carbonation probably produces gradual increases in strength after very long periods of time for all types of cellular concrete.

Compressive Strength of Moist-Cured Cellular Concrete

Data from various sources, including manufacturers' sales literature, are given in Figure 14 for compressive strength and density of moist-cured cellular neat cement and cement-sand mixtures. Strengths are for specimens 28 days old, except for those reported by one manufacturer for specimens 42 days old. Most specimens were tested in a "room-dry" condition, but a few, as indicated, were tested moist; densities cited were for the room-dry condition for some specimens and for the oven-dry (220°F) condition for others. Specimens were 3" x 6" and 6" x 12" cylinders, and cubes of several sizes.

Moist-cured 1:1.5 cement-pozzolan mixtures of the British Building Research Station (38) made by aluminum powder and foaming processes had cube strengths, when tested wet at 28 days, equal to those of some neat cements shown in Figure 14, at oven-dry densities of 40 to 60 lbs. per cu. ft.

Compressive Strength of Autoclaved Cellular Concrete

In Figure 15 compressive strength data from European literature on autoclaved cellular concretes are shown. Precise moisture contents of the various materials, when tested, are not known, but most are believed to have approached constant weight at ordinary temperature.

Strengths of mixtures made with lime by the excess water method were higher than those of mixtures made with cement by foaming or gassing processes, but silica used with the excess water method was more finely divided.

Figure 15 indicates average strength values of European laboratory and commercial autoclaved cellular concretes. The precise nature of the curing cycles and other details of manufacture are known to the author in relatively few cases; range of curing temperatures and durations of complete curing cycles are believed to be 345° to 370°F and 10 to 24 hrs.

Strength results from an earlier study are presented in Figure 16 (1). These materials were 2" x 3-1/2" cores from 6" x 12" cylinders and were tested in an "air-dry" condition after storage at 73°F and uncontrolled humidity for 4 to 8 weeks.

Results in Figure 16 indicate that cellular concretes made by foaming processes with materials available in this country possess strengths at least equal to those produced commercially abroad.

FLEXURAL AND TENSILE STRENGTH

Graf's (3) empirical relationship between compressive and flexural strengths for autoclaved cellular concretes of various compositions and cell-forming processes is represented by the equation

$$y = 0.75\,x + 0.005\,x^2$$

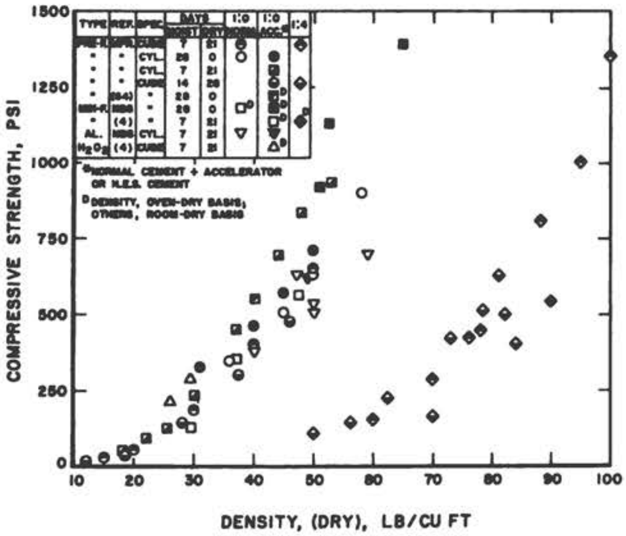


Fig. 14 - Compressive strength of moist-cured neat cement and 1:4 cement-sand cellular concretes.

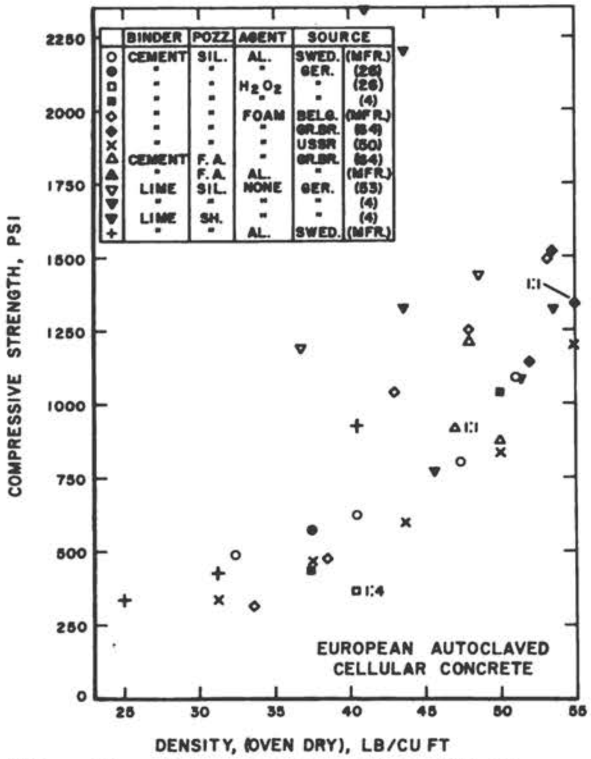


Fig. 15 - Compressive strength of European autoclaved cellular concretes (various processes).

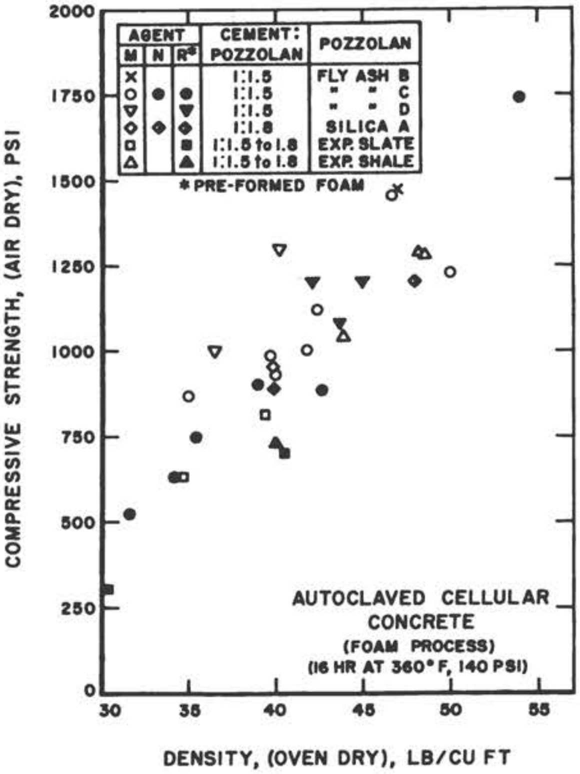


Fig. 16 - Autoclaved mix-foamed and prefoamed experimental materials (from Reference No. 1).

where x is the flexural strength in psi, and y the compressive strength in psi. This equation leads to ratios of flexural to compressive strength of over 0.5 for compressive strengths under 500 psi, 0.35 at 1100 psi, and 0.25 at 2700 psi. Vinberg (30) gave ratios of tensile to compressive strength of 0.11 to 0.12. Ratios of tensile to flexural strength derived from Vinberg's data are in approximate agreement with Gonnerman and Shuman's (39) value of 0.55 for ordinary concrete.

Graf (3) obtained for moist-cured materials ratios of flexural to compressive strength about the same as those indicated for autoclaved materials. Ratios of about 0.2 to 0.35 are given by European manufacturers and the British Building Research Station (16), (38). Dried cellular neat cement tested at the National Bureau of Standards had extremely variable ratios of flexural to compressive strength; values as low as 0.05 were obtained, apparently because of shrinkage cracking, for compressive strengths of 400 to 600 psi (1). Very low-density, dry cellular neat cement may have virtually no flexural strength.

BOND STRENGTH

Despite the dearth of information on bond, an appreciable proportion of commercially made cellular concretes contain reinforcement. The Swedish autoclaved lime-shale type (14) is produced as beams, lintels and other structural shapes in which steel is encased first in dense concrete or mortar and then embedded in the lightweight material. Some manufacturers do not provide denser covering for the steel, although Graf (3) states that corrosion due to reaction products evolved in the hydrogen peroxide process precludes use of that process for ordinary reinforced members.

ELASTICITY

Vinberg (30) has reported average values for a static modulus of elasticity of Swedish autoclaved cement-silica cellular concrete, made by the aluminum powder process, as follows:

Density, Lbs. per Cu. Ft.	Compressive Strength (prism), psi	Modulus of Elasticity, psi
32.4	360	195,000
40.5	705	324,000
47.4	820	376,000
51.1	985	452,000

Stress-strain curves for autoclaved concretes having a density of 40 lbs. per cu. ft. are shown in Figure 17; values for secant E (between the origin and the point on each curve corresponding to one-half of the compressive strength) ranged from 385,000 psi for fly ash D to 280,000 psi for silica (1). Dynamic E values calculated from longitudinal resonance data averaged 5% higher than secant E values. These and other dynamic

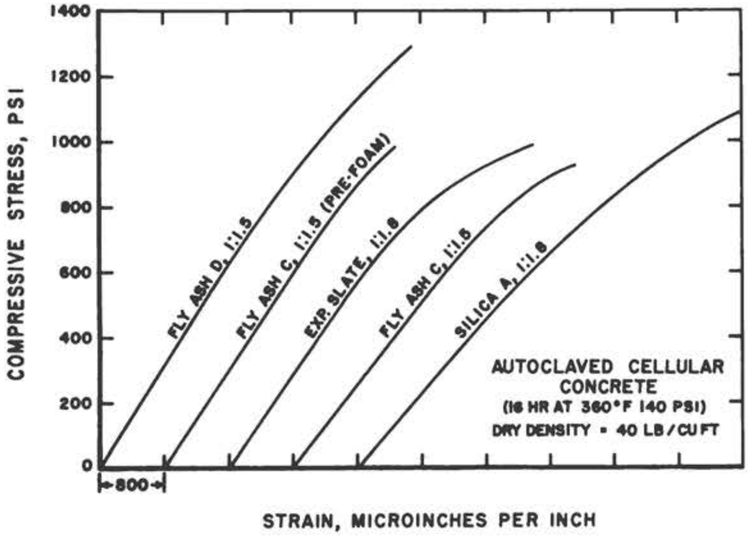


Fig. 17 - Stress-strain curves for autoclaved cellular concretes (from Reference No. 1).

E data indicate that not only cellular concretes of the same density, but also those of the same strength, differ appreciably in E with the nature of the finely ground siliceous material. The ranges appear in the following table:

Compressive Strength, psi	Dynamic Modulus of Elasticity, psi
600 to 700	175,000 to 370,000
1,000 to 1,100	300,000 to 500,000
1,300 to 1,400	400,000 to 670,000

Values for Poisson's ratio reported by Vinberg (30) were close to 1/6 (a value often obtained for ordinary concrete) at all densities and strengths. Values from National Bureau of Standards dynamic tests ranged from 0.15 to 0.25 for mixes of various compositions (1).

Average modulus of elasticity static values from Graf (3) and others for moist-cured concretes formed by various processes are as follows:

Dry Density, lbs. per cu. ft.	28-Day Compressive Strength, psi	Modulus of Elasticity, psi
24 (neat)	85	68,000
43 (1:3)	160	135,000 to 185,000
55 (1:3)	210	165,000 to 260,000
80 (1:3)	530	710,000

These values of E are lower than those for autoclaved materials of similar densities.

ABSORPTION AND CAPILLARITY

Impressions that these cellular concretes possess low water absorption are difficult to reconcile with the magnitude of values in Table III. National Bureau of Standards' moist-cured and autoclaved materials showed relatively low capillary rise (about 0.5" to 1.5" after several days) at ordinary temperature and humidity, but gradually became

TABLE III

Water Absorption of Typical Cellular Concretes*

Type of Cell Former	Binder	Cure	Density (lb./cu. ft.)	Absorption, Percent	
				By Wgt.	By Vol.
Gas or Foam	Neat cement	Moist	40 to 55	-	20 to 30
Foam	Neat cement	Autoclave	50	43	35
Gas	Cement-silica	Autoclave	35	56	28
Gas	Lime-shale	Autoclave	46	49	36
Foam	Cement (sand aggregate)	Atmos. steam	78	20	25
Foam	Cement-silica	Autoclave	43	36	25
Foam	Cement-fly ash	Autoclave	41	43	28
Foam	Cement-burned slate	Autoclave	40	66	43
None	Cement-burned slate	Autoclave	85	30	41

*From Reference No. 1.

saturated when relative humidity was extremely high (1). Capillarity test "absorption" values given for Swedish cement-silica material were 20 to 25% by weight at dry densities of 37 to 25 lbs. per cu. ft. but these values may be of questionable merit, inasmuch as sizes of test specimens and the relative humidity were not stated (15)

Sorption of water vapor from air given for Swedish cement-silica material was, by weight, about 2.5% at 50% relative humitidy and about 6% at 90% relative humidity (15). Kudriashev (4) reported similar values for autoclaved prefoamed lime-silica mixtures.

