

Accelerated Curing of Concrete at Atmospheric Pressure-State of the Art

Reported by ACI Committee 517

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Accelerated curing of concrete is used extensively in the production of precast concrete structural members, pipe, masonry units, and prestressed products. Steam curing is probably the most widely used method at the present time. Recent modifications and changes in this method are discussed, as well as effect of the curing cycles

In addition to steam curing, the effect of variations in the concrete materials on accelerated curing is discussed, as are special cements and accelerators. Special treatments, including carbonation, accelerated drying, and heating prior to molding, are also covered.

In addition, other accelerated curing methods such as electrical, oil, and infrared heating, are discussed.

Keywords: accelerated curing; admixtures; atmospheric pressure steam curing; calcium chlorides; carbonation; concrete blocks; concrete pipes; cooling; curing; electric curing; heating; infrared heating; kilns; masonry; pozzolans; precast concrete; prestressed concrete; regulated set cements; reviews.

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ACI Committee 517 was organized in 1958 as the committee on Low Pressure Steam Curing. Since then, its scope has been enlarged to include means of accelerating curing of structural concrete members, concrete block, pipe, and precast concrete, and the title has been changed to Accelerated Curing of Concrete at Atmospheric Pressure.

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*Assumed chairmanship March 1986.

A previous report¹ of the committee dealt exclusively with steam-curing methods and the effects of various ingredients, i.e., portland cement, aggregate, water, and admixtures.

Accelerated curing involves the addition of heat and moisture to expedite concrete curing. By definition it includes, but is not limited to, steam curing. The primary purpose of accelerated curing of concrete is the early development of strength. Forms, casting beds, and curing devices or facilities can then be reused at frequent intervals, and a low in-process inventory maintained.

The objective of this report is to review new developments in accelerated curing including new types of cements, curing methods, techniques, and their effects on products. Regulated set cements, shrinkage compensated cements, and other special cements for high temperature curing are covered in addition to the effect of variations in steam-curing cycles, special treatments such as carbonation, heating fresh concrete, pressure molding, electric curing, and steam injection.

CHAPTER 1-BASIC CONCRETE MATERIALS

1.1 -General

Concrete products subjected to accelerated curing at atmospheric pressure use the same basic materials as normally cured concrete. Trial batches should be made to determine the effects of accelerated curing on the properties of the concrete. Rapid hydration, for example, may cause a reduction in the strength usually attained at later ages. The production benefits derived from rapid strength development must be balanced with the possible detrimental effects on ultimate properties.

1.2-Cement

All types of portland cement described in ASTM C 150 can be used in concretes cured by any of the various accelerated methods. In addition, the blended cements described in ASTM C 595, as well as the special cements discussed in Chapter 2, can be used.

The cement type to be used is determined in the same manner as normal curing. It should be recognized, however, that different cements of the same type will have significantly different characteristics when cured under accelerated conditions. Types I and III are used most frequently; but where special conditions warrant, such as sulfate exposure, Types II and V or blended cements should be used. Air-entraining cements which meet the requirements of ASTM C 150 and C 595 can be used interchangeably with comparable results except in the production of cellular concrete. For cellular concrete there may be an adverse reaction between the air-entraining addition and the foaming agent used to form and stabilize the cellular structure. The optimum accelerated curing cycle will depend in part on the type and source of cement selected.

The complex cement hydration reactions are influenced by temperature, time, humidity, and other curing conditions.

1.3-Aggregate

Concrete aggregates should be tested for compliance with appropriate specifications such as ASTM C 33, C 330, or C 331. Aggregates with different thermal and absorptive properties, however, will react differently when subjected to elevated temperatures, such as concretes made with normal weight versus lightweight aggregates.

1.4-Water

Water quality requirements for concrete subjected to accelerated curing are the same as for normally cured concrete.

1.5-Admixtures

1.5.1 Chemical admixtures-Most air-entraining and water-reducing admixtures perform as effectively in concrete subjected to accelerated curing as they do in concrete cured under normal temperatures. However, optimum dosage rates of water-reducing admixture may be different than manufacturer's recommendations. Before an admixture is used, it is advisable to make trial batches to determine optimum dosage for a cost-effective curing cycle.

Water-reducing admixtures complying with ASTM C 494 types A, D, E, F and G requirements may allow mixing water reductions of 5 to 25 percent for concrete having similar or higher workability.

Concrete containing Types F and G high-range water-reducing admixtures are particularly benefited by delayed addition to the concrete mix. Laboratory and field data indicate that the increased compressive strengths associated with heat-cured concrete containing high-range water reducers are a result of their lower water-cement ratios. Most concretes with and without high-range water reducers have comparable compressive strengths and comparable density for the same water-cement ratios.

