

SOME PHYSICAL AND CHEMICAL ASPECTS OF HIGH PRESSURE STEAM CURING

By GEORGE VERBECK and L. E. COPELAND

The effect of temperature on the physical and chemical properties of hydrating cement is considered from the effect temperature has on both rate of hydration and on the composition of the hydration product.

The increased rate of hydration produced by elevated temperature is discussed in terms of its apparent effect on the uniformity of distribution of the hydration product within the paste matrix and the significance of degree of uniformity of distribution on strength.

The general chemical and physical nature of the hydration products formed below 212 F (100C) is essentially unaffected by curing temperature. In high pressure steam curing above 212 F the properties of the product can be considerably altered depending upon the temperature and the composition of the cement. The various phases produced for different temperatures and compositions are described in terms of the inherent nature of the basic calcium silicates. The strength of high pressure steam cured paste is shown to depend upon the phase composition of the product primarily through the influence of the phase composition on its relative ability to reduce the capillary porosity of the paste.

Keywords: age; atmospheric pressure steam curing; *autoclaving*; calcium silicate hydrates; *cement pastes*; compressive strength; concretes; curing; *high temperature*; *hydration*; *hydration reaction rates*; morphology; phase diagrams; porosity; *portland cement compound composition*; portland cements; research; shrinkage; silica; sulfates; temperature; x-ray diffraction.

It is a particular pleasure for the authors to have this opportunity to participate in this Symposium in honor of Carl Menzel. Both of us have known Carl Menzel for many years. As a point of fact, it was exactly 28 years yesterday that I (Verbeck) first met him upon my joining the PCA laboratories. We are well aware of the cornerstones he laid in his work concerning high pressure steam curing and also the researches he pioneered in several other important technical areas as well.

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It is not the intent of this presentation today to discuss details of particular products or processes but rather to discuss the broad and underlying effects of elevated curing temperatures:

-First, the effects of elevated curing temperatures on the rate of hydration of cement and the effect that the rate of hydration in turn can have on the properties of the cement paste;

-Second, the effects of elevated curing temperatures, in the high pressure curing region, on the chemical and physical properties of the pastes.

It is hoped that this fundamental approach will help to provide a base of some of the papers to be presented later during the symposium. First, as regards the effects of temperature on rate of hydration the reaction between cement and water is like other chemical reactions in that the rate at which the reaction occurs increases with increasing temperature. Fig. 1-1 shows the relationship between rate of hydration of cement, as measured by the rate at which heat is evolved by the chemical hydration reactions, and the temperature of the hydrating cement paste. The data cover the range from 40 to 230 F (4 to 110 C). The rapid increase of the initial rate of hydration with increasing hydration temperature would lead one to expect that, at a given early age, the strength would also be higher for a higher hydration temperature. That this expectation is true is shown in Fig. 1-2 which compares the 1-day compressive strengths of concretes cured at temperatures in the range of 55 to 120 F (13 to 49 C).

One might expect that this effect would carry over to later ages. However, the effect of curing temperature on the strengths of these same concretes at a test age of 28 days is exactly opposite to that obtained at 1 day. Fig. 1-3 shows that at 28 days, the higher the curing temperature, the lower the strength. Fig. 1-4 shows the strength-temperature relationship obtained at an intermediate age, 7 days, and indicates that there is an optimum curing temperature, around 80 F (27 C), for best 7-day strength with this particular cement. The reason for this behavior is discussed later.

In a search for an explanation for the anomalous results at 1 and 28 days, the inherent general physical and chemical natures of the hydration products obtained at different temperatures have been examined to see if there are significant changes with hydration temperature. Studies of pastes cured at various temperatures from 40 to 230 F (4 to 110 C) show that for all practical purposes the general physical and chemical characteristics of the hydration products are similar. Hence the explanation cannot involve either general chemical or physical differences in the inherent nature of the hydration product.

What then is the explanation for the fact that high curing temperatures are beneficial to early strength, but detrimental to later age strength? The observed reversal in strength implies that there be two opposing factors. One factor is that an increased curing temperature increases the initial rate of hydration and hence is beneficial to early hydration and early strength. The opposing factor is that this same rapid initial reaction is detrimental to ultimate strength because it produces a nonuniformly distributed hydration product. This nonuniformity is detrimental to strength because the less concentrated zones of hydration product are weaker and limit overall strength and also because the more concentrated zones retard subsequent hydration. Fig. 1-5 shows schematically the mechanism postulated.

At the top of the figure is a representation of the original cement-water system before hydration has begun. As shown at the left, if such a paste is kept at a low temperature, such as 55 F (13 C), so that it hydrates slowly, the degree of hydration is only modest at early age but the hydration product is uniformly distributed throughout the paste simply because the slow hydration allowed ample time for more extensive diffusion of the product. At early ages the low concentration of hydration product in the interstitial space accounts for the low strength but at later ages the more uniform distribution and greater degree of hydration produces greatest strength. As shown at the right, a higher curing temperature causes more rapid initial hydration to produce a higher strength at early ages but creates a high concentration of encapsulating hydration product immediately surrounding the cement grain which promotes nonuniform distribution and retards subsequent hydration and

hence strength development at later age. That this dense and encapsulating layer around the cement grain retards subsequent hydration of the cement is demonstrated by several lines of evidence. However, Fig. 1-6 should adequately demonstrate this point. Here we see the degree of hydration of tricalcium silicate pastes initially cured at temperatures ranging from 40 to 175 F (4 to 79 C). The degree of hydration was determined by x-ray diffraction measurements of the remaining unhydrated C₃S. Although at 1 day the beneficial effects of increased curing temperature are noted, the adverse effects of increased temperature are noticeable at 28 days and especially so for pastes initially cured at 175 F (79 C) even after 5 years of water curing. This then is one reason why the rapid hydration associated with elevated curing temperature can be detrimental to later age strength - the hydration is not as complete. Another factor is, of course, that even if the degree of hydration were unaffected by temperature, the paste strength would still be reduced if the hydration product were non-uniformly distributed throughout the paste matrix. This concept is illustrated in Fig. 1-7.

Here we see at the left a typical strength-gel/space ratio relationship as developed by Powers. If the hydration product were uniformly distributed, such as with slow, low-temperature hydration, then for a gel/space ratio (concentration of hydration product in the paste) of 0.7 a compressive strength of about 12,000 psi (840 kgf/cm²) would be anticipated. However, if half of the hydration product concentrated around the cement grain at a gel/space ratio of 0.8 and half in the interstitial space at a ratio of 0.6, the weaker interstitial fraction should control and a maximum strength of about 8000 psi (560 kgf/cm²) should be attained.

Hence, the more rapidly a particular cement hydrates at an early age, the greater the possibility for reduced ultimate hydration and ultimate strength and the greater the possibility for nonuniform distribution of the hydration product, since nonuniformity in itself is detrimental to strength.

It would be misleading not to indicate that cement composition, particularly the SO₃ content of the cement in relation to its other properties, is of importance. Fig. 1-8 demonstrates that the SO₃ content that is optimum for strength depends upon hydration temperature. About 3 percent SO₃ appears optimum for 73 F (23 C) curing and about 7 percent SO₃ optimum for 185 F (85 C) curing, presumably because of more proper control of rate of reaction. This whole matter of optimum composition is very complex, and depends upon factors such as cement composition, aggregates, time-temperature cycle (either low-or high pressure curing), and the properties desired. Much work is needed to clarify these matters properly.

In an earlier figure (Fig. 1-4) it was noted that at certain intermediate ages, a maximum 7-day strength was obtained with a particular cement when cured at 80 F (27 C). Fig. 1-9 is introduced to further emphasize the point regarding the beneficial and detrimental opposing effects of hydration temperature. For the particular cement shown, it can be seen that the temperature yielding optimum strength is dependent upon the age at which optimum strength is desired. For example – at 72 hours about 130 F (54 C), at 30 hours about 140 F (60 C), at 4 hours about 190 F (88 C), and at 1 hour about 270 F (132 C) – under pressure.

Perhaps this discussion is sufficient to indicate the role of various factors on the properties of concrete, resulting simply from the increased rate of hydration brought about by elevated curing temperatures. Both the *rate of reaction*, (which, in itself, is influenced by temperature) and the temperature to which the hydrating cement is exposed, are very important.

Let us now consider the additional situation, that of high pressure steam curing. Here the curing temperature affects not only the rate of reaction and its attendant effects, as just discussed, but also the fundamental nature of the hydration products themselves.

The upper portion of Fig. 1-10 shows an approximate phase diagram for the lime-silica compounds that may be formed as a function of CaO-SiO_2 mole ratio and temperature. The boundaries are somewhat arbitrary, as anyone aware of such matters will appreciate, and also represent, at best, ranges of composition in which the compounds are the major but not the only constituents. However, despite these limitations, the figure should be suitable for the present purpose. The various zones in the diagram represent products having inherently different fundamental structures and hence different physical properties.

The different types of these silica structures represented by these different phases are shown in the lower portion of the figure. The $\text{C}_2\text{S}_0\text{H}$ hydrate phase has an isolated silica tetrahedral structure (monomer). The C_3SH phase has a dimer structure (Si_2O_7 groups). The calcium silicate hydrate tobermorite and hillebrandite phases have infinite silica chains. Xonotlite has a double chain silica structure whereas gyrolite appears to have a sheetlike silica structure and infinite three dimensional network structure. The expressions monomer, dimer, and polymer are used to express the general nature of the silica structure in terms of the number of silicon atoms bound together by oxygen linkage in the basic structural unit. These negatively charged silica units are associated with positively charged calcium ions in the compound.

The steam curing of normal portland cements, which we have just discussed, can be represented in this diagram as is shown in Fig. 1-11. The area of interest has a ratio of lime to silica in the range of 2-3 (since cements contain both dicalcium and tricalcium silicate) and extends up to the boiling point of water, 212 F (100 C). The products formed in the area, Area 1, are normal calcium silicate hydrates with good strength characteristics but, unfortunately, also with a tendency to shrink when dried or carbonated.

If portland cement pastes are autoclaved, hydrated at temperatures in the range of 320 to 380 F (160 to 193 C), the hydration product falls into another area, Area 2. The product is predominantly a material called dicalcium silicate α hydrate that has little tendency to shrink when dried or carbonated but that, unfortunately, also has little strength at practical water-cement ratios.

This problem of the low strengths obtained by autoclaving has been counteracted in commercial practice by the addition of finely divided silica to the portland cement, thereby reducing the lime-to-silica ratio of the cementitious mixture and producing materials falling into another area, Area 3. The mineral species formed in this area belongs to the same class as do the normal calcium silicate hydrates, with high strength and capable of shrinking when dried, but has been obtained very rapidly by the autoclaving process. In commercial practice the aim is to obtain a product that is somewhat intermediate, somewhat of a compromise, between the high strength, high shrinking tobermorite type of product, Area 3, and the low strength, low shrinkage α hydrate of Area 2.

We need to know much more about these matters and bridge the gap between these fundamental aspects and commercial autoclave practices. We need to understand more fully the relationships between the temperature and duration of autoclaving and the chemical nature of the cement in order to know the best type of cement for a particular autoclave cycle and the best type of autoclave cycle for cements having particular characteristics. We especially need to know much more about the technical 'no man's land' between the products of Area 1 and Area 2, for here we may find means of obtaining products having strength and volume stability characteristics superior to those of Area 3. The manufacture of these products by a rapid and economical process would be a significant contribution to the concrete products industry.