Data for autoclaved materials listed in Table III indicate that, for a single type of siliceous material, the volume absorption appears to be independent of density. This is illustrated by the expanded slate-kiln dust mixtures ranging from 40 to 83 lbs. per cu. ft. in density. There was a good correlation between volume absorption and the ratio of mixing water to solids, when average values for each siliceous material were considered. Adsorption did not appear to depend upon either the water-cement ratio or the cement-pozzolan ratio.

Absorption values of moist-cured cellular concretes appear to be consistently somewhat lower than those for comparable autoclaved materials (1). Capillary rise and saturation coefficient values were also consistently lower for moist-cured materials in the few tests made at National Bureau of Standards.

Lowest absorption values in Table III are no lower than those reported for moist-cured lightweight aggregate concretes containing perlite, pumice, or heavier aggregate.

Graf (3) stated that, because of the fineness of pore structure, absorption of cellular concrete made by the excess water method is higher than for materials in which a foaming or gassing agent was used.

RESISTANCE TO FREEZING AND THAWING

Frost resistance of cellular concretes in structures is greater than might be expected from their porosities alone. Where used externally, according to the British Building Research Station (38), cellular concrete is normally protected by stucco. When stuccoed, the gas- or foam-formed pores apparently do not become filled with water under normal conditions of exposure. These materials should not be expected or required to resist laboratory freezing-and-thawing treatments employed for pavement concretes.

In the case of microporous lightweight materials made with lime and excess water, Graf (3) recommends use of a gassing agent to incorporate macropores into the cell structure and thus improve frost resistance.

DRYING SHRINKAGE OF CELLULAR CONCRETES

Drying shrinkage values for various commercial and experimental European cellular concretes, and for National Bureau of Standards' cellular materials, are listed in Table IV. Some of Menzel's (19) values for noncellular mixtures are also shown. Both moist-cured and autoclaved materials are listed. Materials of similar composition from different sources are not necessarily comparable because of differences in duration of moist or autoclave curing and in curing temperatures; possible differences in fineness and chemical composition of silicas, fly ashes, and cements may also account for disparate values, as may also differences in size and shape of test specimens.

Shrinkage of Moist-Cured Materials

Table IV indicates that shrinkage of moist-cured neat cement (cellular or otherwise) is high—about 10 times the values often associated with ordinary concrete. For neat cement mixes of very low density, drying occurs rapidly at ordinary temperatures and cracking, as shown in the upper half of Figure 18, quickly ensues. Some values for cement-pozzolan mixtures cured in steam at atmospheric pressure were about the same as for neat cement.

TABLE IV

Drying Shrinkage of Various Cellular Concretes

Type of Cell Former	Binder	Aggregate	Cure	Density (lb./cu. ft.)	Linear Drying Shrinkage (%)
None	Neat cement	None	Moist	Noncellular	0.30
None	Neat cement	None	Autoclave	Noncellular	0.04
Al. powder	Neat cement	None	Moist	40 to 50	0.50
Prefoam	Neat cement	None	Moist	19 to 31	0.50 to 0.65
Prefoam	Cement	Sand, 1:4	Moist	69	0.18
Prefoam	Cement	Sand, 1:3	Atmos. steam	71 to 88	0.08 to 0.10
Prefoam	Cement-silica	None	Atmos. steam	45 to 65	0.13 to 0.17
Mix-foam	Cement-silica	None	Autoclave	40	0.08 to 0.11
Mix-foam	Cement-fly ash	None	Autoclave	40	0.05 to 0.14
None	Cement-silica	None	Autoclave	Noncellular	0.14
None	Cement-fly ash	None	Autoclave	Noncellular	0.08

*From Reference No. 1.

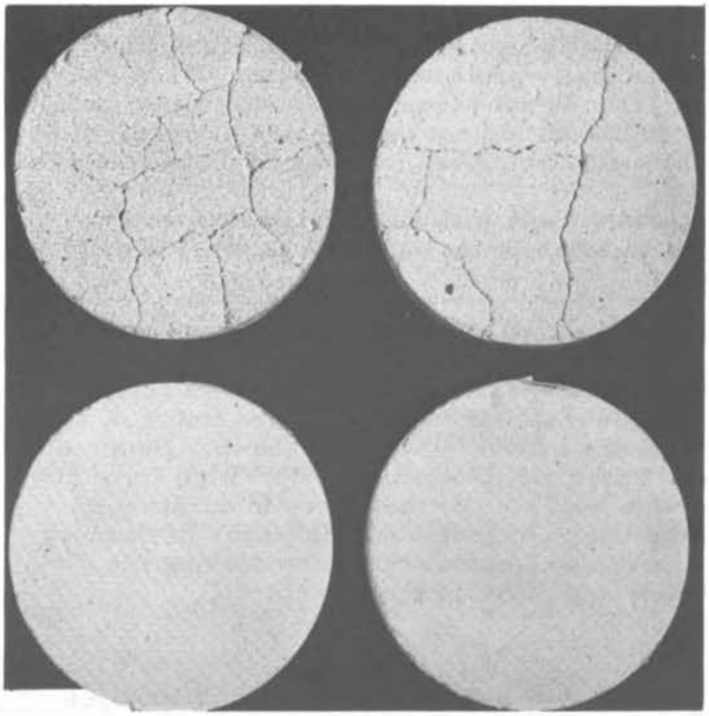


Fig. 18 - Foamed neat cement (6" discs). Upper specimens were moist cured, lower ones autoclaved; specimens at left weighed 20 lbs. per cu. ft., those at right 30 lbs. per cu. ft. (from Reference No. 1).

Fibrous materials such as cow hairs, wood wool, asbestos, etc., have been added to low-density mixtures to avoid formation of large shrinkage cracks, but shrinkage is not materially reduced by this means.

Moist-cured cement-sand mixtures had shrinkage values ranging from 0.06 to over 0.3%, when dried at ordinary temperatures. The lowest values were associated, according to Graf (3), with the highest densities and, according to other literature, with the highest proportions of sand (38). When compared at the same densities, moist-cured cellular concretes appear to be of no lower, and in some cases of higher shrinkage, than similarly cured lightweight aggregate concretes (1).

High-pressure steam curing markedly improves dimensional stability of mixtures containing portland cement. According to Menzel (19), 15 hrs. at 350°F reduced drying shrinkage of noncellular cement-silica mixtures to values ranging from 1/8 to 1/2 of those for similar 28-day moist-cured mixtures, depending upon type, grading, and amount of siliceous material, and on the character of cement used. The greatest reduction occurred with neat cement.

It is difficult to compare drying shrinkage data from various sources for autoclaved cellular concretes because of different methods of conducting tests. Except in England, the practice in Europe appears to be, as indicated in Graf's publication (3), to measure linear shrinkage occurring in a specimen after autoclaving and cooling to room temperature, rather than the shrinkage from an initially saturated condition. Shrinkage values determined in this way by Graf for 1:2 and 1:3 mixtures of cement and silica, ground shale, burned shale, and blast furnace slag, "after three months" were usually less than 0.01%. Some shale mixtures actually showed expansions up to 0.012% during the same period. Graf's tests of lime-silica mixtures showed that materials with the lowest lime content increased in length a maximum of 0.025% and those with the highest lime contents decreased in length a maximum of 0.019%. Smaller length changes were observed for lime-burned shale mixtures.

Values for autoclaved materials listed in Table IV are for shrinkage from a saturated condition. When drying is conducted at ordinary temperature and humidity, the values do not greatly exceed those for ordinary moist-cured sand-gravel concrete tested in a similar manner. Shrinkage of these materials is particularly dependent upon fineness of the siliceous materials according to Menzel (19).

THERMAL EXPANSION

Values for the linear coefficient of thermal expansion of Swedish commercial cellular concrete published in manufacturers' literature are 3.9×10^{-6} per degree F for lime-shale material and 4.4×10^{-6} per degree F for cement-silica material (14), (15). Menzel's (19) values for noncellular autoclaved neat cement and cement-silica pastes for the range of 70° to 140°F averaged 6.5×10^{-6} per degree F. It may be expected that moist-cured cellular concrete containing sand will have thermal expansion coefficients similar to those of dense concrete made with aggregate of similar mineral composition, probably in the range of 5 to 7×10^{-6} per degree F.

THERMAL CONDUCTIVITY

Thermal conductivity values for moist-cured and autoclaved cellular concretes tested in the oven-dry condition are given in Figure 19. These data were obtained from 17 different sources, including descriptive literature of 10 companies in Europe, and publications of Graf, Kudriashev, the British Building Research Station, and the National Bureau of Standards (1). In the range from 20 to 60 lbs. per cu. ft., thermal conductivity is a close function of density, despite the many sources of data and possibly different types of specimens and test conditions. Data reported earlier by the present author indicate an appreciable effect of moisture content on thermal conductivity. For each increase in density of 1% due to free moisture an increase of 5% in conductivity was indicated (23).

FIRE RESISTANCE

Heat transfer through porous materials is effected by conduction and, at high temperatures, by radiation. Heat transfer due to radiation is an inverse function of the number

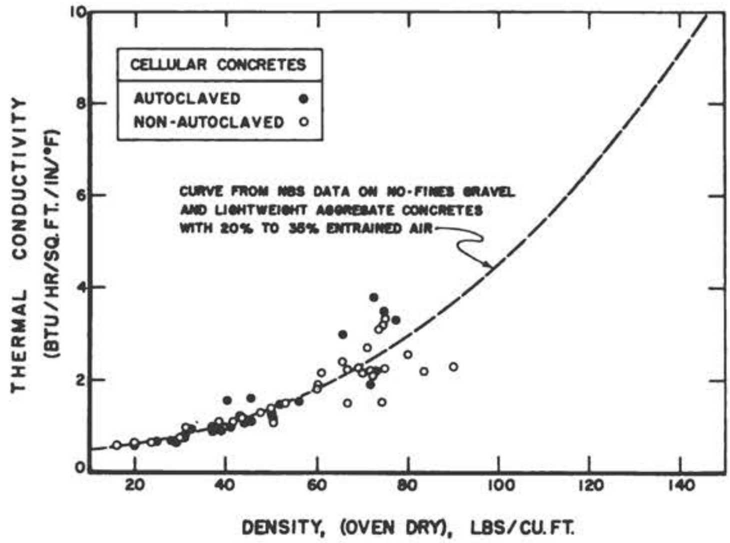


Fig. 19 - Thermal conductivity of various cellular concretes based on data from 17 sources. (From Reference No. 1.)

of air-solid interfaces traversed. This fact and their relatively low thermal conductivity and diffusivity suggest that cellular concretes might possess excellent fire resistance properties. Test results for Danish moist-cured and Russian autoclaved lime-silica materials indicated fire resistance properties markedly superior to those of ordinary dense concrete (1).

ACOUSTIC PROPERTIES

Cellular concretes do not appear to possess unique or even significant sound-insulation characteristics. Transmission loss of air-borne sound through single partitions is a function of the mass per unit of wall area (40). Departures from this law cited in sales literature on cellular concrete are admittedly small, and the practical advantage in selecting this type of material for sound insulation alone would appear to be insignificant, according to the British Building Research Station (38). Beneficial levels of sound absorption should not be expected due to the non-interconnecting nature of the cell structures of most cellular concretes.

CONCLUSION

Moist-cured and autoclaved cellular concretes have been produced in Europe for over 30 years. Autoclaved "gas" and "foam" concretes have become increasingly important as building materials since the end of World War II, first in Sweden and presently throughout most of Europe. The reasons why these materials are still virtually unknown commercially in the United States may be partly economic and partly technologic.