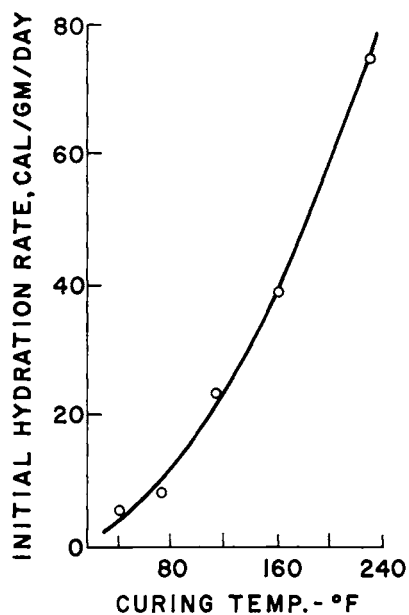


Fig. 1-1—Higher curing temperature increases the initial rate of cement hydration

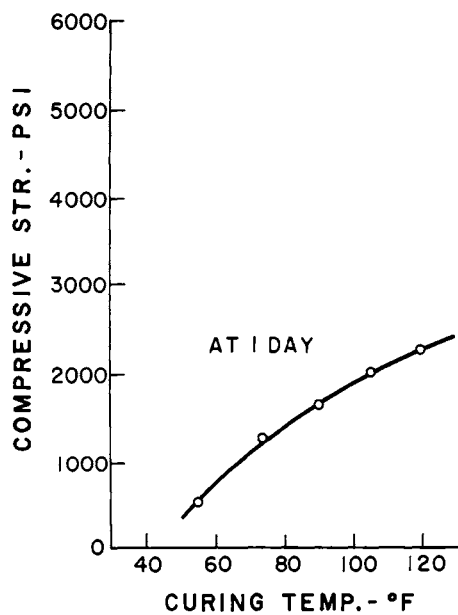


Fig. 1-2—Higher curing temperature increases the one-day strength

HIGH PRESSURE STEAM CURING

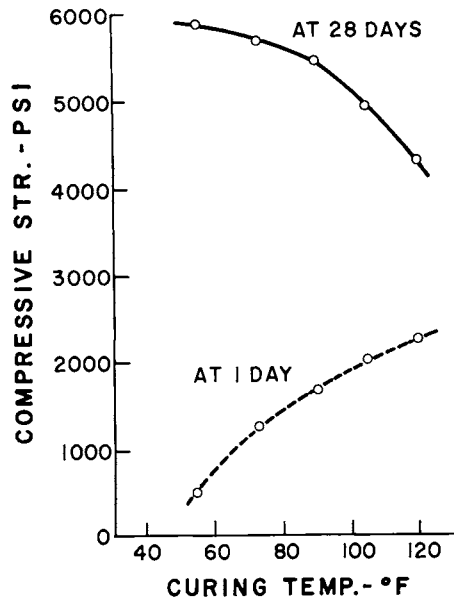


Fig. 1-3—Higher curing temperature decreases the 28 day strength

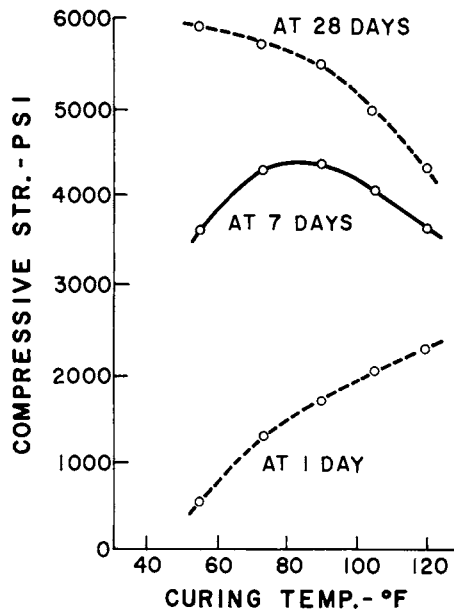


Fig. 1-4—Beneficial and detrimental effects of curing temperature are shown in 7-day strengths

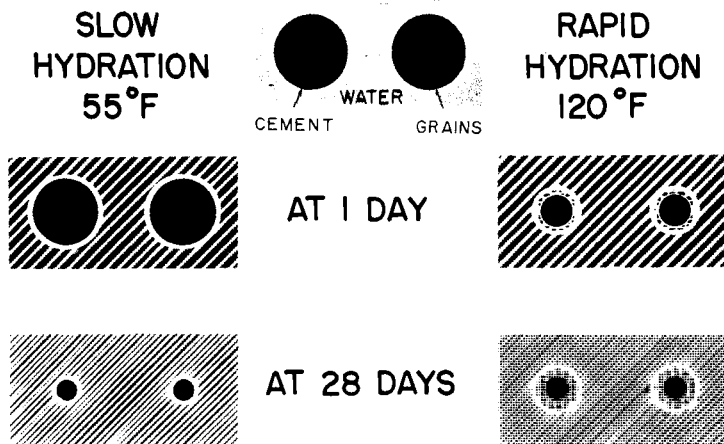


Fig. 1-5—Mechanism by which hydration temperature affects amount and uniformity of distribution of hydration product

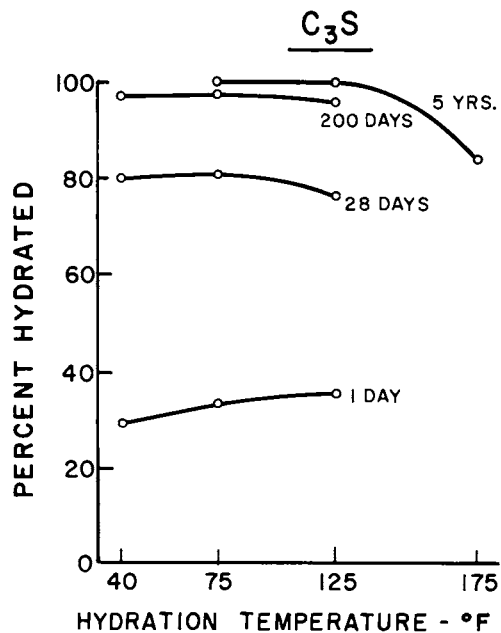


Fig. 1-6—At later ages, degree of C_3S hydration less for pastes initially cured at higher temperature

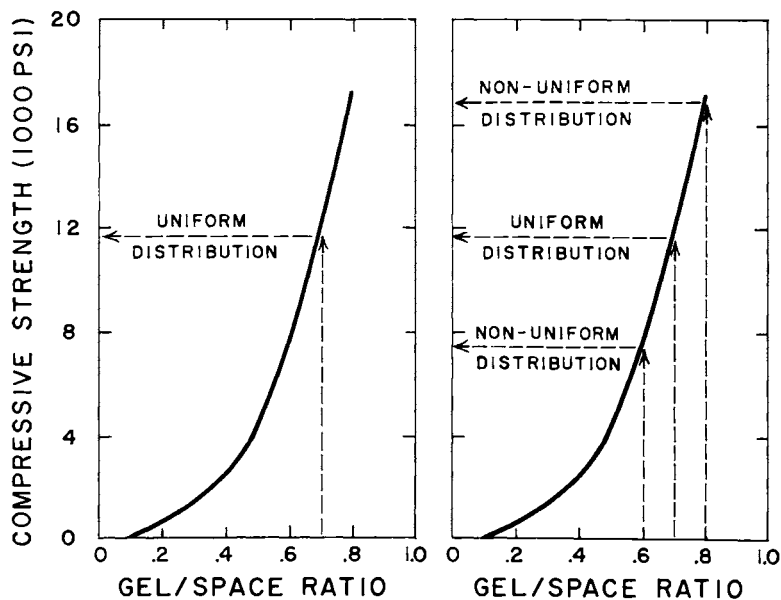


Fig. 1-7—Lowest gel/space ratio governs strength if gel concentration nonuniform

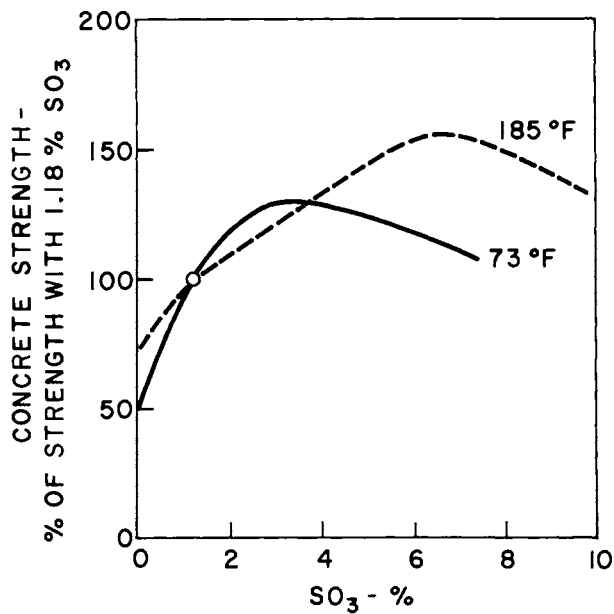


Fig. 1-8—Higher SO₃ required for maximum strength at elevated steam curing temperatures

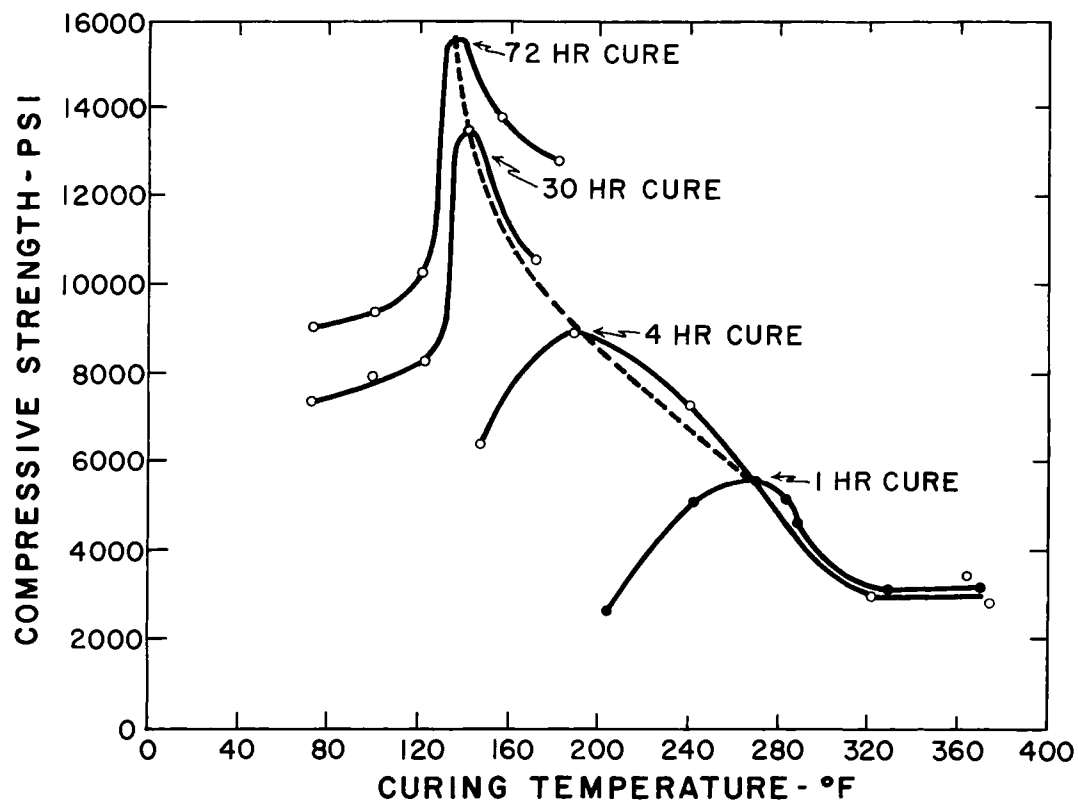
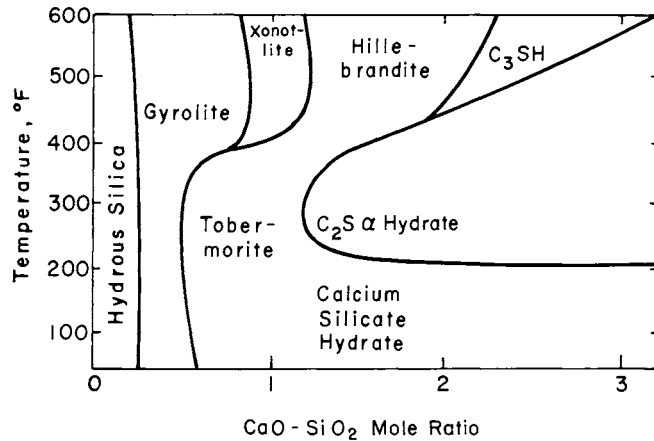