Lightweight concrete masonry units of excellent appearance and dimensional stability are available throughout the country due to the growth in recent years of an industry engaged in production of lightweight aggregates of structural quality. The fact that concrete masonry units are made at high production rates by automatic machinery, and are generally hollow or "cored," accounts for low labor and material costs. Cellular concrete production costs are more than double those of our hollow, lightweight units per equivalent gross volume. The hollow units are laid in the wall more easily by the mason and are sufficiently attractive in texture to require only painting rather than plaster or stucco. These lightweight aggregate units are more stable in dimensions during cycles of wetting and drying. Thus, the immediate future of cellular concrete in this country does not appear to be in the field of masonry units.

Cellular concrete in the form of reinforced plank for floors, roofs and wall panels should be no more expensive to produce here than precast concrete for similar purposes made by present methods, and would offer superior thermal insulation without requiring additional insulation. The application of such cellular concrete members would appear better suited for commercial and institutional buildings than for houses.

Moist-cured cellular neat cement mixtures having densities of 15 to 30 lbs. per cu. ft. possess little strength, and drying shrinkage of 0.3 to 0.6%, but appear to have good thermal insulation properties. Where the function of the material is essentially structural, adequacy of cellular neat cement appears questionable. Cement content and drying shrinkage of this material are undesirably large at densities high enough to produce adequate compressive strength.

Some moist-cured mixtures are made with sand in sufficient amounts to reduce shrinkage to a tolerable value; but to attain adequate strength, density must be increased to values attained by some lightweight aggregate concretes having higher strength, equal or lower shrinkage and, in certain cases, superior moisture properties.

Great advantages in lowered shrinkage and essentially complete strength development may be attained in less than one day by autoclave curing, particularly if a finely divided siliceous material comprises a major portion of a mix. Low-cost siliceous material suitable for autoclaved concrete occur in abundance throughout the United States.

Autoclaved cellular concretes have greater strength and dimensional stability (including lower shrinkage), but also have higher moisture absorption than moist-cured lightweight aggregate concretes of comparable density.

It is possible that the next decade will see more of the bold initiative required to provide a foothold for cellular concretes in our building materials industry. Then, if the present rapid growth of the use of this important building material in Europe may be taken as a criterion, the use of cellular concretes will become well known to the architectural and engineering professions in this country.

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Foamed Metals

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The interest in foamed materials of construction has led to many developments in the technology of foamed cements and concretes, glass and plastics. The list of useful properties of these materials has been extended to include lower densities and higher insulating values. The inclusion of metals in the group of foamed materials represents a new concept in the field of metallurgy and offers a material characterized by an entirely new category of properties.

Solid metals have many useful properties such as strength, elasticity and resistance to wear and corrosion, which are important in engineering technology. However, their densities are for the most part comparatively high; the problem of combining light weight with other useful properties becomes one of great significance. This is shown by the interest in cellular or honeycomb assemblies made by brazing, welding or other methods.

The patent literature (U.S. 2,434,775; January 30, 1948 and U.S. 2,553,016; May 15, 1951) describes a foam-like metal made by heating under pressure a mixture or composite of a metal and a gas-forming material to a temperature above the melting point of the base metal and then releasing the pressure to permit thegas-forming material to decompose. On solidifying, the metal assumes a foamed structure.

It may not be surprising that a laboratory with a broad experience in foaming plastics should see the possibilities of applying the techniques of dealing with low melting organic compounds to the problem of foaming metals, and should exploit the concept. This has been the contribution of the Bjorksten Research Laboratories to a completely new field of metallurgy. Much of the basic technology has been developed, and has been described in the literature and in patents and patent applications.

Most of the work has been on aluminum and its alloys. This a light metal; the melting point is low; it has good mechanical properties; it is comparatively cheap and it is easy to handle in the liquid state. Another consideration is that foaming agents, the gas-producing materials, can be introduced at atmospheric pressure and the foaming reaction also proceeds at atmospheric pressure. Accordingly, work to date has dealt chiefly with aluminum and its alloys, having in mind, however, the foaming of other heavier, high melting metals, such as copper and iron. These foams have been produced on a laboratory scale but the emphasis on the aluminum systems has resulted in a technology that is ripe for commercial development.

Basically, the procedure for producing a foamed aluminum body comprises adding a foaming agent to a pool of molten aluminum or aluminum alloy, mixing thoroughly, and

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pouring into a mold. It should be stated that a pilot plant has produced foam by a continuous process. Full development of such a continuous casting operation only awaits more complete engineering studies.

A laboratory pilot plant is being built at Madison (Wis.) under an industrially sponsored contract with the first objective of producing 4' x 8' panels, 1/2" and 1" thick.

A large number of process variables can be employed to produce differences in the foamed metal. The composition of the metal, whether pure aluminum or an alloy, the operating temperatures, the type and amount of foaming agent, the mixing operation, the type of mold, whether heated or cold metal, ceramic or sand, all are controllable variables that contribute to the versatility of the operation.

Foam can be produced from pure aluminum, but for many operations the aluminum-magnesium alloys in the 7 to 10% magnesium range are preferred. The 10% alloy has a liquidus-solidus range of 1122° to 968°F in which the plasticity contributes to stability of the foam. Since surface tension is a factor in controlling bubble size and foam stability, the effects of minor constituents such as oxygen, accidentally or intentionally introduced, can be important.

The foaming agent obviously must not introduce into the metal harmful elements which affect its mechanical and physical properties. It should possess chemical and thermal stability, so that it can be handled and stored safely. Its thermal stability should allow complete dispersion in molten metal without undergoing much premature decomposition, and yet it should decompose completely when the mix is poured into the mold. The volume of gas evolved per unit weight should be large. A number of possible foaming agents are known; those presently preferred are the hydrides of zirconium or titanium. The amounts required are small, being of the order of 0.5% by weight. Obviously, the density of a foam depends on the amount of foaming agent used.

The density of the foamed metal and the structure of the foam are of primary interest in its use as an engineering material. One determining factor that controls these properties is the type of mold. Obviously a melt that is chilled rapidly by contact with a cold, heavy metal plate will have little opportunity to produce a foam, and an essentially solid casting will be formed. However, as the rate of chill is reduced, either by heating the metal mold or by substituting a material with lower thermal conductivity, such as sand or a ceramic, the solid wall formed in contact with the mold wall becomes thinner and a lower density casting is produced. The ratio of porous structure to solid wall is increased.

An interesting and important characteristic of foaming metal lies in its expansion. In the simplest operation, the metal is poured into the bottom of the mold and, as foaming takes place, the metal rises. In a casting with a 2" x 8" cross-section, a rise of 8' has been observed. The density of the foam in the casting, measured in sections taken from top to bottom, is essentially constant. Another consideration inherent in this expansion is that a complicated mold will be filled. The exact foaming pressures have not been measured, but they are known to be high.

The size of the bubbles forming the foam and their structure, whether isolated or connected (an open foam), are subject to operational control.

The uses of any material, and especially of a material for general structural use, are based on several factors. Among these are availability and cost, workability, mechanical and physical properties, fire resistance, and performance in terms of resistance to corrosion and weathering, and to rot and other types of biological decay. A brief statement about each of these is in order.

There will be no shortage of raw materials. The aluminum and magnesium industries are well established. Projections of uses for foamed aluminum show that the productive capacity of the aluminum industry in both primary and secondary metal can meet the demands, although a welcome expansion of the aluminum market will result. The availability of foamed aluminum depends primarily on the growth of the industry itself. Since the major item in the production cost of foamed aluminum is the base metal, costs will be fixed to a large degree by the cost of aluminum.

The workability of foamed aluminum is good; it can be cast into thin sections (1/2") and into large dimensions without warpage. The accuracy of the casting is limited only by the closeness of dimensions of the mold. The surface may be a plane, or if so desired a design can be cast into the surface. The casting can be dressed by sanding or other conventional means. A casting can be cut on a band saw or with a hand saw. Assemblies can be made with nails, screws, bolts, and by welding.

The strength is dependent in part upon the inherent properties of the alloy used.

The mechanical strength as measured by transverse rupture of a 2" wide test piece, supported on a 12" span, is approximately proportional to density.

Density/lbs/ft^3	Transverse Rupture-2" Wide-1" Thick'12" Span
15	110 - 175 lbs.
20	180 - 250 lbs.
25	240 - 310 lbs.
30	280 - 400 lbs.

The data given are those of the 7% magnesium alloy.

It should be mentioned that there is no directionality of physical properties.

The K factor for foamed aluminum is reported as follows:

Density/lbs/ft^3	temperature	K factor
11.24	75°	3.1
18.18	75°	3.65
27.17	75°	4.7

The density of foamed aluminum may be varied by suitable processing from 8% of that of pure aluminum to values approaching that of solid metal. Comparison with common wood is interesting.

Wood	Density - lbs/ft^3
Balsa	7.5 to 12.5
Ash	33.0
Cypress	30.0
Douglas Fir	26.0
Sugar Maple	42.0
White Oak	44.0
Walnut	35.0

These densities, excepting that of the lower density balsa, can be duplicated in foamed aluminum.

The use of aluminum and its alloys under conditions where resistance to corrosion is important does not need elaboration here. The composition of the foamed metal is essentially that of the parent metal and any statement made about the latter will apply to the former.

The physical structure and insulating properties of the material make it remarkably flameproof. An oxy-acetylene flame, directed onto the surface of a 1" thick panel, caused only localized melting and oxidation. The porous structure limits conductance of heat into the mass of metal. Its nonsparking characteristic may be the basis for specialized uses. With these properties in mind, potential uses can be envisioned. Those mentioned will be typical and do not cover all suggestions.

Fig. 1 - Foamed aluminum closed cell structure in water.

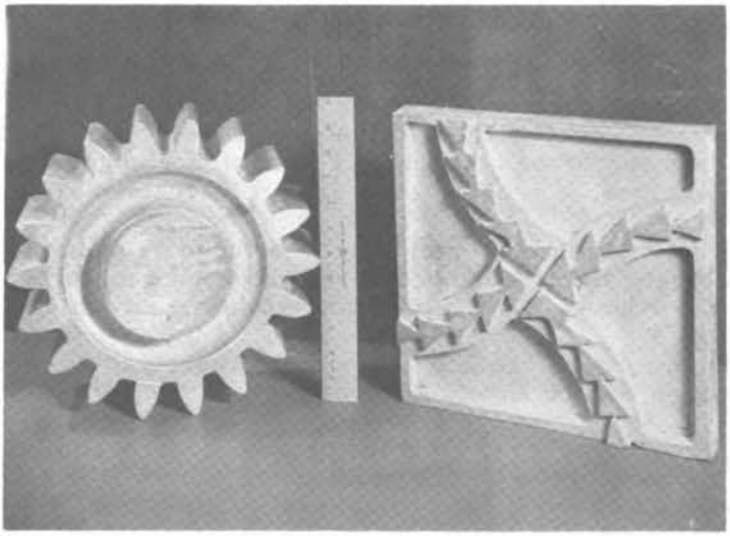

Fig. 2 - Foamed aluminum gear (wt. - 6 lbs.) and decorative panel sand mold.

Fig. 3 - Foamed aluminum planter sand mold.

One of the obvious uses that can be considered is in wall panels 1/2" and thicker in a standard 4' x 8' size and larger, as the technology progresses. Such panels, the first product of the pilot plant now being readied for operation under an industrially sponsored contract, can find use in both interior and exterior construction. The fact that panels may be cast with a plain surface or with a design offers possibilities in architectural planning. The inherent resistance of aluminum and its alloys to atmospheric corrosion and to rot can be exploited. This use is obvious and needs no elaboration. The panels can, if desired, serve as a plaster or paint base.

The fire-resistant properties suggest use in marine construction for bulkheads, and the like. The strength and lightness can be used to advantage in roof decking and in the side walls of trailers, boxcars, etc.

An interesting application is as the core of a laminated door. All householders have experienced the warpage of outside doors which shrink on the inside and swell on the outside. One can envision a composite, a foamed aluminum core, covered with wood or plastic, that would be no heavier than a conventional construction and that would be warp-free.