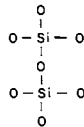
Fig. 1-9—Curing temperature for maximum strength depends on curing time



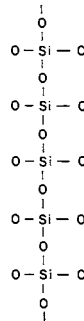
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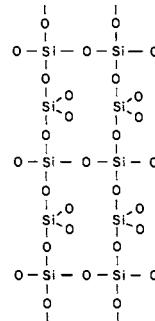
Si₂O₇ GROUPS



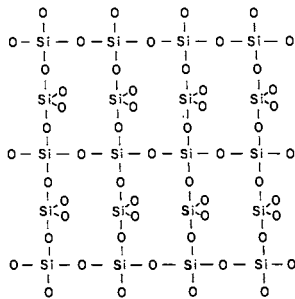
SINGLE CHAINS



DOUBLE CHAINS



SHEETS



FRAMEWORKS

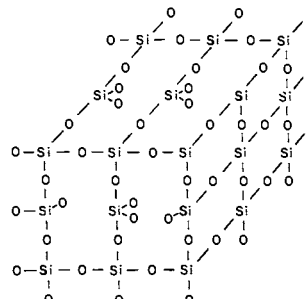


Fig. 1-10—Phase diagram of the hydration products of various lime-silica mixtures at elevated temperatures and the different type of silica structures represented

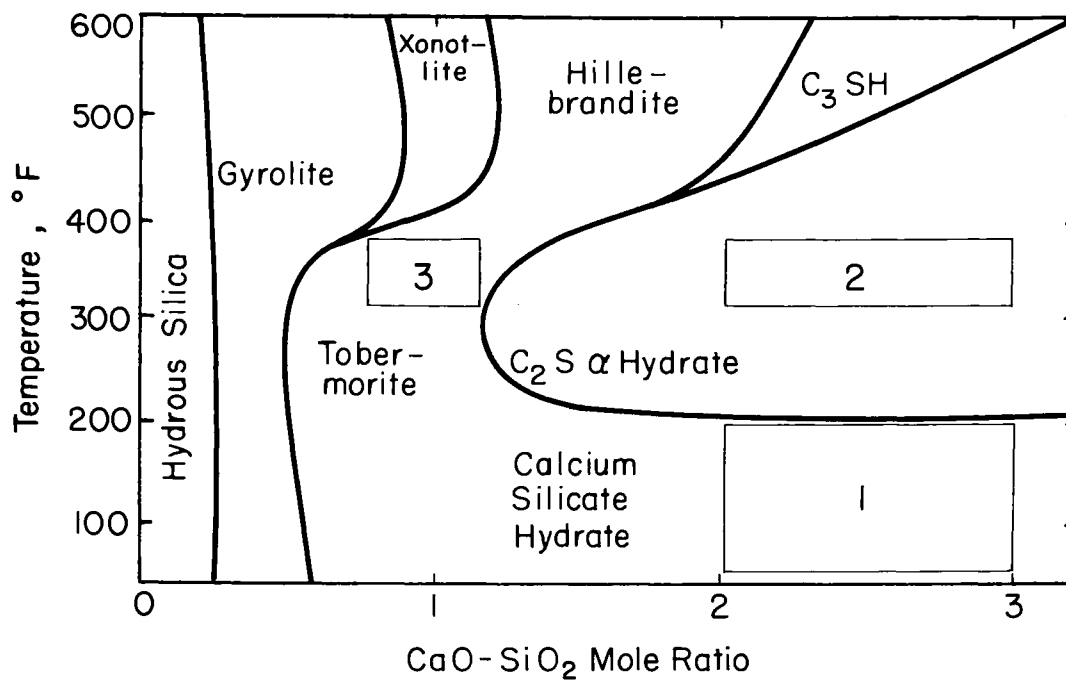


Fig. 1-11—Phase diagram showing hydration products of: Area 1, C₂S-C₃S mixtures, normal and steam cured; Area 2, C₂S-C₃S mixtures, autoclave cured; and Area 3, C₂S-C₃S plus silica mixtures, autoclave cured

TRENDS IN THE DESIGN OF MANUFACTURING FACILITIES FOR AUTOMATED PRODUCTION OF AUTOCLAVED CONCRETE BLOCK IN THE UNITED STATES AND CANADA

By JAMES C. BAILEY and ERNEST C. CLAY

Automation in the block industry is at a primitive stage compared to some other industries. Within the block manufacturing process, the greatest advancement of automation has developed in proportioning and mixing. Those plants constructed in recent years that have been the most automated have all utilized single-stage autoclaving in some form.

The efficiency of autoclave production depends on using a maximum portion of each 24 hr for curing, and a minimum for loading and unloading the autoclave. Thus, efficient and rapid movement of block from one end of the flow diagram to the other is important. It may be accomplished either by using transfer cars in a shuttle system or by using trains that operate over curved tracks and switches. Disadvantages of these systems suggest the desirability of a completely circular system if technical difficulties could be surmounted.

Keywords: *autoclaving; automation; concrete blocks; curing; manufacturing; mixing; optimization; plant layout; plants.*

Automation of concrete block production has made enormous strides in recent years. While most of the technology and the equipment involved has been available for a considerable number of years, it has really been within the past five years that the almost completely automatic production of concrete block has become a practical consideration in the design of new facilities.

It should be pointed out at the very beginning that even the most highly automated block plants in existence today are operating at a relatively primitive level when compared to automated processes in the petroleum, chemical, or even cement industries. It is from these that much of the future technology can be borrowed and adapted.

As used by the concrete masonry industry, automation really refers to a continuous materials handling system in which processes follow one another in a predetermined order. The use of automatic feedback, monitors and/or other processes to make either qualitative or quantitative adjustments is virtually nonexistent. For example, we know of no

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concrete block plant in which batch quantities of aggregate are automatically adjusted for moisture content by servo-mechanisms actuated by electronic sensing devices in the bins. Yet the hardware is readily available for this purpose.

This paper, as part of a symposium on high pressure steam curing, will concern itself primarily with the concepts and machinery involved in, or directly influenced by, the autoclave curing process. First, however, it may prove of interest to consider the entire manufacturing process in general, before concentrating on the curing process in particular.

Fig. 2-1 shows a flow diagram for the material handling process in a typical concrete block plant. Basically this diagram is the same whether applied to the most modern autoclave plant in existence or an early block plant as operated in the 1920's. The only difference is in the complexity, size, and capacity of the equipment involved and in the methods utilized to transport materials from one stage to the next. In other words, the job once done by one man with a wheelbarrow, a shovel, a hoe, and a mixing pan may be done today by a quarter of a million dollars worth of conveyors, silos, bins, batchers, mixers, and automatic controls. The question of how the job is done best is strictly a matter of economics.

Unloading and stockpiling of aggregates has become extensively mechanized. Various types and gradations, usually all passing the 3/8 in. (9.5 mm) screen, arrive by rail or truck. Except for the need at times to attach a vibrator or car shaker to a railroad car, all that is required to load these materials into silos or other bulk storage facilities is the pushing of two buttons - one to select the silo for storage, the other to start the conveyors - and even these may be combined. The aggregate then flows out of the car or truck into hoppers and onto conveyors, then into the preselected silo or bin compartment, to be stockpiled until needed by the manufacturing process.

Depending upon the layout of the plant and the problems involved in the scheduling of aggregate shipments and production, this storage may lead directly to the proportioning system, or, more commonly, serve as the reservoir from which smaller bin compartments are kept filled. If the latter, individual compartments are equipped with high and low-level probes. Each compartment is keyed to a silo and, as the level of aggregate drops below the level that has been set, the probe automatically actuates the appropriate gates, conveyors, and drives. The resulting aggregate flow continues until the bin compartment is filled, at which time the high-level probe closes the silo gate and the conveyors shut off after emptying themselves of the remaining aggregate.

The actual proportioning of aggregates may be accomplished by weighing in weigh batchers, by weighing on a conveyor belt, by the use of volumetric level probes on batchers, or even by checking the electric load of the drive motor turning the blades of the mixer into which aggregate is discharging.

Cementitious materials (cement, silica flour, pozzolans, and lime) are usually conveyed into tanks or sealed bins by pneumatic means, often utilizing the capability of the delivery vehicle itself. These materials

are usually proportioned by weight after being conveyed to the batcher by screw conveyors operating at low speeds for greater accuracy.

Aggregates, cementitious materials, water, and admixtures, if any, are introduced into the mixer in a predetermined order which may include intermediate periods of mixing. The electrical conductivity of the concrete mixture is monitored through probes mounted in the mixer liners, and water is added at various stages to make actual readings correspond to preselected values. These moisture meters are probably the most sensitive equipment utilized in the manufacturing process because with the no-slump mixes utilized in the production of concrete block, even minor variations in moisture have serious effects on the texture and color of the manufactured product. After completing the mixing cycle, the mixed concrete is supplied to the block machine as required, one full mixer load at a time.

Automation of the proportioning and mixing, or of the 'mixer floor' in industry slang, is more advanced than any other phase of making concrete block. This is the first area of production which was automated by most of the industry, probably because two purposes were served at the same time: replacement of manual labor and more consistent quality day in and day out.

The modern block machine molds concrete block and extrudes them upon steel pallets at a rate approaching, and in some cases exceeding, 1500 8 x 8 x 16-in. (20 x 20 x 40 cm) equivalent block, commonly referred to as 'equivalents'; per hour. This compares with a rate of about 1000, five years ago. These steel pallets with freshly molded block, commonly referred to as 'green' block, upon them are taken away from the block machine by means of belt or chain conveyors and are then stacked on the shelves of racks by automatic 'loaders'. These racks of block are then conveyed through the curing cycle - which is discussed in detail later in this paper. The flow diagram of block from block machine to final cubing is shown in Fig. 2-2.

After going through the entire curing cycle, the racks, now filled with hardened block, are taken to a station where pallets and block are removed or 'stripped' by an automatic 'unloader.' Subsequently the block are pushed off the pallet by a 'depalleter.' Pallets are returned to the block machine, after any buildup of concrete is removed by cutting or scraping, and the block are conveyed to a 'cuber' where they are turned, rotated, and otherwise arranged to form any one of many different types of packages or 'cubes.' Often these cubes are palletized on wooden pallets of strapped with steel strapping to facilitate handling. At present, of all the various processes, cubing is the most likely to be performed only semiautomatically - perhaps because

of the many different package arrangements, the high cost of this equipment, and the need to provide visual inspection at some point for quality control.

From the cuber, block are generally removed to the plant yard for storage by fork lift trucks handling two, three, or four cubes, side by side, at the same time. We know of no plant in the United States which stockpiles block cubes with overhead lifting devices such as the rail cranes used by some plants of the European sand-lime brick industry.

So much for the overall manufacturing operation. Now let us look at the various concepts employed in the autoclave curing process and related handling operations.

Before considering the materials flow related to the autoclave curing process let us consider the processes themselves. At one time, there was much controversy in the industry about the relative merits of single-stage curing versus two-stage curing. In the context used here, single-stage curing is defined as curing block while on racks. Two-stage curing consist of a period of curing in steam at atmospheric pressure long enough so that block can be removed from racks, and then cubed onto skids or cars that are placed in the autoclave for final curing. The main advantage claimed for two-stage curing was the better utilization of autoclave capacity (i.e., more block could be placed into an autoclave of given size). It is fair to say, without going into relative merits, that all highly automated block plants constructed in recent years have utilized some variation of the single-stage process.

Within the 'single-stage' operation are many variations, and these of course affect plant layout. Their requirements have certain factors in common. Autoclaving is not a continuous process but a batch operation in which periodically a charge of racks, pallets, and block is removed from the autoclave and replaced by another. Depending on size of autoclave, a single charge will contain from 4000 to 8000 block. Thus it becomes apparent that in addition to an autoclave, there must be provided the following: a preautoclave storage area where a full charge of green block is accumulated, and a post-autoclave storage area for cured block that have been removed from the autoclave. For a number of reasons, it may be desirable to provide heat, moisture, or both during a portion of the former stage; in any case, enough storage capacity must be provided to allow a certain amount of setting, or hardening before autoclaving.

With this brief background discussion, it is possible to construct a flow diagram (Fig. 2-3) which is self explanatory.

This paper is not concerned with evaluating the relative merits of various process or plant designs. Instead, the authors will attempt to point out why they believe certain decisions were made. Following is a list of some of the factors that influence decisions.

Autoclave time at maximum pressure Not so long ago, some authorities advocated curing block at maximum pressure for at least 8 to 12 hrs. Recent experiments have shown that periods of less than 2 hr may be adequate under certain conditions. Intermediate periods are in common usage.

Preliminary curing Depending on aggregates, cements, coloring agents, desired qualities, and climatic conditions, the time required for these may vary from a full eight hours of atmospheric-pressure steam curing at 160-180 F (71-82 C), to no preliminary curing at all - with some of the block going into the autoclave immediately after being molded without apparent harmful effect. Some plants make provision during the period prior to autoclaving for providing moisture only in the summer to prevent drying out, or heat in the winter to prevent freezing and thermal shock. Many intermediate combinations of these are found.

Size and configuration of racks At one time, rack size was determined by the size of rack that could be loaded and unloaded by a man. This limited height to about six tiers or shelves. Weight of racks was limited by the capacity of fork lifts or platform trucks. Both of these restrictions are no longer valid, and racks with eight, nine or ten tiers are not uncommon. Such racks may hold more than 500 equivalents.

Size and number of autoclaves For a given rate of production, with a predetermined curing cycle, one of the most difficult decisions to be made is whether to utilize two or more smaller autoclaves or one large vessel. Several small vessels offer the advantage of less variation in age between the youngest and oldest block, which may be a major factor in quality control. However, when the economics of initial investment, multiplicity of valves and controls, boiler or hot oil system size, recovery of heat, labor for opening and closing doors, and related matters are also considered, it can readily be seen why this problem must be determined anew for each individual installation.

Length versus diameter of autoclave For a given capacity, there are an infinite number of combinations of diameter and length, the two being inversely proportional. As the diameter increases, shell thickness of the vessel must be increased considerably. On the other hand, the corresponding shorter length reduces the time required for loading and unloading. In general, those ratios of length to diameter have been

chosen which, when accompanied by careful rack design, result in the greatest number of block per foot of length of vessel. Inside diameters of 10.0 ft (3.05 m) are common, and vessels of 10.5 ft (3.20 M), 10.75 ft. (3.28 m), and 11.0 ft (33.5 m) are in use. While shorter lengths are more common vessels with tangent length in excess of 150 ft. (45.7 m) are in use. In some instances the dimensions of the vessel were ultimately governed by the limitation of the medium transporting the autoclave from fabrication yard to plant site.

Nonproductive autoclave time During the period that the autoclave door is open, the curing operation is strictly nonproductive. It is fair to state that the largest single capital investment in an automated autoclave block plant is in autoclaves, and related equipment. Thus it is obvious that every effort must be made to reduce the time required for loading and unloading the vessel. For example, if an autoclave is cycled three times per day, or once every 8 hr, and the loading and unloading requires $2\frac{1}{2}$ hr, then $5\frac{1}{2}$ hr are available to bring up pressure, hold at pressure, and blow down. If the loading and unloading time is reduced to $\frac{1}{2}$ hr, then 4 cycles per day are entirely feasible, with a resultant saving in initial investment in autoclaves, etc., of 25 percent, certainly a major consideration.

Number of racks Obviously, enough racks and pallets must be available to hold block at every stage of the curing facility. Thus, if the total average 'turn-around time' for a rack - from being loaded until unloaded and reloaded again - is 16 hr, twice as many racks and pallets will be required as if this time were only 8 hr. At an investment of as much as \$4.00 to \$5.00 per equivalent block capacity, this is a major consideration.

Daily period of operation It can be stated almost categorically that a 'round-the-clock' or at least two-shift operation is required to justify the investment required for one of the newer automated autoclave block plants.

Considering all these factors, it is amazing, that in all the automated plants whose plans the authors reviewed the final decision on plant layout appears to have been governed by the problems caused by the use of coupled racks, each equipped with its own wheels.

In every instance, in order to load and unload the autoclave in the shortest period of time the decision was made to utilize racks with wheels running on steel rails. Individual racks are connected to each other by various designs of self-couplings. This permits the movement of racks in trains and thus is most efficient. Each of the autoclaves was equipped with only one door; thus couplings need to act in both tension and compression.

Wheeled racks move best in straight lines. When they are forced to follow even mild curves, wheels may not track properly; The pulling or pushing force is no longer applied to the rack in the exact direction of movement, and couplings must have a great deal of play to permit the angular displacement that must take place between two rigid racks as they pass around a curve. All of these present problems of operation and maintenance.

At the time an autoclave is ready to be unloaded, an entire train of freshly loaded racks is ready to be loaded into the autoclave. If this train is stored in line with the autoclave, then some means must be found to displace laterally the racks being removed from the autoclave, before the vessel can be reloaded.

This problem of lateral displacement has been solved in two different ways, each having advantages and disadvantages. One school of thought is that speed of loading and unloading is of greatest importance, and the problems of tracking in other than straight lines can be adequately handled by coupling and wheel design, and maintenance. These plants then are designed with curves in the tracks to permit the necessary displacement.

The other school of thought is that the problems of racks moving in other than straight lines should be completely avoided. Groups of racks are transferred laterally on 'transfer cars' which move on their own wheels at right angles to the wheeled rack movements. This system lends itself to easy, complete automation, eliminates all but straight-line movement of racks, and permits compact plant design - but at the cost of considerably longer time requirements for loading and unloading of the autoclave. This increase in time is composed of the extra time required to load racks on and off the transfer car, and the time used for the lateral movement of the transfer car itself.

Incidentally, it is in the movement of trains of racks in and out of the autoclave that questions must be raised about the benefits of total automation. In many instances, racks or trains are moved by pushing devices, located in fixed positions, propelled by screws, electric motors, hydraulic motors, or hydraulic cylinders which, by their very nature, are effective only on the forward stroke and cause all train movement to stop on the return stroke. This may explain why, in many otherwise completely automatic plants, the loading and unloading of autoclaves is still performed under manual control by either a pushing or pulling vehicle, or by a cable-and-winch arrangement.

An analysis of the various plants indicates that they can be clearly classified as either 'Transfer car plants' or 'Curved track plants'. Transfer car plants can be further subclassified as 'One-transfer car plants' or

“Two-transfer car plants”. In addition to these groupings, plant layouts can also be grouped according to the method by which racks are moved during block loading and unloading as follows: ‘Racks on rack conveyor while block are loaded,’ and ‘Racks as part of train on tracks while block are loaded.’

Schematics of typical plant layouts for each of these groupings are shown in Figs 2-4, 2-5, 2-6, 2-7, and 2-8. When arranged in tabular form the various designs appear as follows:

A. Transfer Car Plants

1. Two-transfer car plants

- a. With racks on rack conveyor while block are loaded
see Fig. 2-4
- b. With racks as part of train on tracks while block are loaded - see Fig. 2-5

2. One-transfer car plants - see Fig. 2-6

B. Curved Track Plants

- a. With racks on rack conveyor while block are loaded -
see Fig. 2-7
- b. With racks as part of train on tracks while block are loaded - see Fig. 2-8

It is believed that all plants constructed to date fall into one of these categories as illustrated by the typical layouts. Plants have met their requirements for greater productive capacity, longer presetting of steam curing time, or accommodation to special site conditions by duplicating some or all of the equipment shown in our typical layouts and by rearranging the relative positions of these stages.

Descriptions of the sequence of actions for each of the typical plant layouts are as follows:

Fig. 2-4 Typical two-transfer car plant layout, version A Racks loaded and unloaded while on rack conveyor)

- A. Loader (1) places pallets on racks.
- B. As each rack bay is loaded rack conveyor (2) moves rack so that next bay is available for filling.
- C. When rack is completely filled it is pushed onto the green block accumulator (3). As successive racks are pushed against each other they become coupled automatically.
- D. When accumulator (3) is filled, transfer car (4) already in position pulls coupled racks onto itself.
- E. Transfer car (4) then moves into position opposite Kiln (5) and pushes racks into kiln.

- F. Transfer car (4) then moves in front of cured block rack storage (8) and pulls a number of racks onto itself, uncoupling these automatically from remainder of racks in storage area.
- G. Transfer car (4) carries racks into position facing the racks awaiting unloading area (9).
- H. When this area (9) is emptied, transfer car (4) pushes racks upon it and then moves to position opposite green block accumulator (3) and waits.
- I. As rack conveyor (2) moves, racks with cured block are pulled onto it from position (9).

- J. As racks on rack conveyor (2) are pulled by the unloader (10), it unloads block and pallets, one bay at a time.

While the above process is going on, the actual curing cycle is in operation. Whenever a cycle is completed, and autoclave door has been opened, the following sequence of action occurs,

- K. Transfer car (6) moves in front of autoclave (7) and pulls a number of racks upon itself, uncoupling them from the train.
- L. Transfer car (6) moves into position in front of cured block storage (8) and pushes racks into it.
- M. Steps K and L are repeated until autoclave is completely unloaded.
- N. Transfer car (6) then moves back in front of autoclave (7) and kiln (5) and pulls all the racks in kiln (5) across itself and pushes them into the autoclave (7).
- O. After transfer car has moved away from this position, autoclave door can be closed, and another pressure cycle can begin.

Fig. 2-5 Typical Two-Transfer Car (or multitransfer car) Plant Layout Version B (Racks loaded and unloaded while still part of train)

- A. Loader (1) loads green block onto rack which is part of coupled train being pushed along track (2).

- B. As racks approach trench, transfer car (4) uncouples racks and pulls them onto transfer car.
- C. Transfer car (4) moves to position opposite kiln (5) and pushes racks into kiln where they again become coupled to form train.
- D. Train of racks of cured block on track (2) (3) is pulled toward unloader (9), which unloads block.
- E. As track (2) empties, transfer car (6) moves into position and replaces racks by pulling them from surge track (8).

Whenever autoclave is opened,

- F. Transfer car (6) transfers racks from autoclave (7) to surge track (8) or track (2).
- G. Transfer car then moves into position next to kiln (5) and pulls train of racks from kiln and pushes them into autoclave (7), after which door is closed.

Fig. 2-6 Typical One-Transfer Car Plant Layout (Racks loaded and unloaded while on rack conveyor)

The movements on this system are the same as in Fig.2-4 except that one car performs the function of the two cars in Fig. 2-4.

Fig. 2-7 Typical Curved Track Plant Layout - Version A (Racks loaded and unloaded while on rack conveyor)

- A. Loader (1) loads rack sitting on rack conveyor (2).
- B. Rack conveyor (2) carries filled rack to position in front of kiln (3)
- C. Rack is pushed into kiln (3) for storage and partial steam curing. As racks make contact with each other they are automatically coupled to form train.
- D. Train with block that have been autoclaved already is stored in cured block rack storage (6).
- E. As required, racks with cured block in position (6) are uncoupled and pulled onto rack conveyor (2).
- F. As racks on conveyor (2) pass unloader (7) pallets and block are stripped from rack.

Whenever autoclave cycle is completed and door is opened,

- G. Train of racks of cured block in autoclave (5) are pulled across connecting tracks (4) into cured block rack storage (6), where they are automatically coupled to any remaining racks there.
- H. Train of racks in kiln (3) is pulled out of kiln and pushed into autoclave (5), after which door of vessel can again be closed.