This concept may also be used in the construction of small boats, particularly in the decking and transoms. When fabricated of wood and a plastic, there are problems of forming a composite wood structure into arched or curved shapes. The foamed aluminum can be cast accurately into a required shape and then covered with plastic or another finishing surface. The absence of moisture in foamed metal eliminates the possibility of bubble formation when the plastic is applied. Another point for consideration lies in the elimination of swelling and warping that may be caused by moisture penetrating accidental holes in the plastic.

A specialty use in the printing industry has been suggested. A "back-up plate," a piece of hardwood such as cherry, is used in the printing of pictures to position the surface of the picture in the same plane as the type. The variation in thickness in the wood plate occasioned by changes in humidity suggests use of a material of constant dimensions, a condition that is met by foamed aluminum.

Foamed aluminum panels may be used as open storage tank covers to control evaporation and the fire hazards present in such materials as petroleum. Low densities can be produced that will provide a floating cover.

Furniture, particularly lawn furniture, can be made of this material. Chairs, benches, tables will be light and weatherproof.

The architectural uses are perhaps chiefly limited by the imagination of designers. Decorative panels can be cast; the material may be anodized for color effects; it can be used for decorative fireproof ceilings; one skin surface can be removed to expose the cellular structure which has an inherent decorative value.

There are many other uses. The metal casting industry can find uses in metal molds and patterns. Shipping boxes and containers for fragile equipment are potential applications, because of the shock absorption property.

The usefulness of a material must be judged by many criteria which can be briefly summed up in two questions. First, is it competitive in cost with the traditional materials? Second, is its performance equal or superior? If the answer to these is affirmative, the material has a place in commerce. There is also a third consideration that can be of major importance. Does it possess a property, or combination of properties, that can be applied to completely new uses? An old but good example of this is the use of glass for windows to admit light but to exclude the vagaries of weather. When a new material becomes available, the development of entirely new uses presents an interesting challenge to the imagination.

Open Forum Discussion

Moderator - Thomas E. Werkema, Staff,
Director of Research, The Dow Chemical Co.

Panel Members - Messrs. Lovett, Valore and Yntema

Robert Sheridan, Eastman Kodak Co.: No aluminum assemblies in current use in building construction have fire resistance ratings because of the low melting point of the material. Have any standard fire tests been made on foamed aluminum? Is the melting point higher than that of the solid metal?

Mr. Yntema: To my knowledge the melting point of the foamed and the solid material is the same.

R. Zbinden, DuPont: Is the foaming agent dissolved or dispersed in the molten aluminum?

Mr. Yntema: It is dispersed, and then it's possible that there is a solution that takes place later.

Mr. Zbinden: What is the density range of foamed glass?

Mr. Lovett: Foamed glass is made only in one density, 9 lbs. per cu. ft.

Mr. Zbinden: How do glass tiles compare with other sound absorbers available in performance and in cost?

Mr. Lovett: We are speaking now of the foamed glass with the open cell which I discussed. The one unit of the foamed glass which is illustrated in my paper will equal, in sound absorption, possibly six to seven sq. ft. of other products on the market today. The cost of the unit is perhaps 2 to 2-1/2 times as expensive, but you don't need as many units to do a sound-conditioning job.

David Countryman, Douglas Fir Plywood Assoc.: Can you discuss use of foamed glass for core material of sandwich panels, particularly bonding of faces? Can structurally rigid glues be used?

Mr. Lovett: Foamed glass has been bonded. The most common practice of bonding is in the curtain wall field, where a neoprene base adhesive is used to bond the foamed glass directly to porcelain enameled stainless steel or aluminum panels.

J. M. McClellan, Wyandotte Chemicals: What is the cost of foamed glass per board foot?

Mr. Lovett: The present cost of foamed glass, manufactured and shipped to the nearest rail siding, freight allowed, averages about 13¢ per board foot.

F. M. Scantlebury, B. F. Goodrich Co.: What is the k factor of the foamed metals?

Mr. Yntema: At a density of 11-1/4 lbs. per cu. ft. the k factor is 3.1. At a density of 22 lbs. per cu. ft. the k factor is 4.7.

W. M. Lukacs, YMCA National Bldg. Div.: In pouring concrete foam into a cavity wall, is there a depth limit at which the weight of material will cause "defoaming" or collapse of the bottom part?

Mr. Valore: There is a very low limit for the chemically foamed, cellular foamed concrete, as we may call it. That limit is usually about 20", vertical lift of pour. But I believe that single pours up to 20' or 30' are possible with the preformed foam variety, or even higher.

L. E. Rivkind, Mearl Chemical Corp.: Expansion of the use of precast foam concrete in the U.S. has been slow for a number of reasons. While the chemistry and engineering has been fairly well established for the precast type of product, a substantial capital investment is required for the autoclaves: high pressure steam plant, molds, cutting equipment, materials handling and other accessory equipment. The problems of promotion of a new material, in the face of the multiplicity of building codes and the labor relations problems, have also been a deterrent.

Where foam has been combined with conventional aggregate concrete in the manufacture of moist-cured masonry products and for poured-in-place construction, it contributes to lower density, superior texture and lower cost. However, the foam character is submerged in the final product and not generally recognizable as a structural foam concrete. It is therefore not possible to estimate with any degree of accuracy the current usage of foam in these applications. On the other hand, the growth of poured-in-place foam concrete has been very rapid in the last few years. During the post-World War II period, the promotion of insulating aggregate concretes and monolithic poured gypsum decks created a more favorable climate. Furthermore, with the development of the superior protein-base foaming agents and improved preformed foam generators, foam concrete became a more controllable product.

By improved formulation, the use of special additives and proper moist curing, the drying shrinkage of 0.3% to 0.6% reported by Mr. Valore for moist-cured foam concrete may be reduced to 0.18% to 0.30%. This is well within the acceptable range for roof deck systems in which foam concrete is combined with either rails and form boards, high tensile corrugated galvanized steel or structural concrete.

With completely portable, self-contained equipment, mounted on a small trailer or flat bed truck, it is now possible to make foam concrete continuously at the rate of 40 cu. yds. per hour. Still higher rates are in the immediate offing. In terms of 2" thick insulating concrete roof decks this is equivalent to 6,500 sq. ft. per hour, a truly fantastic rate compared to what was considered satisfactory as little as two years ago. Cement, with or without sand or other aggregates, may be handled in bags or bulk and continuously conveyed to the mobile mixer where they are intimately blended with water and foam, and then discharged into a pump which propels the foam concrete through hoses to the point of placement. Foam concrete has been pumped as high as 250' vertically in a single lift for use in multi-story floor fills and has been pumped horizontally as much as 900' from the mixing point.

Use of this continuous automatic equipment makes it possible to minimize the human errors inherent in batch operations. Once the rate of foam generation for the required density is established for the desired pouring rate, it is only necessary to check sample weights periodically of the product issuing from the hose.

Mr. Lukacs: Are these concrete foams hygroscopic?

Mr. Valore: They are hygroscopic to the same extent that ordinary concrete products are. That is, they may be dried to an oven-dried condition and then placed in various relative humidities, and they will pick up a certain small percentage of moisture. Generally, at a 50% relative humidity, after oven drying, at 230°F, they will probably pick up some 2 or 3%. The air-dried variety will pick up more; the autoclaved variety will pick up less.

Mr. Werkema: Is the paper to which you referred available? Could you give us that reference again?

Mr. Valore: The paper is titled "Cellular Concrete." It was published by the American Concrete Institute in May-June 1954, and may be ordered from the American Concrete Institute at a cost of $1.00.

N.A. Lombard, Douglas Aircraft Co., Aircomb Div.: Would a door panel of foamed aluminum core, faced both sides with plywood, remain flat under normal conditions?

Mr. Yntema: It would.

Mr. Werkema: Have you made any speculations relative to the cost of these foamed metals yet?

Mr. Yntema: There has been a series of studies made, but I don't feel qualified to discuss it.

James L. Pease, Jr., Pease Woodwork Co.: What is the cost of equipment necessary to produce 3' x 7' x 1-1/2" slabs?

Mr. Yntema: Cost of the equipment to process a considerable quantity of material, in other words the ratio of value of output to capital investment, is very favorable. For the most part, the expensive items of equipment are regular commercial items on the market today.

Mr. Werkema: This is truly a research subject, and the kind of subject that should be included in more and more BRI Conferences. This is an item which is not yet in production; how can we answer this question of cost? We know what these metals cost. I think we can speculate that as soon as they are in mass production, they could be quite inexpensive.

Mr. Valore: Mr. Chairman, as long as we are talking of research, I would like to direct a comment to Mr. Yntema with respect to foamed aluminum. Since I was good enough to mention the use of aluminum as a foaming agent of concrete, I wonder if he has tried concrete as a foaming agent of aluminum.

P.A. Elias, Food Machinery Co.: What is the current usage of glass (tons/year) for foamed glass?

Mr. Lovett: Foamed glass is being used extensively today mainly as an insulation for hot and cold piping, tanks, freezer room installation, freezer tunnels, and in curtain walls. Also, it has gained a large market in the roof insulation field. We make approximately 100 million board feet a year, or a little less.

Mr. Elias: What is the long-term price and volume outlook?

Mr. Lovett: The price could possibly come down as quantity goes up and the technique of manufacturing is improved. We don't know what will happen to labor cost.

L.E. Rivkind, Mearl Chemical Corp.: How does the thermal conductivity or k factor of foam concrete compare with perlite or vermiculite concrete of equal density?

Mr. Valore: It is the same.

B.B. Christensen, Alcan International: Have any tests been made to establish values for the resistance of foamed aluminum?

Mr. Yntema: No, we do not have any quantitative measures on that.

R.S. Cook, Virginia Metal Products: Is there a foaming agent for cement which aids the binding strength between the cement and the aggregate, as well as introducing the gas which causes foaming? If there is such an agent, by what degree does it increase the strength as compared with a purely gas-foaming agent?

Mr. Valore: I don't know of any such agent. The binding characteristic, as far as I know, is due entirely to the chemical nature of ingredients other than the foaming ingredients.

D.J. Valsvic, Wood Conversion Co.: Has foamed glass been evaluated in a section for wall or roof and found to pass a one-hour fire rating under ASTM E-119?

Mr. Werkema: May I rephrase this question somewhat to relate to the fire resistance of foamed glass or foamed glass-type construction. Have you had any tests in this regard?

Mr. Lovett: Yes, when you get up to a temperature around 1,350°, foamed glass will start to soften. It will not burn or support combustion. A pure foamed glass panel 4" thick subjected to the standard time-temperature curve will last about 17 to 20 minutes. Of course, when it's in the sandwich, that is entirely different. It's a good, fire resistant material.

D. Tikker, Monsanto Chemical Co.: Why didn't the house of foam glass ever go into production?

Mr. Lovett: As you know, in every city we have building codes. When you come along with a glass material, that in many people's minds is very fragile, there is a real problem, a promotional problem, in getting a house built, approved and accepted by the proper authorities in the various cities. I think, more than any one fact, that is why it has never gone into production. You could build it, if you had a lot in an area where there were no codes, and you would have a pretty nice house.

Don S. Poole, Goodyear Tire & Rubber Co.: Would you comment on why you think foamed concrete homes have not been accepted here in the U.S.?

Mr. Valore: I think it's because we are a very conservative people. We tend to go with the tried and true. For example, in the Southwest, almost all the houses over the price of $15,000 have cedar shingle roofs, and there doesn't seem to be anything that can be done about it. Whether or not anybody should do anything about it, I don't know—they make very good roofs.

Mr. Lovett: There are problems of development techniques, and problems of codes. For instance if a manufacturer goes to the Federal Housing Administration and wants to get his material approved, he must develop test data, present engineering data by established organizations, etc. In other words, there is a certain amount of procedure that has to be gone through before new materials can be established, and then, of course, there is the problem of bucking our standard type of architecture, etc. We haven't particularly had the need here, as they have in Europe, for new types of building materials. We have been rather rich in conventional materials.

Unsigned question: I have a question relative to structural uses of other types of foams, particularly foamed steel.

Mr. Yntema: We are attacking the problem of foaming iron and other metals. Just what the success will be, of course, is questionable and after we've got it, we still have the problem of application of these materials. It is an intriguing problem and well worth studying.

Mr. Lovett: We are foaming a few silicates at high temperatures, about 3,400°, and the finished block is about 14 lbs. density.

Mr. Valore: Research has been going on for a number of years in foamed ceramics. I believe the Structural Clay Products Research Foundation sponsors some of that research and is carrying out some of its own. There was a publication six or seven years ago in the Bulletin of the American Ceramic Society on some work done, I believe at Ohio State, making an attempt at foamed building materials. I refer to expanded clay, shales and slates used as lightweight aggregate. These, of course, are used in structural concrete. There are also the foamed slags which are used as aggregates for making concrete blocks and for structural concrete.

Urethane Foams in Structures

By R.H. Harding, Research Department
Union Carbide Chemicals Company

(Note: Illustrative materials were prepared with the help of Mr. R.L. Rollins and Miss Idair Smookler. Background information was provided by Union Carbide Chemicals Company, the companies and periodicals credited in this paper, and other publications which have appeared during the past three years.)

The commercial history of urethane foams dates from the 1940's. Although some aspects of urethane chemistry were recognized long before this period, applications of rigid foams were fostered by the stresses of war production. Engineers in the German aircraft industry, faced with material shortages, recognized in these durable materials a key to the rapid production of strong wingtips, rudders, and other control surfaces. The exterior metal shell of these components was fabricated and a urethane mix was simply poured into the cavity. This liquid quickly expanded and cured to fill the unit with a lightweight, self-adhering rigid foam which survived the continuing strains of all weather battle flight.

Following World War II, urethane technology commanded more attention in the United States. Although the aircraft industry continues to expand its use ot rigid foam-cored structures, established applications presently center about flexible urethane foams. Produced by adjustments in chemistry, lightweight flexible foams are rapidly supplanting other cushioning materials. They are of value also for their sound-absorbing ability, and for thermal insulation and "soft hand" when used in garments.

To depart momentarily, then, from the rigid foams that will form the basis of this discussion, Figure 1 may give some idea of the general versatility of urethane systems. The walls of the office are faced with an attractive acoustical tile manufactured from flexible foam. The secretary's chair can be upholstered with a comfort-cushioning foam at low cost. A thin sheet of flexible foam may provide a nonskid underlay, giving a luxurious, deep-pile feel to the carpet. Similarly, another thin sheet may be incorporated in the drapes to provide sound absorption and insulation with no effect on appearance.

The secretary's office equipment may have been shipped in lightweight containers utilizing tough, rigid or semi-rigid foam as spacers to prevent damage in transit. This same equipment may be finished with urethane surface coatings and the typewriter platen might be made of a wear-resistant urethane elastomer. The thermos in which she carries coffee for the morning break might be insulated with a rigid urethane foam, as may the frost-proof refrigerator in which she stores the cream.

Interesting as these observations may be, they do little to reveal the ultimate utility of urethanes on the American scene. In the examples just cited, urethanes were welcomed as inexpensive or more effective replacements for existing materials in conventional products. Generally speaking, utility was established mainly through a single outstanding property. Yet, the greatest benefits of these new products will probably accrue to the consumer only when applications utilizing their unique combinations of properties are fully developed.

Work along these lines is now being pursued by farsighted chemicals companies and manufacturing firms across the country, but it is still in its infancy. Efficient appli-

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Figure 1.

cation of rigid foams in structures is particularly challenging: not only to the foam technologist but also to the architect, the structural engineer, the building contractor, and even to administrators of the nation's 2,200 building codes. By the same token, the reward for increased extent of usage promises to be great: not only for pioneers in the field but also in terms of lower cost, high quality buildings for the public.

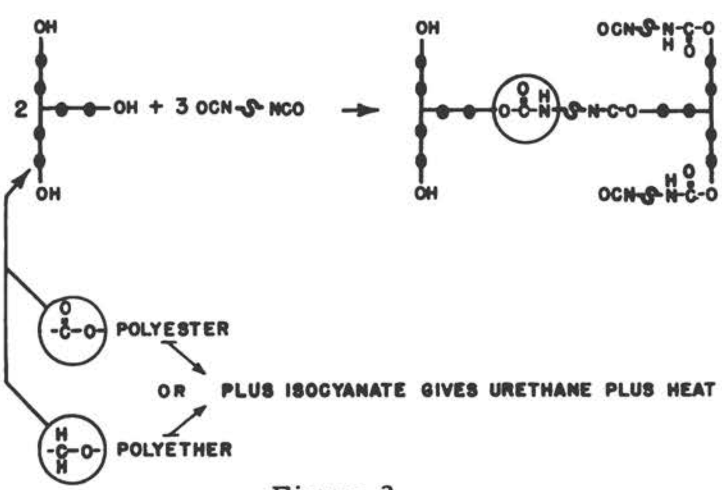
The remainder of this report will outline objectively just what rigid urethane foams are, and what they offer that makes them attractive in structural applications.

First, what are urethane foams? Figure 2 gives a simplified version of their nature. At least two reactive liquid ingredients are needed. The first is normally a "polyol" having two to six "legs," each terminated by the hydroxyl group common to all alcohols. While a "three-legged" polyol is shown as an example, the number, length and chemical structure of these chains determine whether a foam will be rigid or flexible. These same factors can also affect properties of foams within either class appreciably.

You may have heard these polyols called "polyethers" or "polyesters," since both types of compounds are manufactured for use in foams. A major chemical difference between these materials appears in the circles shown at the left in Figure 2. Other distinctions include a tendency toward higher viscosity and higher cost among polyesters than for most polyethers.

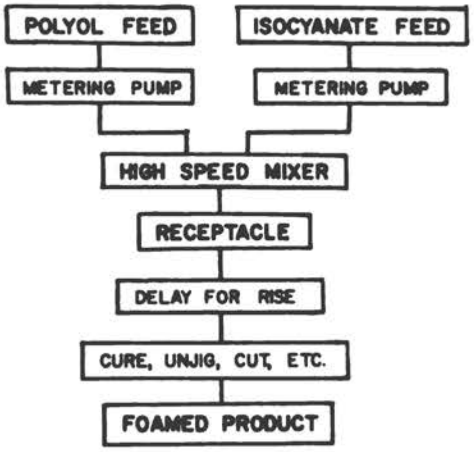
A diisocyanate model is shown as an example of the second main ingredient. Commercially available products contain just two isocyanate groups, and are more expensive than most polyols. Fortunately, this molecule is small: one pound commonly yields two to four pounds of rigid foam, depending on the polyol used.

An isocyanate adds spontaneously to a hydroxyl, liberating heat and forming a urethane group like the one circled at the right. Clearly, this process increases the size and complexity of the product molecule. Although only the first steps in the reaction are



ESSENTIALS OF URETHANE FORMATION

Figure 2.



BASIC URETHANE FOAMING PROCESS

Figure 3.

shown, it continually repeats so long as mobile groups are present. The molecule thus proceeds to grow and branch until its intermeshed chains eventually link to each other. The result is a solid, cross-linked matrix having entirely different properties from the starting materials. Any urethane foam block thus represents essentially one large molecule, analogous in character to a single pour of concrete.

The practical significance of this discussion might be clarified by Figure 3. Here, the manufacturing technology for urethane foams is reduced to its essentials. As can be seen, two feeds are customarily used. While each is based on one of the starting materials just described, additional ingredients may be required in one feed or the other. These include "catalysts" which adjust the rates of foaming and curing, "surfactants" which stabilize the wet foam and help control cell structure, and "blowing agents" which cause the mass to expand.

In present-day rigid foams the blowing agent is usually an inexpensive, non-combustible, low-boiling liquid which absorbs its heat of vaporization from the reacting chemicals about it. The gas generated is dispersed throughout the foam as invisibly small bubbles. Density of the final product, and thereby its raw material cost per board foot, is determined largely by the amount of blowing agent included.

How are urethane foams actually made? The two composite liquid feeds are charged to the tanks of a foam machine. From here they are metered to a mixing head in correct proportions. The mixer may be continuous or intermittent in operation, and large or small. The major requirement is that it thoroughly blend the streams, which may have very different viscosities, in the fraction of a second available.

When the foaming reaction has been initiated, the object to be filled or covered with foam is placed at the mixer outlet. Within minutes, the viscous liquid dispensed by the machine has expanded to many times its original volume (about 36 times for a 2 lbs. per cu. ft. product), and solidified. The raw foam is then well on its way toward developing its final properties although, because of the heat generated, its interior temperature may still be rising toward a peak in the neighborhood of 300°F. Depending on the product desired, the foam may then be considered finished or it may be cured further in an oven, permitted to cool, warehoused, removed from its mold, or cut into boards and other shapes.

One example of a foam machine in operation appears in Figure 4 (1)*. Here we see an operator applying foam with a spray machine at a rate of about 2 or 3 lbs. per minute. Only the feed hoses are visible; the metering system is out of sight on the ground below. The ability of urethane polymers to adhere to almost any clean surface is utilized, as are their rapid self-foaming and self-curing properties.

Notice the operator's protective clothing. Although the foamed product is inert and non-allergenic, prolonged contact with isocyanate liquid and its vapors should be avoided since it might induce an asthmatic condition. Fumes are more pronounced when spraying than when pouring, so in the latter case normal ventilation usually provides needed protection.

A second example of a foam machine in use appears in Figure 5(2). A portable machine is filling the between-shell void in a steel tank at a rate of about 10 lbs. per minute. Expanded foam is visible above the drip shield. Flaws can be touched up by refoaming where necessary, with perfect adhesion.

This tank, incidentally, will be used as a liquid nitrogen container. If it were a production item rather than a specialty, it could be formed with no imperfections on a mechanized line at throughputs of 100 lbs. per minute. Continuous slabs of foam are, in fact, made in this manner and then slit into boards of desired dimensions. Since urethanes are adhesives only while wet and foaming, cured foams can be cut and machined on conventional woodworking equipment.

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*Raised figures in parentheses refer to list of references at end of paper.

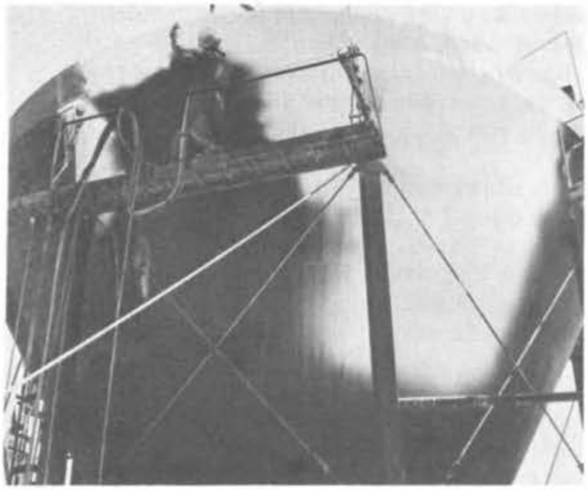

Figure 4.

Figure 5.

It was mentioned earlier that the amount of blowing agent used is a major factor in determining the final density of a foam pour. A second important consideration is that of mold configuration. Not only is the operation we see here filling the sidewalls of the tank, it is also filling the bottom. Since the steel walls exert frictional drag on the rising foam that will soon adhere to them, and since a limiting void is filled, the product will have a higher density than would be obtained in free expansion. Experience indicates that a higher content of blowing agent is needed to overcome such constraint and obtain a specified foam density. Other factors influencing the density and physical properties of foams include the temperatures of feeds, the type of pour used when filling molds, and the fluidity and chemical activity of the system.

While listing these manufacturing variables, it occurs to me that an impression may be conveyed that urethane systems are too complicated to be useful. Quite the contrary, these are desirable features that partially explain the versatility of the materials. In producing any given item, handling conditions are optimized and fixed, but each different item can be treated in the manner best suited to its particular requirements. It is for these same reasons that various types of steels and concretes are developed.

We have looked briefly into what urethane foams are and how they are made. We know that a liquid poured into a container quickly expands to fill the void completely, simultaneously bonding strongly to the container walls and serving as a rigidizing connective web. We know that a liquid sprayed on a surface quickly expands into a thick, tough coating of preselected density and that no adhesives or other expensive treatments are normally required. But, so far, we have only a few clues as to why people go to such lengths to dispense these inert products. The subject of foam properties is certainly one worthy of further discussion.