Fig. 2-8 Typical Curved Track Plant Layout - Version B (Racks loaded and unloaded while still part of train)

- A. Train of racks with cured block in cured block rack storage (7) is pulled or pushed along track (2).
- B. Unloader (8) strips rack and loader (1) reloads freshly molded block onto rack.
- C. Train of freshly molded block is pushed into kiln (3). When autoclave cycle is completed.
- D. Train of cured block is pulled from autoclave (5) onto switching track (6).
- E. Train of block in kiln (3) is pushed across tracks (4) into autoclave (5), after which door is closed.
- F. When room becomes available in cured block rack storage (7), train of racks on switching track (6) is moved into this storage track.

A number of equipment manufacturers have furnished the equipment indicated in these layouts. While these and perhaps many others could furnish any of this equipment, the following have furnished the major components for plants already in existence or under construction: Besser Co., Alpena, Mich.; Columbia Machine, Inc., Vancouver, Wash.; GOCORP, Inc., Adrian, Mich.; and PACO Corporation, Montreal, Canada.

It is of interest to note that the great preponderance of automated autoclave plants that have been constructed so far are transfer car plants. Also of interest is the fact that no attempt has been made in any of these plants to automate the opening and closing of the autoclave door, even though this would be relatively simple from a mechanical standpoint - especially in transfer car plants. Probably the basic

reason for this is the feeling that these critical steps must be supervised by a responsible man because of the extreme danger of any malfunction of the autoclave door locking mechanism.

The foregoing covers the present status of automated autoclave block plants in the United States and Canada. Before closing the writers would like to propose a plant of the future which would have all the advantages and none of the disadvantages of the plants that have been discussed. All that would be required is an autoclave whose center line, rather than being straight is curved with a constant radius, and which is equipped with doors at each end. In other words, a circular track plant would be built as shown in Fig. 2-9. Advantages would include rapid loading and unloading of autoclave, and rack tracking and coupling would provide no problem since either racks or entire trains could be built with wheels set to follow the constant angle of curvature.

And if the authors may dream, they would propose an autoclave without doors in this same circular layout. Diaphragms would be introduced between racks which would form individual pressure compartments within the autoclave as the rack train passed through it. Numerous pressure control valves along the length of the autoclave would control the pressure required within each compartment. This development would finally change autoclaving from a batch process to a continuous process, which is believed to be the ideal.

Unfortunately, the writers have neither the money nor the inclination to gamble on a concept so radically different. Although both are within the scope of present technology, any such departures from common practice risk extensive delays while unforeseen practical operational problems are solved. Consequently when the time comes for them to build another plant, it will probably be a variation of one of the layouts discussed because in the final analysis plant layout is strictly a matter of economics.

ACKNOWLEDGEMENT

The authors wish to thank the many people in the industry who helped in accumulating and reviewing the information presented in this paper, and especially Mr. E. R. Woodruff, Vice President of Besser Company, Mr. Walter Neth, General Sales Manager of Columbia Machine, Inc., and Mr. Robert O. Davis, Vice President of GOCORP, Inc.

APPENDIX

Automatic Autoclave Block Plants in the United States and Canada

This listing includes all plants in operation or under construction of which we are aware. It is quite possible that we have unintentionally omitted some.

STATE or PROVINCE	TOWN	COMPANY
<i>A. Two-transfer car plants (Racks on rack conveyor during loading)</i>		
Iowa	Fort Dodge	Johnston Corp.
Minn.	St. Paul	Anchor Block Co.
Ohio	Cleveland	Cleveland Builders Supply Co.
Ohio	Cleveland	Ideal Builders Supply & Fuel Co.
Ohio	Maple Heights	Charles Svec, Inc.
Penn.	Pittsburg	Rennekamp Supply Co., Inc.
Penn.	Wesconsville	Lehigh Building Block
Tenn.	Memphis	Fisher Lime & Cement Co.
Texas	Amarillo	Crowe-Gulde Cement Co.
Texas	Houston	Delta Concrete Industries
Utah	Salt Lake City	Wm. H. Prince & Sons Block Co.
Va.	Gainesville	Washington Concrete Products, Inc.
Ontario	Kingston	Marker Building Materials
Ontario	Kitchener	Forwell, LTD
Ontario	London	Canada Building Materials
Ontario	Woodbridge	Canada Building Materials
Quebec	St. Vincent DePaul	H. Beaudry Concrete Block Co.
<i>B. Two-transfer car plants (Racks as part of train during loading)</i>		
Ohio*	Cincinnati	Reading Concrete Products Corp.
Va.	Norfolk	Southern Brick & Pipe Corp.
<i>C. One-transfer car plants</i>		
Ariz.*	Tuscon	San Xavier Rock & Materials Div., Union Rock & Materials Corp.
Fla.	Auburndale	Eger Concrete Co.
Ga.	Austell	Concrete Manufacturing Co. of Cobb
Ga.	Lithonia	Concrete Manufacturing Co. of DeKalb
Ill.	Ottawa	Materials Service Corp.
Mich.	Ypsilanti	Precision Concrete Industries, Inc.
N. C.	Winston-Salem	Dixie Concrete Products, Inc.

STATE or PROVINCE	TOWN	COMPANY
<i>C. One-transfer car plants (cont.)</i>		
Va. Alberta*	Richmond Calgary	Solite Corp. Con-Force Concrete Products, LTD
<i>D. Curved track plants (Racks on rack conveyor during loading)</i>		
Texas B. C.	Houston Vancouver	Hydro Conduit Corp. La Farge Cement Co. of North America, LTD
Saskatchewan	Regina	Ready Mix Concrete, LTD
<i>E. Curved track plants (Racks as part of train during loading)</i>		
Conn. Ind. Mass. Mo. Okla. Quebec	North Haven Fort Wayne Acton St. Ann Tulsa Montreal	Plasticrete Corp. Old Fort Concrete Products Plasticrete Boston Corp. Jadavco Veale Brothers Concrete Products Montco, LTD (Track makes complete loop.)

* Plant does not utilize autoclave at present but does utilize the identical machinery for rack movement and transfer in an atmospheric pressure, high temperature steam curing operation.

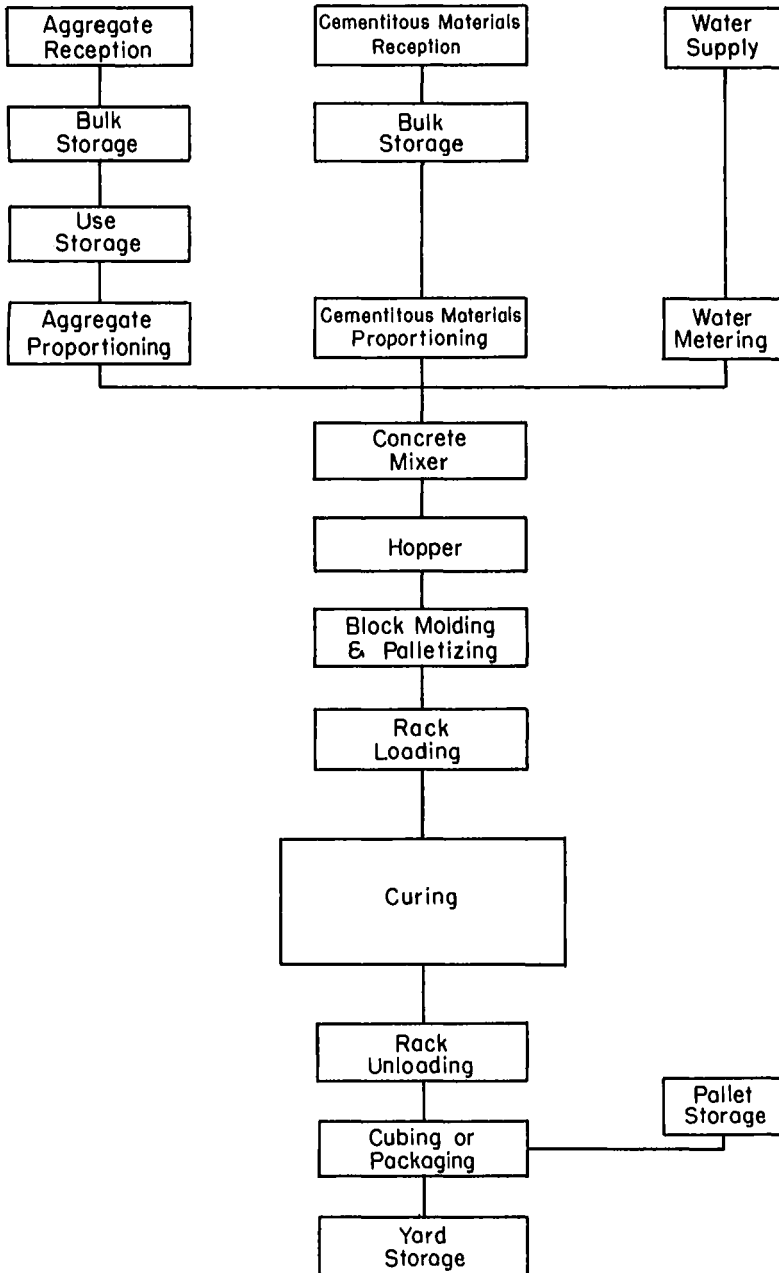


Fig. 2-1—Concrete block manufacturing process—flow diagram

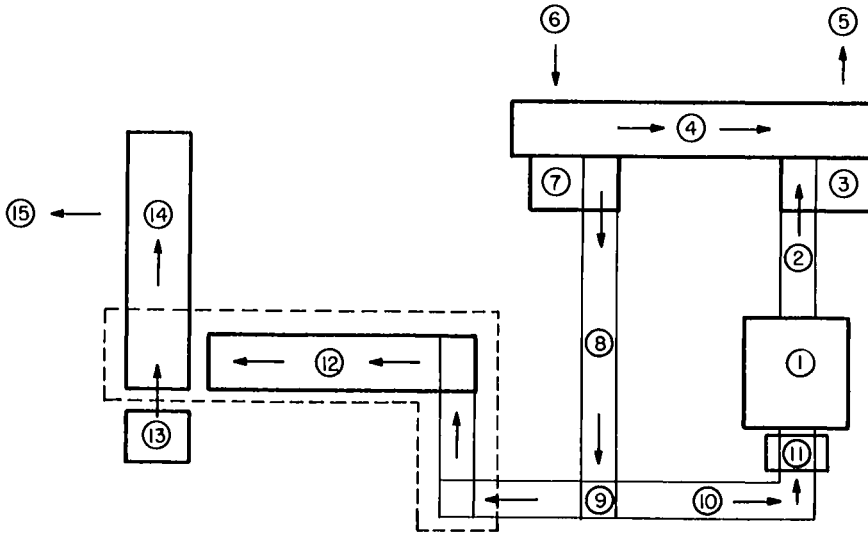


Fig. 2-2—Typical plant layout of an automatic concrete block plant (curing facility excluded), components: 1. block machine, 2. loading conveyor, 3. loader, 4. rack conveyor, 5. to curing facility, 6. racks from curing facility, 7. unloader, 8. unloading conveyor, 9. depalleter, 10. pallet return, 11. pallet cleaner, 12. cuber, 13. wooden pallet hopper, 14. cube conveyor, 15. forklift truck

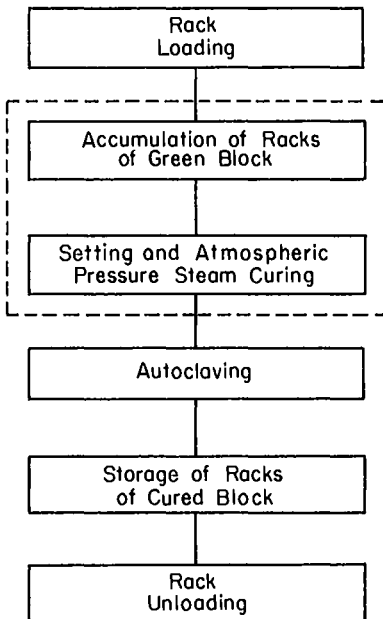


Fig. 2-3—Curing facility—basic flow diagram

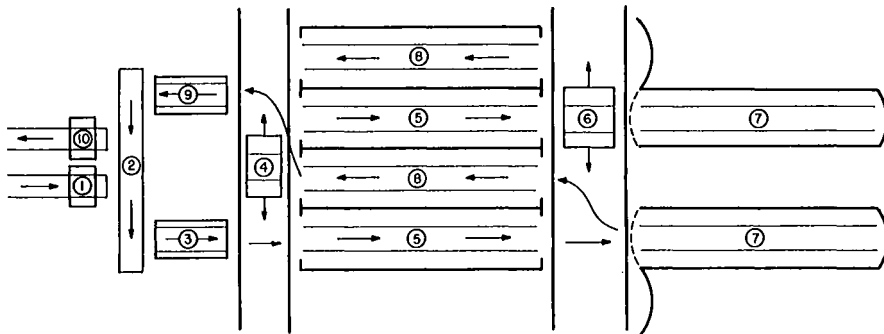


Fig. 2-4—Typical two-transfer car plant layout: Version A, rack on conveyor while block are loaded; components: 1. loader, 2. rack conveyor, 3. green block accumulator, 4. kiln transfer car, 5. kiln, 6. autoclave transfer car, 7. autoclave, 8. cured block rack storage, 9. racks awaiting unloading area, 10. unloader

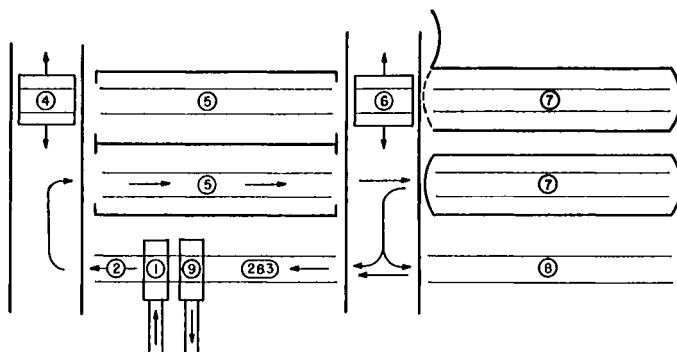


Fig. 2-5—Typical two transfer car plant layout: Version B, rack part of train on tracks while block are loaded; components: 1. loader, 2. and 3. rack track with indexer and ram, 4. kiln transfer car, 5. kiln, 6. autoclave transfer car, 7. autoclave, 8. surge track, 9. unloader

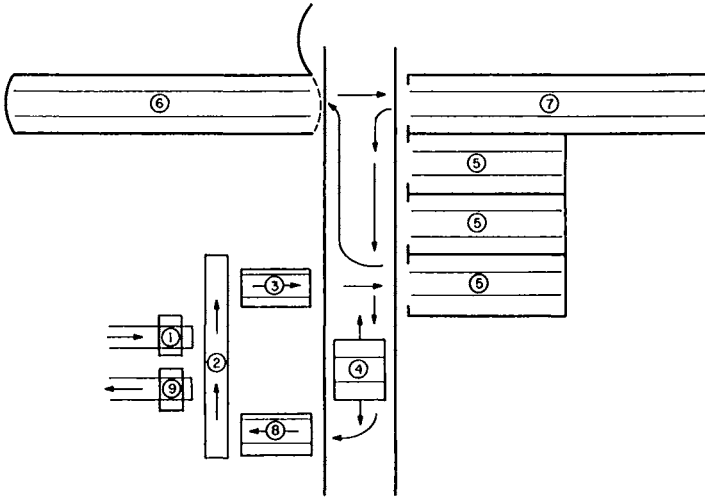


Fig. 2-6—Typical one-transfer car plant layout; components: 1. loader, 2. rack conveyor, 3. green block rack accumulator, 4. transfer car, 5. kiln, 6. autoclave, 7. cured block rack storage, 8. racks awaiting unloading area, 9. unloader

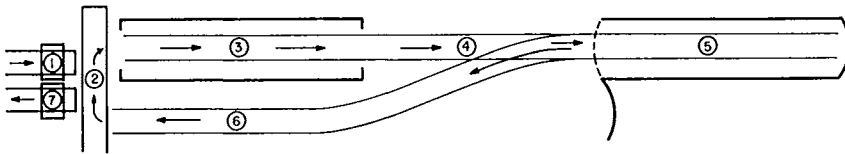


Fig. 2-7—Typical curved track plant layout: Version A, racks on rack conveyor while block are loaded; components: 1. loader, 2. rack conveyor, 3. kiln, 4. connecting track, 5. autoclave, 6. cured block rack storage, 7. unloader

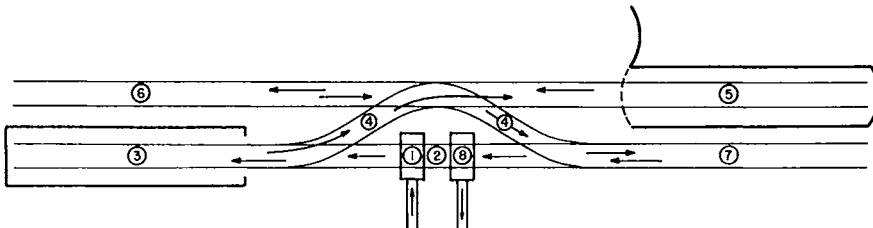


Fig. 2-8—Typical curved track plant layout: Version B, rack part of train on track during loading of block; components: 1. loader, 2. rack track, 3. kiln, 4. connecting tracks, 5. autoclave, 6. switching track, 7. cured block rack storage, 8. unloader

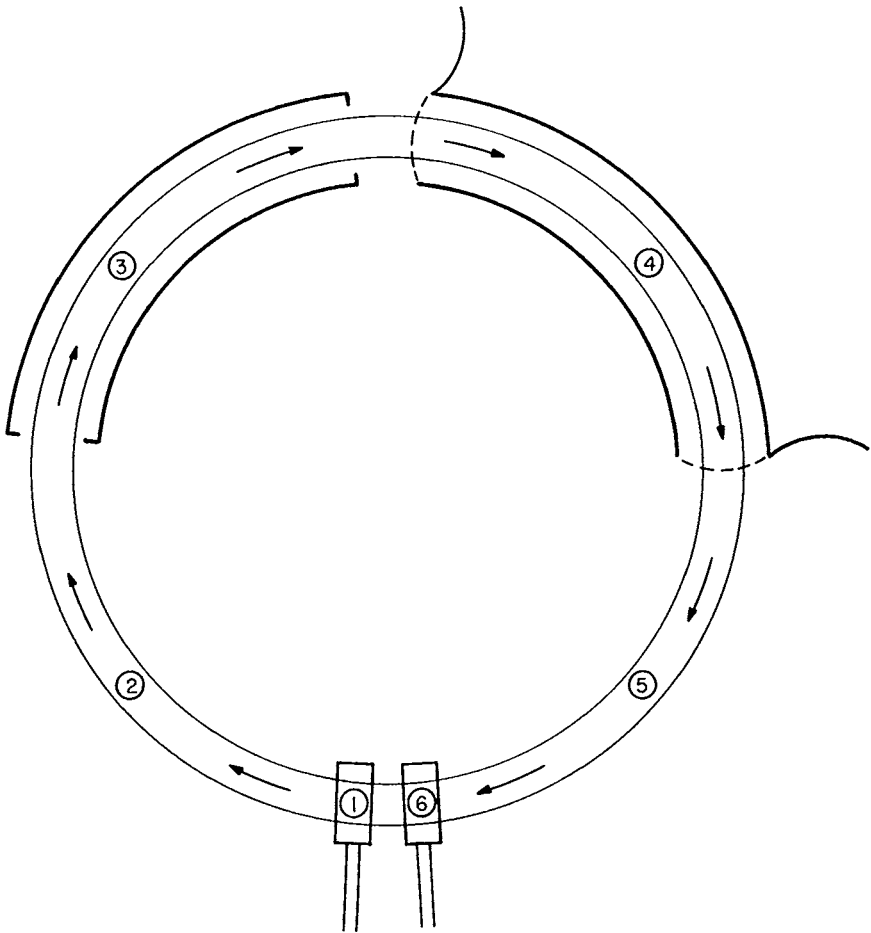


Fig. 2-9--Proposed circular track plant layout; components: 1. loader, 2. green block accumulation, 3. kiln, 4. autoclave, 5. cured block rack storage, 6. unloader

INFLUENCE OF THERMAL DEFORMATIONS AND PRESSURE OF STEAM-AIR ENVIRONMENT ON STRENGTH OF AUTOCLAVE-HARDENED CONCRETE

By SERGEY A. MIRONOV, LARISA A. MALININA,
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The disruptive expansion of concrete which is experienced with either early or rapid application of heat in the autoclave is caused almost entirely by the expansion of the air and water vapor enclosed within the concrete. Deformations in concrete specimens caused by this gaseous expansion during autoclaving have been measured. It has been found that if external steam-air environment pressure is applied properly, these deformations can be prevented. The method used is to seal the autoclave immediately after introduction specimens, and not vent the air during steaming. The result is that the pressure buildup inside the specimen is actually offset by the counter-pressure of the environment. Higher strengths were obtained on 10-cm cubes cured in this manner than those cured in the usual way.

An additional benefit of the method is that moisture is "locked into" the specimen. Apparently the lack of air migration toward the exterior helps retain moisture, as indicated by the lower moisture loss measured when curing with steam-and-air pressure. Even when curing at normal temperature, tests using a pressure of 1 atmosphere of air show that pressure reduces moisture loss and increases strength.

Keywords: air entrainment; *autoclaving*; compressive strength; *concretes*; corrosion; curing; damage; *deformation*; heating; hydration; lightweight aggregate concretes; microstructure; mortars (material); *pressure*; research; temperature rise; *thermal expansion*.

From various work carried out in recent years 1,2,3,4,5 it has been established that the physical and mechanical properties of concretes subjected to heat treatment are determined not only by the degree of cement hydration and the phase composition of new formations, but also to a considerable extent by conditions that create a concrete with a dense structure as a whole. Structure-formation of concrete is influenced by both the phenomena related to the physical and chemical processes of hardening of the binders (variation in absolute volume in the cement-plus-water system; volumetric changes in solid, liquid, and gaseous phases; kinetics of increase in strength of cement paste; etc.) and the

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physical phenomena related to thermophysics of the process (heat expansion of constituents, heat exchange within the material, heat exchange between the material and the environment, and the like).

The phenomena of the first group influence the micro-structure formation, and those of the second group the formation of concrete macrostructure.

Therefore, when specifying the rates of heat treatment, one should strive to obtain the optimum composition and structure of the cementing agent in addition to the maximum acceleration of hardening chemical reaction, and should also strive to weaken or completely eliminate destructive processes. Admitting a determining role of physical and chemical processes, one should not ignore the great significance of the thermo-physical process in developing concrete strength during heat treatment. Recently at the Scientific Research Institute of Concrete and Reinforced Concrete (NIIZhB) we have given considerable attention to the study of effects of physical processes on structure-formation and concrete strength during heat treatment.

The results obtained in laboratory studies were confirmed in the practice of factory manufacture of reinforced concrete products.

During the heating period internal pressure develops in concrete products due to thermal expansion of the concrete constituents (mainly the liquid and gaseous phases), and due to internal and external variation in thermal conditions. This pressure produces a state of stress which in turn has a damaging effect on the structure of the concrete and adversely affects development of strength.

To judge the nature and degree of damage to the concrete structure during the heat treatment, a method has been developed for determining the amount and the nature of maximum and residual temperature deformations of concrete. These are an integral indication of the state of concrete stress. The procedure and devices for determination of thermal deformations during steam curing and autoclaving, as well as the resulting general relationships were reported earlier,^{2,5,6}

It has been established by those studies that after heat treatment concrete tends to maintain a residual expansion, the value of which depends, basically, on curing time before the beginning of the heat treatment and on the rate of rise of temperature.