Among the outstanding features of rigid urethane foams are their low weight and their high strength-to-weight ratio. Figure 6 gives some notion of the densities which are achieved by these products, and of the mechanical properties to which they lay claim. In addition to strengths, moduli of elasticity and rigidity are estimated conservatively. At 185°F, polyether foams commonly retain 80 to 90% of these indicated room temperature strengths, because of their thermoset chemical structure. Foams suitable for continuous service at temperatures as high as 350°F have been reported but are not economical in all applications.

A general word of caution—like wood, urethane foams tend to be orthotropic. Although homogeneous to the eye, their properties can vary with cell structure and the conditions

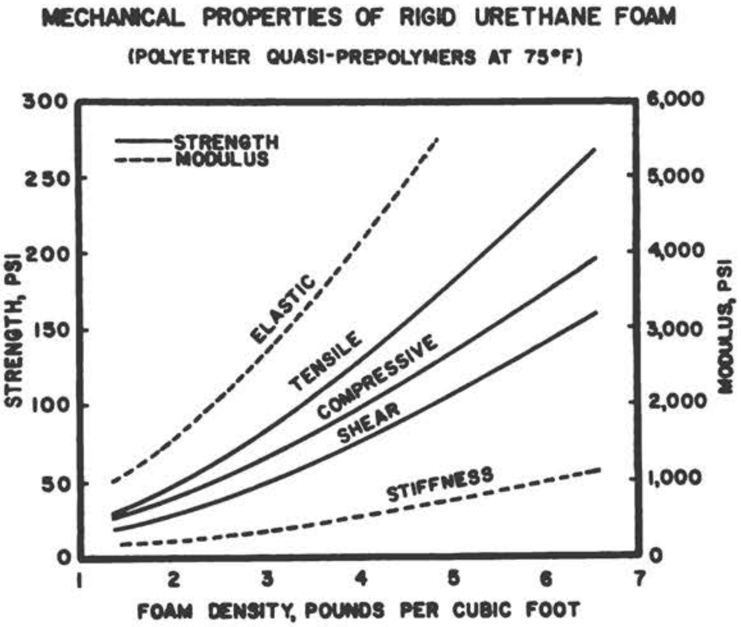

Figure 6.

under which they were made. For these reasons the final test of properties should be made on the finished item in which foams are used.

By virtue of their high strengths, properly formulated urethane foams with densities of approximately 2 lbs. per cu. ft. can be maintained indefinitely at -300°F to +160°F and higher with no permanent change in volume. Because urethanes are very stable, such exposures cause no physical deterioration. At 160°F and 100% relative humidity foam specimens do change in volume: long-term exposures can lead to 10% swell, or less at higher densities, but again with no degradation. However, these latter "accelerated aging" conditions may induce effects which would not exist in practice. Enclosure of specimens within skins is usually sufficient to arrest this dimensional change. We may therefore conclude that rigid urethanes are both tough and durable.

The effective thermal conductivity of urethane foams at 75°F may vary between about 0.10 and 0.15 Btu-inch per hour per sq. ft. per °F, the actual value depending on cell structure and direction of heat transfer. By contrast, the effective conductivity of cork at 75°F is about 0.30. These exciting values result from the low conductivity of the blowing agent (which occupies 97% of the volume in a 2 lbs. per cu. ft. product) and the fact that each of the 100,000 individual cells in a cubic inch of foam is enclosed by polymer. The foam therefore retains the blowing gas, excludes more conductive vapors, and minimizes internal convection.

Urethane forms are unaffected by mildew and fungi, they do not rot, and are not attacked by rodents or insects, and they are inert to greases, oils, detergents and many chemicals and solvents. Although they will transmit water vapor at very low rates, commonly below 1 perm-inch at 75°F, they are unaffected by contact with cold or hot tap water. The usual absorption tests reveal merely that cut cells at specimen surfaces have filled with water.

Closed-cell rigid foams are probably not as effective sound absorbers as their open-celled, flexible counterparts but still provide a useful dividend in this regard. Noise reduction coefficients near 0.4 might be expected from a 3/4" thickness of rigid, 2 lbs. per cu. ft. urethane foam.

While so highly transparent to radar that they are normally used as aircraft radomes, rigid urethane foams are excellent electrical insulators with high dielectric strengths.

One property of universal interest for structural applications is flammability. Most urethane foams are normally slow-burning materials which can be modified to extinguish themselves upon removal of the igniting flame. A few foams are inherently self-extinguishing. In any case, this property is more important in finished products than separate components. By preventing the "chimney" effect common to stud construction, for example, foam-cored panels retard the spread of fire whether or not the foam itself is self-extinguishing. By completely occupying voids and supplying noncombustible vapor, urethane foams actually help smother fires, while their strength retention at elevated temperatures and their thermal insulating power help maintain panel integrity. Further, urethane foams do not support "punking," which occurs in some conventional structural materials and permits re-establishment of an "extinguished" fire.

In addition to their utility in aircraft, rigid urethane foams are achieving industrial prominence through their insulating efficiency. On this basis they have been applied in household refrigerators, truck bodies and ships. They are also used in boat hulls to absorb the repeated impact of waves, to distribute loads between the inner and outer hulls, and to prevent sinking in event of accident. Similarly, unsinkable marker buoys and fishing floats have been constructed of foam.

An all-foam military radome appears in Figure 7(3). This 26' Canadian dome, although not a sandwich structure, approaches the type of construction in which we are interested. It is designed to bear wind and snow loads and to survive cold, heat and sunlight. Individual rigid urethane foam panels were prefabricated, then cemented together on the site with more rigid foam.

Figure 8 shows the construction of a building with steel-faced curtain walls. The urethane foam panel core has a density of only 2 lbs. per cu. ft. In addition to this office building, the same type stressed skin panels have been used successfully on a bank, a power house, and a college addition. Desired thermal and acoustical properties are obtained in flat, rigid panels without the expense of glue lines, heavy skins, or stiffening members (4).

While these examples indicate encouraging progress in a material introduced for large structures only a few years ago, great progress is still expected. Prefabrication of larger panels is possible because of their light weight. Such prefabrication permits improved quality through factory supervision, and lower cost through reduced labor. Since the foams can be molded, structural shapes can be designed to distribute loads so framing can be minimized or even eliminated. Again, the reduction of hand assembly operations provides economies. Load-bearing panels can be prefabricated into complete

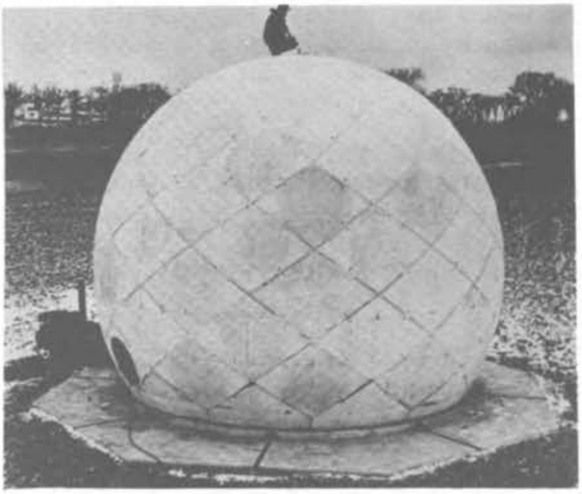

Figure 7.

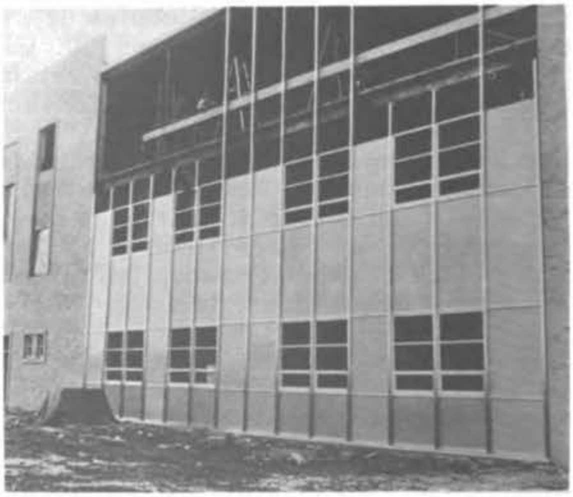

Figure 8.

utility cores in the factory and trucked to the construction site with attendant efficiency gains. As we learn to handle smaller numbers of larger components, on-site construction time and its obvious problems will be reduced phenomenally.

It is likely that a key to this type of structure will be effective design of the joints between load-bearing panels. While use of larger panel sections will reduce the problem, it cannot be eliminated. A second problem hinges on the details of designs to provide more economical utilization of the thermal, acoustical and strength properties offered simultaneously by urethane foams. This requires consideration of panel dimensions, facing materials, foam density and manufacturing conditions.

A third problem involves acceptance of the new architectural shapes which may evolve as solutions to the preceding considerations. Everyone would grasp the opportunity to own and trade homes as casually as automobiles are handled today. Everyone would doubtless welcome homes that could be operated at half the cost of present structures, but everyone might not enjoy living in an unconventional house resembling a star-shaped pavilion, for example. If such designs are recommended for foam-panel homes, public acceptance may be delayed until their efficiency is clearly demonstrated in practice, despite the favorable comparison in structural economy of foam construction with the complexities of conventional framing.

It is expected that the application of rigid foams in structures may continue growing for the next 10, 20, or perhaps 50 years before it approaches maturity. We are only sure that it will grow—progressing through the joint efforts of foam technologists, structural engineers, and architects with an eye for the future. We may not end up with spheroid or paraboloid structures, but whatever shapes we have will be comfortable, easy to maintain, attractive, durable, and readily available at low cost, to foster higher over-all living standards.

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Foamed Polystyrene in Thin Shell Construction

By E.E. Ziegler,* Manager, Fabricated Products Group,
Plastics Technical Service, The Dow Chemical Company

Some organic and inorganic foamed materials have been used in construction for a number of years, whereas others are relatively new. In all cases, a great deal of research and development on these products assures us of improved properties and more widespread use in the months and years to come. This paper will review a new concept of construction making effective semistructural use of a well known plastic foam that has been on the market over 15 years, but on which continuing research has made repeated improvements in recent years.

It has been true in the past, but will be more true and more important in the future, that we must have better and more useful materials of construction, as well as more economical methods of construction, in order that the widely heralded building boom of the 1960's may go forward as rapidly, economically, and aesthetically as our ingenuity will allow.

It is natural, therefore, in this period of national growth and accompanying construction that synthetic materials, in many cases tailor-made for specific uses, and new techniques for the proper use of these materials, may offer potential solutions to the problems of shortage and ever-rising cost of skilled labor. The growing popularity of plastics for use in construction (estimated to be over one billion lbs. in 1960) may be attributed to both economic and aesthetic reasons. The economic factors include significant weight reduction, ease of transportation, ease of installation, lower installation and maintenance costs, more uniform availability, and in many cases, longer use-life. The aesthetic factors include color, texture, pattern, design flexibility, and, recently, new concepts in architecture.

One of the latest advances in a combined structural and architectural use of plastics has to do with the use of thermoplastic foam in thin shell construction. Actually, thin shell construction has been used in monumental buildings throughout the world for several decades. Internationally famous architects such as Nervi, Toroja, Candela, Saarinen, and Yamasaki have molded concrete into flowing spans for beautiful thin shell roofs. More and more architects are letting their thoughts and ideas wander along unlimited horizons of shape and surface, and are emphasizing an aesthetic approach to modern architecture more than ever before. Already domes, scalloped domes, barrel vaults, and hyperbolic paraboloids stand in testimony to the aesthetic flexibility of this architectural concept.

It might be said that thin shell construction has assumed the proportions of a worldwide parade, the more rapid acceptance of which has been hampered in the United States by the high cost of the formwork and supporting falsework necessary for casting the concrete roofs.

The new and rather revolutionary approach which we have taken in an attempt to solve this portion of the problem involves the use of continuously extruded polystyrene foam

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simultaneously as:

1) Permanent thermal insulation.
2) Permanent vapor barrier.
3) A nonremovable form board on which to cast wet cement.
4) A base for interior decoration.