The use of a presteaming period diminishes the residual expansion of concrete sharply, and, if the period is long enough, completely eliminates it. Because of the influence of many factors on the rate of initial hardening (activity of cement, w/c, ambient temperature, etc.) the optimum presteaming period is not a constant value and varies over a wide range from 2-4 to 8-12 hr and more. The presteaming periods of 0.5-3.0 hr used in factories usually are insufficient to prevent damage within the structure of the concrete.

At present rates have been developed that permit the heat treatment of products to be carried out without damage in the structure of the concrete and for a minimum period of presteaming or even for no presteaming at all. Earlier still there were suggested rates with step-by-step rise of temperature and a progressively increased rate of rise, and these are now successfully used.

The analysis of the basic physical phenomena that occur during autoclave treatment has shown that excess pressure in the environment when products are heat-treated, especially during an initial period, has an independent significance, contrary to the existing opinion of a secondary role of increased pressure that provides only the presence of saturated steam necessary for the hydration reactions of binding materials. As a result, a method of autoclaving materials was presented that consists in applying the excess pressure of the steam and air environment in the initial period of the temperature rise. The essence of this method of autoclave treatment consists of admitting steam into a hermetically sealed autoclave without permitting the enclosed air to escape. The heating of this air immediately exposes the concrete specimens to an increased gas (air plus water vapor) pressure of several tenths of an atmosphere. This external pressure is sufficient to prevent the development of destructive processes in the concrete. This method is suitable primarily for autoclave treatment of freshly molded reinforced concrete elements without the necessity of a presteaming period. On the basis of the earlier investigations it was concluded that, besides other factors, the intensity of

the destructive expansion during heating of freshly molded specimens depends on the variation of properties of the liquid and gaseous phases (water and entrapped air).

On the basis of the investigations carried out earlier the conclusion was drawn that when freshly molded concretes are heat-treated, the intensity of destructive phenomena is influenced, in addition to other factors, by variation of the properties of the liquid and gaseous phases (water and entrapped air).

The present investigations were designed to establish quantitatively the influence of the content of the liquid and gaseous phases on the gaseous environment (both pressure and pressureless) when autoclaving dense concretes. One should understand treatment in a "pressure" environment to be autoclaving at excess pressure of the steam-and-air environment from the very beginning of heating, without venting to allow the escape of air; and "pressureless" autoclaving refers to conventional autoclaving with a slow increase in temperature during which air is driven out by steam, and with steam pressure applied after the temperature has reached 100 C (212 F).

The results of the studies are given in Fig. 3-1 and Table 3-1.* Measurements of the deformations were carried out according to the procedure described in Reference 5.

Specimen No. 3 was prepared of normal weight concrete of 1:1.5:2.5 proportions with $w/c = 0.45$. The binder, or cementitious material, was a slag binder (slag = 55 percent, lime = 15 percent, gypsum = 5 percent, ground quartz sand = 25 percent). In Specimen No. 1 a heavy aggregate (crushed limestone) in concrete was replaced with an equal volume of air-dried volcanic slag. The coarse aggregate for Specimen No. 2 was water-saturated volcanic slag. The initial mortar content was the same in all three specimens. Entrapped air taken in with the mix during mixing and casting amounted to:

Specimen No. 1	-	5 percent
Specimen No. 2	-	3 percent
Specimen No. 3	-	1.5 percent

To judge by the curves of linear thermal deformation (Fig.3-1a) of the above mentioned specimens in the autoclaving treatment with venting

*Editor's Note: A pressure of 1 atmosphere is approximately equivalent to 1 kgf/cm², and in European practice the two designations are often used interchangeably, as in this paper.

of the air, and application of pressure after the temperature of 100 C (212 F) has been reached, it may be expected that Specimen No. 1, containing the largest amount of air, should have the greatest damage to structure, and that Specimen No. 3 should have a somewhat lesser one.

This is confirmed by the results of tests for compressive strength (Table 3-1).

This picture changes qualitatively when autoclaving the above specimens with excess pressure of the environment from the very beginning of treatment, i.e., without venting the air. The curves of thermal deformations of all the specimens lie close together (Fig. 3-1b), and the specimens expanded in accordance with a coefficient approaching that of the linear thermal expansion of hardened concrete. One may consider that in this case an excess pressure building up inside a specimen is exactly offset by the counterpressure of the environment.

An excess pressure of the environment from the very beginning of the heating process (by not venting) permits an extremely rapid increase in temperature without reducing the quality of products made of concretes with various contents of the gaseous phase.

This is also proved by the results of experiments given in Fig. 3-2. Specimen No. 1 of Fig. 3-2, with 4.5 percent entrapped air content, undergoes greater negative deformations (compression deformations) than Specimen No. 2, containing 2 percent entrapped air. With further heating the positive deformations (expansion deformations) of Specimen No. 1 are less than those of Specimen No. 2. But the total deformations of both the specimens are equal in absolute value; i.e., one may consider that while autoclaving with "pressing-up" (without venting the air) an increased content of entrapped air does not cause an additional increase in deformations and the resulting damage to structure of the concrete and decreases in strength (other than what is normally to be expected from the larger amount of void space in Specimen No. 1).

It is noteworthy that the role of excess pressure is not exhausted only by controlling of thermal deformations in the course of heating. The comparison of the weight losses of specimens autoclave-treated at the initial stage using excess pressure and those without such a pressure indicates that those in the first case are somewhat less than those in the second one (see Table 3-2).

Excess pressure seems to decrease rate of evaporation. This may occur from the following causes:

- 1) It is known that when heating in a nonpressure environment

(under atmospheric pressure) partial air pressure in a heating environment decreases with increase of temperature. For this reason the difference increases between the partial air pressure in the voids of a material and in the environment. Due to the influence of this gradient of pressure, a part of the air is displaced from the voids into the free space. This air movement is countercurrent to moisture migration into the depth of concrete, and opposes its free migration.

2) Usually entrapped air is contained in freshly molded concrete. If it is supposed that entrained air bubbles are enclosed in a water film, then one may consider that one of the causes of resistance to water movement into the depth of concrete during the heating period is the change in the properties of the liquid-gas interface which is caused by the dependence of surface tension on temperature.

In autoclaving treatment with excess pressure from the very beginning of heating the pressure counteracts the above phenomena and in effect "locks in" moisture, diminishing the intensity of its evaporation.

Because under conditions of autoclave treatment the hardening concrete is under the influence of the variable temperature and pressure of its environment, the desire to clarify the influence of only small excess pressure at normal temperature (20 C or 68 F) on concrete hardening led us to special experiments. Note that studies of the influence on cement hardening of pressures in excess of the normal steam pressures, in combination with increased temperature, were carried out by different investigators, particularly by Ludwig and Pense.⁷

These experiments were conducted by us as follows: Specimens (7 cm or 2.75 in. cubes) of freshly molded mortar were stripped from the molds and placed in an autoclave which was then sealed hermetically by closing the valves, and compressed air was forced in, up to a specified pressure. The specimens were cured at normal temperature under the specified pressure for 5 hr, and then the pressure was allowed to drop down to atmospheric during a period of 10-12 hr. The specimens were tested for compressive strength immediately after treatment, and after 7 and 28 days of curing in a moist chamber at normal temperature. The experimental data are given in Table 3-3.

As seen from the data, excess pressure of the environment leads to an increase in concrete strength up to 28 days age. Increase of strength of specimens hardened under pressure is explained by consolidation of concrete at the expense of compression of entrapped air present in the mix, and reduction of defects which may take place from insufficiently careful compaction. It may also be considered that the internal tensile stresses that inevitably arise in concrete in the course of hardening

are neutralized by means of external pressure, and that this is one of the causes of the strengthening effect of the small excess pressure supplied by the presence of air. Moreover, it is necessary to note that when hardening concrete in the investigated range of pressures at normal temperature, weight losses (evaporation of moisture) are less than with hardening at atmospheric pressure. As shown above, this effect of excess pressure is maintained for autoclave treatment with pressing-up as well.

A considerable influence of entrapped air, contained in concrete, on structure-formation processes may be judged to some extent by a characteristic of the compression curve of freshly molded concrete and a curve of deformations during release of pressure. Measurements of deformations of specimens (12x12x28 cm) 4.7x4.7x11 in. in size were carried out with the help of the device described in Reference 5. Experimental results have shown that in the course of increase in pressure, a volume decrease of specimens took place, which may be explained by elastic compression of entrapped air contained in them.

With rapid decrease in pressure the unhardened specimens did not return to their initial dimensions; they even took a residual expansion and visible defects in structure (characteristic longitudinal cracks) similar to those observed after intensive heating of freshly molded concrete in a pressureless environment. Obviously, the cause of damage of structure in the first case is that the concrete strength is not sufficient to take up the internal pressure in the concrete.

On the basis of the identical character of visible damage it may be assumed that under heat treatment without pressure the cause of damage to the structure also consists in the presence of internal pressure, and a pressure gradient through its thickness; but if in the first case this pressure and gradients are created artificially, then in the second case these arise due to the above-mentioned thermophysical processes.

The above related to consideration of the physical processes occurring during heating of concrete. At the same time it was substantiated that there is a considerable effect of the liquid and gaseous phases present in concrete on concrete strength. This applies to processes that result in variations in the properties of these phases during heating and cooling of concrete products.

CONCLUSIONS

1. When heat-treating freshly molded concretes, the degree of damage to structure, other things being equal, depends on the content of liquid and gaseous phases in concrete.

In high-pressure steam treatment of concretes the most efficient rates are those with excess pressure of the steam-and-air environment applied in the initial period of rise in temperature. This permits a rapid increase in temperature without damage to the hardening concrete structure.

2. Excess pressure of the environment not only restrains thermal expansion of freshly molded concrete during heating up to a value approaching its coefficient of linear expansion, but also reduces the rate of moisture evaporation.

3. Hardening of mortar and concrete at ordinary temperatures, under air pressures of 1 to 5 atmospheres gage, leads to an increase in strength up to 28 days age, this increase being especially considerable (up to 2.5 times) during the first days of hardening.

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TABLE 3-1—EFFECT OF TYPE OF CONCRETE AND ENVIRONMENT
PARAMETERS ON COMPRESSIVE STRENGTH

Type of Concrete	Compressive strength of 10-cm (4-in.) Cubes After Autoclaving*											
	Without venting of the air						With venting of the air					
	In mold			Without mold			In mold			Without mold		
	kgf/cm ²	psi	%†	kgf/cm ²	psi	%†	kgf/cm ²	psi	%†	kgf/cm ²	psi	%†
1. Lightweight concrete with volcanic slag (air-dried)	263	3740	100	270	3840	102	258	3670	100	110	1560	43
2. The same (water-saturated)	215	3060	100	174	2470	80	196	2790	100	115	1640	57
3. Normal weight	420	5970	100	411	5840	98	410	5830	100	255	3630	62

* Presteamming period = 45 min.

Heating period = 4 hr

Curing period = 2 hr at 8 atm. gage pressure.

† %of the strenght of specimens cured in the molds.