Before developing the details of this construction, it should be understood that extruded polystyrene foam has been widely accepted as thermal insulation for over 15 years. It has a permanent low K factor of 0.28, weighs less than two lbs. per cu. ft., is so water resistant that it is commonly used as marine flotation, and yet is easily handled and fabricated with tools ranging from a jackknife up through power wood-working equipment. It is available in a self-extinguishing formulation. Because of its distinctive cellular construction, it has an unusual ability to bond securely to cementitious products. For many years, this foam has been adhered to interior masonry surfaces with a uniform layer of cement mortar. After the mortar has dried, plaster may be applied directly on the foam surface, thereby eliminating the need for furring and lath. We consider this use of extruded polystyrene foam as a plaster base to be very practical and, in many cases, very economical since the foam serves both as permanent insulation and vapor barrier.

Extruded polystyrene foam, because of the outstanding characteristics mentioned above, has been used for years as a core for sandwich panels. Surface skins may include aluminum, steel, plywood, asbestos board, particle board, or other thin but strong materials. The foam's ability to bond tenaciously to cement and plaster has also made it usable for curtain wall panels with concrete, ceramic tile, or colored stone facings. Again, this lightweight, foamed plastic core is an integral insulation and vapor barrier.

The next logical step in the development of this concept makes use of the above-mentioned properties in the use of rigid polystyrene foam as "form liners." The on-site casting of concrete roofs over wood forms often requires later addition of insulation, vapor barrier, and a base for interior surface finishing. Foam boards bent over and fastened temporarily to irregularly shaped formwork prior to casting the concrete serve all three functions simultaneously. Once the concrete is set and the form boards are removed, the exposed foam surface serves as insulation and vapor barrier on the warm side of the roof and remains available for the application of interior finishes which might include gypsum plaster, acoustical plaster, or sprayed plaster-based paints.

A variation of this "form liner" concept involves the use of rigid polystyrene foam boards in "tilt up" or "lift slab" construction where large flat or contoured sections might be cast from concrete on horizontal forms or even contoured earth and then tilted or lifted into position with the foam boards remaining on the underside.

A further advance in the development of this concept permits on-site construction of continuous, insulated structural sandwich panels. Wire mesh is first attached to the building frame and extruded foam boards are fastened to it. Covering the foam with additional wire mesh permits the spraying or troweling of mortar or direct application of plaster to form the finished walls. In this use, the foam serves as a temporary vertical form board during construction and as permanent insulation and vapor barrier thereafter. Flat or angled roofs can also be constructed by essentially this same technique. Even a folded plate roof has been successfully constructed by this technique in which the basic roof elements were folded-plate segments of foam boards reinforced by steel rods and wire mesh and sprayed with cement on top and bottom.

From the architectural viewpoint, thin shell construction allows for unlimited architectural freedom in the creation of graceful, flowing structures. From the construction viewpoint, this concept offers two advantages:

1) The roof may be erected first with a bare minimum of vertical supports, providing

protection and cover for exterior wall construction and interior decoration.
2) Large areas may be spanned without intermediate vertical supports by roofs requiring an economical minimum of construction materials.

Conventional construction of thin shell roofs has involved the creation of elaborate forms, the erection of extensive supports, and the casting of adequately reinforced concrete. After the concrete has attained sufficient strength, removal and, in many cases, destruction of the form work and supports has been necessary. Further steps are often involved, particularly the application of vapor barrier and thermal insulation as well as additional interior decoration. A simplified construction technique for thin shell roofs appears, therefore, to be of prime interest (Fig. 1).

For many shell configurations, the plywood forms and much of the falsework can be eliminated through the use of extruded polystyrene foam as a structural form board to serve as such only while the cement is wet. In the construction of a scalloped dome, for example, boards of foam have been arched and placed between steel angles, covered

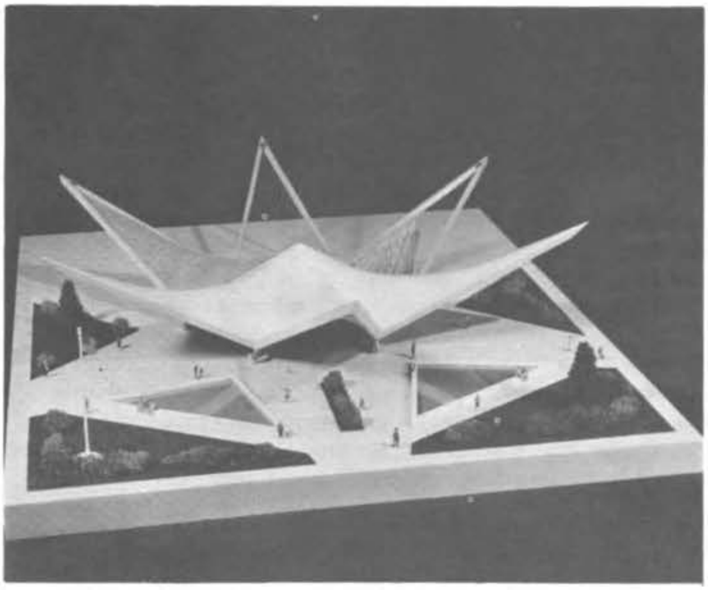

Fig. 1 - Progressive model of thin shell construction technique. One section shows conventional roof forming techniques with many upright supports. The others show hyperbolic paraboloids with use of extruded polystyrene foam as the permanent roof form.

Fig. 2 - Full-scale section of 100' diameter dome, showing extruded polystyrene foam "form boards" arched in place before spray application of concrete surface.

with wire mesh, and sprayed with concrete. The arched boards had adequate strength to support the weight of wet concrete during its curing cycle. A full-scale test section of a 100' diameter dome has been erected by this technique and has been tested to prove its unusually high load-carrying ability (Fig. 2).

Hyperbolic paraboloids are formed by straight-line generators on two axes. One way to use this principle in constructing a hyperbolic paraboloid roof is to use high-tensioned steel wires as straight-line generators. The wires could then be covered with insulating foam boards. After the installation of reinforcing wire mesh over the foam, this surface could then be covered with cement. If properly designed, such sandwich combinations would have sufficient strength to withstand the load imposed by a layer of wet concrete. With dried concrete as the top surface of the sandwich, they would provide a weather-resistant roof surface of considerable strength and rigidity. This straight-wire hyperbolic paraboloid concept has already been used in the construction of a five-unit sport lodge wherein each unit's roof was a grouping of four identical hyperbolic paraboloids.

A straight-wire system was recognized in early studies at Purdue University as a possible key to shaping hyperbolic paraboloids from boards of extruded foam as a form for the permanent shell cover. Some consideration was given to sandwiching a layer of foam boards between two sets of tightened straight wires. Tightening the wires sufficiently to form true straight-line generators while the wires were supporting and warping the foam boards would require excessively high tension, which would have then resulted in sizable lateral deflections of the edge beams. The deflections could have been partially overcome by driving wedges between the foam and the edge beams, essentially prestressing the foam and exerting an outward pressure on the beams. As research progressed, it became apparent that framing could be simplified and stresses could be lowered by offsetting the wires. Further studies and experiments were therefore undertaken to develop an "offset-wire" system.

The case for offset-wire generation of the desired shape is summed up by a quotation from a Purdue University report (1):*

> "Much has been written on the geometry of the hyperbolic paraboloid surface, and much has been made of the fact that the surface can be generated by a series of straight lines. Indeed, the straight-line generators are the key to ease of forming a permanent hyperbolic paraboloid shell in the conventional manner of utilizing falsework and wood forms. However, it is proposed that the true "magic" in the forming of the hyperbolic paraboloid structural shell lies not in its straight-line generators, but in the parabolas formed by the intersection of vertical planes and the hyperbolic paraboloid surface."

Thus, one set of offset wires forming parabolic traces concave upward may be crossed at approximately right angles by another set of wires, also concave upward, on which may be laid extruded polystyrene foam boards of desired thickness aligned to each other by sheet metal clips. A similar set of crossed wires, mounted on top of the polystyrene foam and oriented so as to be concave downward, completes the elements of the structural sandwich. Tightening the wires thus mounted brings the elements into snug alignment so that the foam boards (when additionally compressed by edge beam wedges) act as a shell membrane with appreciable strength.

The same Purdue University report concludes:

> "The Styrofoam** shell serves as a temporary structural formwork for placing and curing permanent shell material and would remain bonded to the permanent shell as insulation and vapor barrier. Furthermore, the Styrofoam can serve as a base for plastering the interior of the shell roof."

A 20-foot square hyperbolic paraboloid model was constructed to prove the practicability of this novel approach and to allow for load-deflection tests. When completed, the

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*Numbers in parentheses refer to list of references at end ot paper.

**Editor's Note: The Dow Chemical Company's brand name for foamed polystyrene.

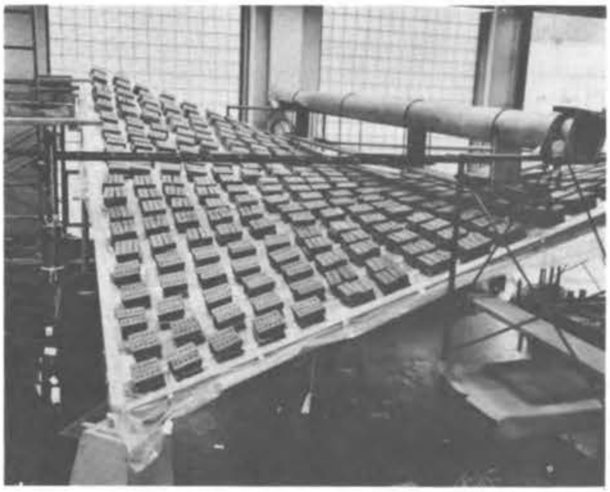
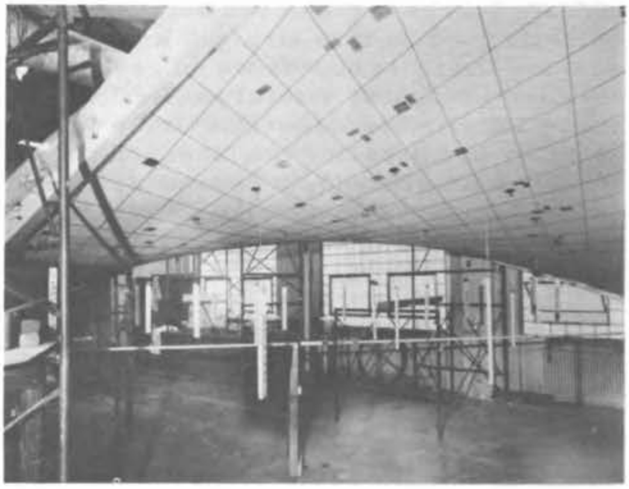


Fig. 3 - A 20' x 20' shell loaded with 19.2 psf dead load.

Fig. 4 - Underneath view of the 20' x 20' shell at Purdue supporting a 19.2 psf uniform load.



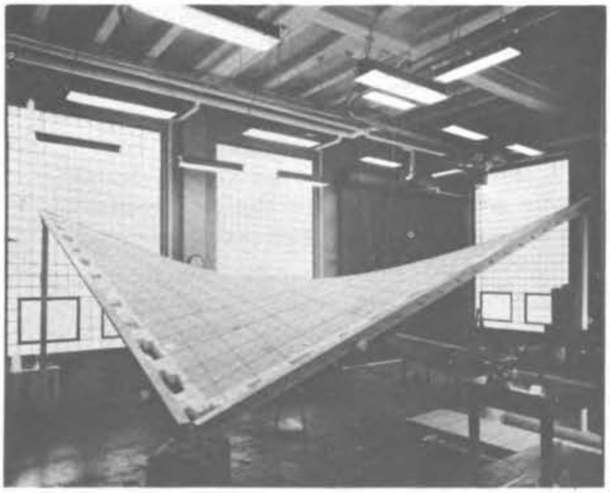


Fig. 5 - Close-up elevation from low corner of 20' x 20' shell.

offset wire-polystyrene foam (3" thick) sandwich with 7' "saddle depth" varied from a true hyperbolic paraboloid by less than 1/2" over its entire surface. A uniform load of 20 lbs. per sq. ft. over the entire area resulted in a maximum deflection at its center point of approximately 2-3/4", with no buckling. This deflection was reduced to less than 1/2" under the same loading after a 1/4" thick layer of cement was troweled and cured on the top surface.

The possibilities opened up by the successful construction and testing of this model are extensive. Plans are now under way for building a 30' square hyperbolic paraboloid with a weatherproofed concrete surface, as well as a four-sectioned hyperbolic paraboloid roof for a new and distinctive gasoline station. Models have been constructed of essentially rectangular and round plan views by using elongated, diamond-shaped hyperbolic paraboloids and truncated sections of the same basic shape combined in a variety of designs.