TABLE 3-2—RELATIONSHIP OF CONCRETE AND MORTAR
LOSSES IN WEIGHT TO CONDITIONS OF
HARDENING

Name of material	Hardening conditions	Loss in weight, %
Mortar of 1:3 mix; w/c = 0.4	Normal curing (1 day)	5.0
”	Normal curing (1 day) but with pressure of 0.5 atm. gage	3.7
”	Normal curing (1 day) but with pressure of 1 atm. gage	2.6
Heavy concrete of 1:1, 87:2, 78; w/c = 0.4	Autoclave treatment with steam pressure of 8 atm. gage with venting of the air	4.7
”	Autoclave treatment with steam-and-air pressure of 8 atm. gage (without venting of the air)	2.5

TABLE 3-3—CHANGE IN STRENGTH AND UNIT WEIGHT OF 7 cm CUBES HARDENED
UNDER PRESSURE OF AIR ENVIRONMENT AT NORMAL TEMPERATURE

Type and Mix Proportions of Mortar or concrete	Pressure of environ- ment for hardening, atm. gage	1 day					7 days					28 days				
		Compressive Strength			Unit Weight		Compressive Strength			Unit Weight		Compressive Strength			Unit Weight	
		kgf/cm ²	psi	%	g/cm ³	lb/ft ³	kgf/cm ²	psi	%	g/cm ³	lb/ft ³	kgf/cm ²	psi	%	g/cm ³	lb/ft ³
Cement-sand mortar-1:3 w/c = 0.4 Portland cement “M” 500 (GOST)* 970-60	0	36	510	100	2.18	136	183	2600	100	2.19	137	220	3130	100	2.20	137
	0.5	43	610	119	2.20	137	215	3060	119	2.26	141	273	3880	124	2.20	137
	1.0	58	820	183	2.23	139	244	3470	203	2.26	141	353	5020	160	2.27	142
	2.0	93	1320	258	2.26	141	259	3680	143	2.25	141	324	4610	147	2.25	141
	5.0	87	1240	241	2.27	142	—	—	—	—	—	312	4440	142	2.25	141
Keramzite concrete with quartz sand of 1:1.54:0.97 mix w/c = 0.45 Portland cement M “500” (GOST* 970-60)	0	75	1070	100	1.60	100	145	2060	100	—	—	159	2260	100	1.55	97
	1.0	86	1220	115	1.71	107	170	2420	121	—	—	205	2920	129	1.60	100

* USSR State Standard.

TABLE 3-4—PRESSURE-TEMPERATURE RELATIONSHIPS OF STEAM ATMOSPHERES WITH AND WITHOUT AIR

Autoclave temp., deg. F	Absolute		Absolute pressure		Gage pressure	
	Air temp., deg. R	Air pressure, psi	Sat. steam, psi	Air plus steam, psi	Sat. steam, psig	Air plus steam, psig
(1)	(2)	(3)	(4)	(5)	(6)	(7)
70	530	14.7	0.0	14.7	-----	0.0
200	660	18.3	11.5	29.8	-----	15.1
300	760	21.1	67.0	88.1	52.3	73.4
320	780	21.6	89.7	111.3	75.0	96.6
325	785	21.8	96.1	117.9	81.4	103.2
330	790	21.9	103.1	125.0	88.4	110.3
335	795	22.1	110.3	132.4	95.6	117.7
340	800	22.2	118.0	140.2	103.3	125.5
345	805	22.3	126.1	148.4	111.4	133.7
350	810	22.5	134.6	157.1	119.9	142.4
355	815	22.6	143.2	165.8	128.5	151.1
360	820	22.8	153.0	175.8	138.3	161.1
365	825	22.9	162.6	185.5	147.9	170.8
370	830	23.0	173.4	196.4	158.7	181.7

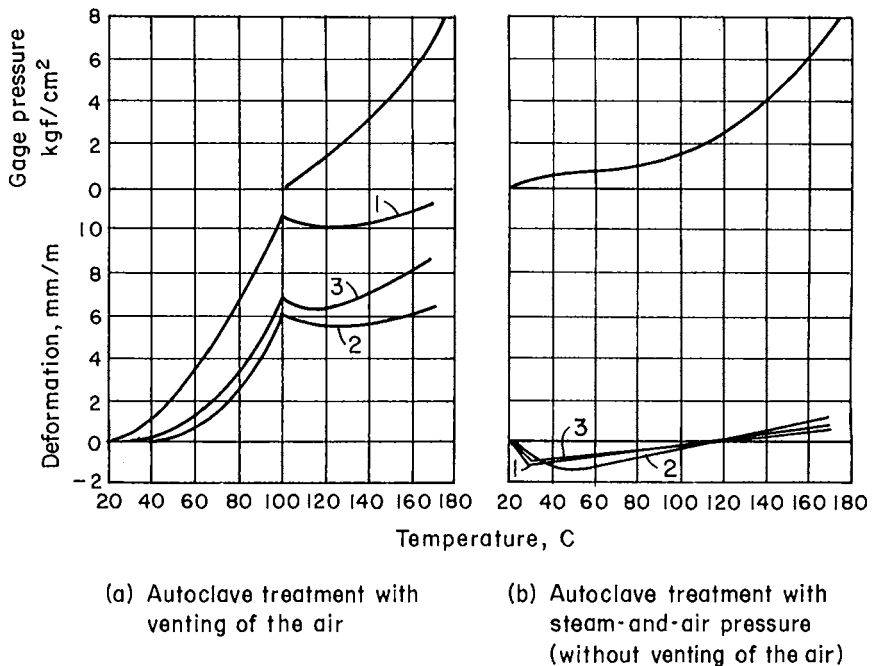


Fig. 3-1—Dependence of deformations of concretes of different mixes on environment parameters, specimen: 1. air-dried volcanic slag, 2. water saturated slag, 3. normal weight concrete

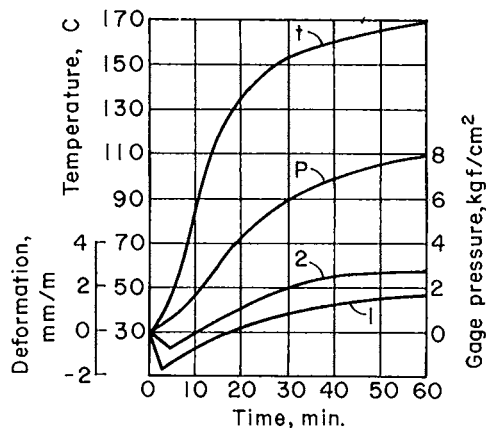


Fig. 3-2—Effect of entrapped air on concrete deformations during heating in an environment with excess pressure (without venting the air); specimen: 1. 4.5 percent air content, 2. 2 percent air content; P - pressure curve, t - temperature curve.

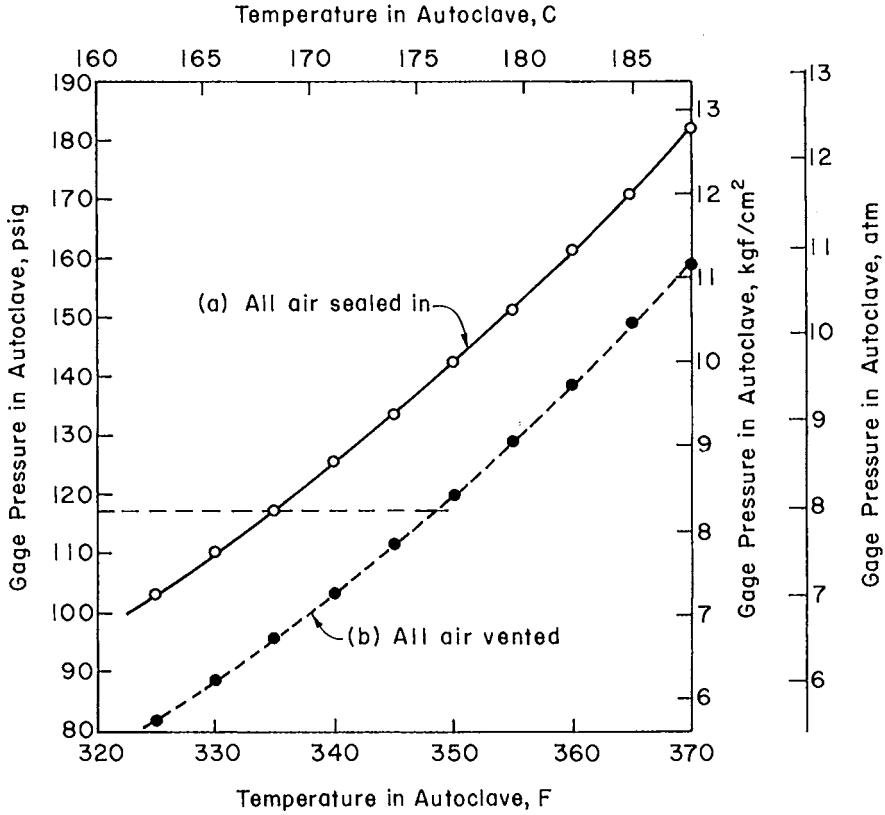


Fig. 3-3— Curves showing that when all air remains seated in, the autoclave curing temperature is reduced from 12 to 14 F (7 to 8 C) for various gage pressures

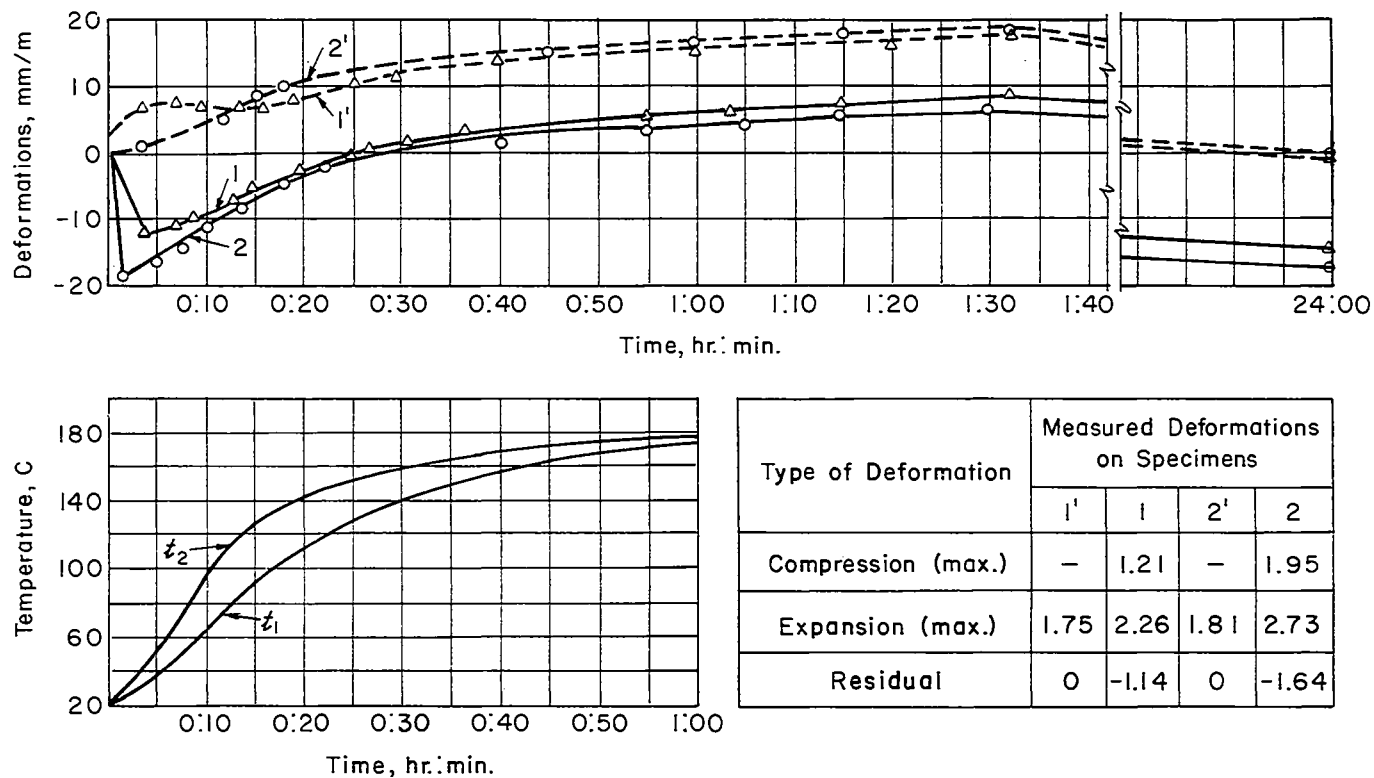


Fig. 3-4—Deformations of specimens of freshly formed and hardened concrete during the heating period in autoclave curing with excess pressure