It would appear that the possibilities for unlimited architectural freedom, engineering advances, and more economical thin shell construction are limited only by the imagination.

Professor F. J. McGarry, Department of Civil and Sanitary Engineering, Massachusetts Institute of Technology, has summed up his opinion of this new and intriguing concept as follows (2):

> "The use of Styrofoam as a construction aid in the fabrication of thin shell concrete structures could well prove to be one of the most significant advances in building technology since the advent of curtain wall construction. The construction economies and architectural freedom which can be simultaneously achieved with this new technique will certainly expand use of these new buildings far beyond their present rather narrow limits. It represents one of the most intelligent and rational combinations of the dynamic field of plastics technology with that of civil engineering which has yet occurred."

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Open Forum Discussion

Moderator - Thomas E. Werkema, Staff,
Director of Research, The Dow Chemical Co.

Panel Members - Messrs. Harding and Ziegler

J.N. Siegfried, Johns-Manville Corp.: Discuss and compare briefly the relative moisture sensitivity of urethane and styrene foams.

Mr. Harding: Our experience is that a urethane foam generally has a water vapor permeability rate somewhat less than 1 perm-inch, and we find those polystyrene materials that we have looked at fall within the same range.

Mr. Siegfried: Discuss the probable products of combustion of each when consumed by fire.

Mr. Ziegler: I am most familiar with the products of combustion of foamed polystyrene, but I believe the same thing is true of urethane. Once it has been cured and aerated, as both foams need to be after manufacture, similar products result from the burning of either of these foams as from the burning of wood, paint, upholstery or clothing. You almost always have carbon monoxide given off and if there is enough of that, you are in trouble, but as far as the giving off of noxious gases against which you would need protection, I don't believe this is any problem.

L. Dean Sneary, Phillips Petroleum Co.: Do you foresee much use of polyethylene foam in building and, if so, of what order of magnitude vs. polystyrene foam?

Mr. Ziegler: Polyethylene foam has roughly the same density as the polystyrene foam. It is characterized by being much softer, however. I would say at the present time that its horizon in construction will be very limited because, for one thing, its price is rather high and it is not characterized as an excellent thermal insulator. It is better used for buoyancy. Its noncellular, flexible structure allows you to bend it right around yourself for ski belts, life jackets, etc. It is also useful for packaging, since its impact resistance allows the dropping of otherwise fragile items from quite a high distance without damage. Also, it has some gasketing uses, but at the present time, with its characteristics and price, its use in building is probably very limited.

Robert Sheridan, Eastman Kodak Co.: Is it not true that a system of falsework or scaffolding is required for placing the polystyrene in hyperparaboloid roofs, which in effect replaces the formwork which you say has been eliminated?

Mr. Ziegler: It depends on the size of the roof being constructed as well as the code requirements in the area. The 20' x 20' hyperparaboloid constructed at Purdue University had absolutely no vertical support under it. Were it to advance in size to 100' or 200', or even more along one length, I am sure you would want some supporting falsework underneath. But, instead of supporting it every square foot with another 4" x 4" or larger, it has been proposed by some consulting engineers in New York that for a structure which measured 280' across we might use a 1" x 6" piece of supporting wood every 6' or 8'. This would assure safety of the workmen walking around on top and prevent them from falling through, although the men at Purdue walked around on this 400 sq. ft. test roof with just plain shoes on. There are all sorts of ways to provide even more protection, for instance, reinforcing the foam with a burlap skin or chicken wire skin, but I certainly do not agree that the same amount of falsework would be needed underneath this system as is used in conventional construction at the present time.

Leon Lipshutz, Carl Koch & Assoc., Inc.: What is the latest price per pound of polyurethane?

Mr. Harding: The raw material costs of many polyurethane systems will run in the neighborhood of 40 to 60¢ a pound, depending on the materials that are chosen, etc.

Unsigned question: Have you evaluated polyurethane foams as a core in a laminated structural panel other than a filler in a stressed skin panel? How does it compare to a wood stud wall?

Mr. Harding: With respect to conductivity in panel construction, with some more rigid material used as the panel face, if we assume no thermal short-circuits occur, the K factor of the foam itself is approximately 0.10 to 0.15. The entire assembly then would have a U factor that could be calculated from that of the foam, if there are no short circuits. Some strength tests have been made. To go into the details of the results of these tests would be time-consuming, but in general, we can simply say that they performed better than they were designed to perform. They withstood direct loads that were amazingly high and, in combination with wind loads, still performed over and above any housing requirements or codes.

Unsigned question: Does moisture penetration of urethanes cause breakdown of foam or other undesirable characteristics in cold climates?

Mr. Harding: We have never seen any evidence that either low temperatures or moisture caused any deterioration in the foam itself. In fact, we have accumulated a good deal of evidence to show that cold temperatures leave these foams essentially unaffected, and moisture has practically no effect, significantly no effect, on the strength of foams that have been exposed to it for quite some time. Whether the combination of low temperatures with moisture, as for example in a house constructed in very cold climates where we have moist warm air on the inside and cold air on the outside, would cause any damage, would really depend more on the over-all structural design. Obviously, moisture barriers can be used if it looks like there is going to be such a problem. The additional thickness could easily be designed to maintain the temperature of the foam at high enough levels to avoid freezing within the foam wherever the water concentration would be high enough to cause a problem.

Mr. Werkema: Mr. Ziegler, in the experiences you've had with low temperature insulation particularly, do you know of any bad effects on these foamed polystyrene insulations from moisture permeability?

Mr. Ziegler: One of the main problems is not the transfer of moisture through the foam, but rather the transmission of the moisture at low freezing conditions in the joints. Extruded polystyrene foams, however, have an exceedingly low pick-up of moisture. Even in marine flotation use, with subsequent freezing in the winter, this has not been a serious problem.

Howard E. Phillips, American Telephone and Telegraph Co.: You mentioned the "slow burning" property of foamed polyurethanes. Have any tests on fire resistance been made by the National Fire Protection Association, The National Board of Fire Underwriters, or other laboratory tests which would indicate what construction applications would be approved by most building codes?

Mr. Harding: I have seen the results of some large-scale tests. I don't believe I am free to discuss them in detail. They are not our results directly, but the end indication of this work was that there is no problem in curtain wall structures, or even in some load-bearing applications. I have seen results of flammability tests where a non-treated foam was used as the core in the panel with gypsum board as the facing material. A stud wall panel and this foam-cored panel were exposed simultaneously to a gasoline fire. Both panels held up for about 20 minutes. There was a difference of several minutes in favor of the standard stud construction because a split occurred in the gypsum board face of the foam panel. The foam showed no signs of damage so long as it was protected from direct access to the flames and to air at the same time. The foam, of course, has no air or other combustible gas in it, and so it must have access to air before it can burn or be burned. In this case, the performance of the foam-cored panel was very nearly the same as that of the stud construction.

Unsigned question: On equivalent spans what has been your cost per sq. ft. experience with the conventional rigid or trussed frame as against the thin shell hyperbolic paraboloid

Mr. Ziegler: At the present time we are not far enough along to give actual per foot cost. We might use one illustration, however, to indicate its lower cost. TWA's Idlewild airport construction is using this particular form arched over the curved concourses running out to the emplaning areas because of lower cost than that of typical construction. It's going to take us just a little bit more time to get these sq. ft. costs worked out, and then we will publish them. We don't have them yet.

A. J. Steiner, Underwriters' Laboratories: How has the "fireproof building" mentioned by Mr. Ziegler been demonstrated?

Mr. Ziegler: When you encase a low burning material, or a self-extinguishing material, such as was used for the Inland Steel Building in Chicago, with 2" of concrete all around it, you don't have much of a fire hazard left. In addition, even if this concrete were not there, the contribution made to the fire by so few pounds of material is practically inconsequential. Between those two things I think we have the answer.

Unsigned question: Is polyurethane or polystyrene being sprayed on cold piping as insulation?

Mr. Ziegler: Polystyrene is not being sprayed on for any use. The sheets may be formed around piping if a source of heat is supplied to form up these materials containing compressed gas, softening them while the gas expands. In the case of the extruded board, it is available as preformed pipe covering. It is not available for forming on the spot.

Mr. Harding: One comment with respect to spraying pipe in place, present-day equipment in the spray line generally gives such a large amount of blow-by that spraying would be an uneconomical approach for pipe. Preformed pipe insulations are frequently made of polyurethane.

John Odegaard, Kingsberry Homes Co.: In the production of foam-filled panels how could a quality control inspector be assured that voids were not present and that good adhesion takes place?

Mr. Harding: This is largely a matter of developing the proper foaming technology in the plant. It happens to be one of the items that separates the men from the boys in the manufacturing field at this time. This matter of adhesion and voids is a good, healthy technological problem, but it is not one that can't be solved.

T.H. Beals, Pittsburgh Plate Glass Co.: Can polyurethane rigid foam be used as the insulation and form board in the thin shell construction you have described?

Mr. Ziegler: Yes, however in our preliminary thinking we have not made thermal insulation No. 1 on the list of requirements. You can hardly afford to pay twice as much for rigid urethane foam as you would for rigid polystyrene foam which will do essentially the same job for non-removable form board, essentially the same job or at least as good as the paper barrier, and is plenty good enough in unit thickness for thermal insulation.

W. Oberdick, University of Michigan: Can water be entrained in foamed polyurethanes?

Mr. Harding: Perhaps that question has reference to the fact that one possible way of expanding the urethane foam is by a water reaction with the isocyanate. As for actual entrainment, the polymer itself would have no water left as such. Once the foaming reaction were completed, the water present during the foaming operation would be consumed by the isocyanate and converted to carbon dioxide and other chemicals. I have never seen a polyurethane foam with water in it.

Julian H. Scott, Standard Bldg. Prod. Co.: You discussed foamed glass as a sound-absorbing material. What are its sound transmission properties, i.e., as a noise isolator between rooms?

Mr. Lovett: The transmission property of a foamed glass material about 4" thick would give a reduction of about 28 decibels. It's a lightweight material.

Nils Ohlson, Dyfoam Corp.: How can it be stated that polystyrene is a vapor barrier, when the National Bureau of Standards states that a vapor barrier must have a rating of less than 1.0 perms and the same organization plans to reduce this to 0.5 perms?

Mr. Ziegler: Yes, our perm rating right now is generally considered well below 1.0. I certainly do know that in the case of deep freeze units we do not use the vapor barriers except at intersecting corners where the passageway between the foam creates a problem, as I mentioned before. Where this is a problem, I am sure you get bad frosting and freezing in areas of this nature.

Unsigned question: Is there any information on the bond between foamed polystyrene and plaster vs. plaster and standard lath?

Mr. Ziegler: We haven't published any figures on that yet. There is some work going on right now both in Midland (Mich.) and at Armour Research Foundation to determine characteristics of plastering on foam, from which we hope to have data that will answer your question directly. The data we have today are really not broad enough or specific enough to warrant publication, but from the experience we've had in over 11 years of plastering directly on polystyrene foam, we don't anticipate any problems in this area.

D.S. Poole, Goodyear Tire and Rubber Co.: Have you any information relative to use of expanded polystyrene beads in concrete?

Mr. Valore: I have read of that work with much interest, and I would be very much interested in knowing the properties of such concrete. It's hard for me to conceive how you might not get some of the disadvantages of both materials. Possibly it would be better to use polystyrene foams. It would also, I think, be quite an expensive aggregate.

Mr. Ziegler: I agree generally with this. We have done some work with the addition of foamed polystyrene beads to cement. Each individual bead is very water resistant, while added to a matrix which isn't water resistant. It is an expensive way to lighten concrete, particularly in the face of competitive materials which are already doing a good job and which treat the concrete better than prefoamed beads.

H.S. Segalas, Procter & Gamble: Is there a type of paint which might be used directly on foamed polystyrene for interior decoration, rather than on plaster?

Mr. Ziegler: Any water base latex paint is an excellent medium for covering polystyrene foams. They will not attack chemically, they can be brushed, sprayed, or rolled, and they adhere tenaciously to the foam surface, which isn't very glass-like anyway, and this creates a very nice effect.

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