Concretes containing chemical admixtures that retard the set normally benefit from an extended preset time, even though the total curing cycle remains the same as for non-retarded concrete. As is true for nonretarded concrete, the initial set must be attained before application of the steam or heat. When accelerating admixtures are used, the preset time may possibly be shortened. The time of initial set for freshly mixed concrete should be determined by the standard method of test ASTM C 403.

Comparative evaluations are necessary to determine the most cost-effective class and type water-reducing admixture to use for a given set of concrete materials and an accelerated curing cycle.

1.5.2 Pozzolans and slags--Fly ash that meets the requirements of ASTM 6 18 has been used as a partial replacement for portland cement or an additive in concretes cured by accelerated means with satisfactory results.

High-temperature moist curing is a means for accelerating the slow reaction between a pozzolan and the free calcium hydroxide $\text{Ca}(\text{OH})_2$, liberated during cement hydration. Temperatures above 190 F (88 C), however, are required to accelerate the reactions sufficiently to increase the early strengths.

Ground iron blast-furnace slag that meets the requirements of ASTM C 989 has been used as a partial replace-

ment for portland cement in concrete production. When cured in accelerated conditions, it has been shown to be highly active resulting in increased early strength gain. Curing temperatures above 140 F (60 C) result in further activation of the slag.

CHAPTER 2-ACCELERATORS AND SPECIAL CEMENTS

2.1-General

Materials which accelerate hardening and promote early strength development of concrete are advantageous in the manufacture of many concrete products. Early attainment of strength in a building block, for example, compensates in part for slow hardening in cold weather and decreases the time required to produce a fully matured block. Similar advantages are obtained in the manufacture of other concrete products. During warm weather, accelerators must be used judiciously so as not to produce too rapid a set. Many plants employ high temperature curing without accelerators during summer months and a combination of high temperature curing with an accelerator during the winter months.

2.2-Accelerators

Chemicals that accelerate the hardening of mixtures containing portland cement and water include some of the soluble chlorides, carbonates, silicates, nitrates, thiocyanates, fluosilicates, hydroxides, and also some organic compounds. Use of accelerators may result in a reduction of long-term strength. Those with a chloride base have occasionally had detrimental effects on plant equipment. Any chemical accelerating admixture should be trial tested prior to full production use.

2.2.1 Calcium chloride-The use of one percent calcium chloride by weight of the cement is usually sufficient to accelerate setting and increase strength sufficiently for cold weather concreting, with protection as described on ACI 306R. The selection of the optimum amount should be based on the setting time and the early strength desired. A complete discussion of the use of calcium chloride in concrete is given by Shideler.^{2.1} The effect of calcium chloride on corrosion of reinforcing steel is covered in ACI 201.2R, ACI 212.1R, ACI 212.2R, and ACI 222R, as well as in a number of other papers.^{2.2-2.5} Proprietary organic accelerators are available for use where chloride-bearing admixtures are not acceptable because of the likelihood of corrosion.

2.2.2 Water-reducing accelerating admixtures-Water-reducing accelerators conforming to ASTM C 494, Type E, may be beneficial in accelerating setting time and in increasing strength at early and later ages.

If adequate information is not available, tests should be made to evaluate the effect of a particular admixture using job materials with expected temperatures and manufacturing procedures. Since most of these materials contain calcium chloride, the user should determine the percent by weight of the cement which its use will introduce into the concrete.

When requested, admixture manufacturers generally will disclose the amount of chloride in their admixture. ACI 212.1R and ACI 212.2R provide detailed information on accelerating and other admixtures.

2.3-Special cements

Calcium aluminate cements have been used to shorten the time of setting of portland cement.^{2.6,2.7} Due to problems of strength reduction by conversion of the hydrates, the committee recommends it not be used for this purpose.

2.3.1 Regulated-set cement-Regulated-set cement is a modified portland cement which contains a substantial amount of calcium fluoaluminate. Initial and final set occur almost simultaneously, and therefore the time between mixing and set is often referred to as handling time. Regulated-set cement can be manufactured to have a handling time from 2 to 45 min. The level of early strength gain is adjusted by the cement producer by controlling the amount of calcium fluoaluminate.

The time of set is reduced and the compressive strength gain rate is increased in regulated cement mortars and concretes when: (a) the cement content of the mix is increased, (b) the water-cement ratio is reduced, (c) the mix temperature is increased, and (d) the curing temperature is increased.

In hot weather it may be necessary to slow or retard the setting action of the cement to have adequate time to place and consolidate the concrete, especially when batch mixing and manually transporting the concrete. Setting time usually will not be a problem when the regulated set portland cement concrete is being produced in a continuous mixer and mechanically conveyed to the forms. When too rapid a set is encountered, citric acid can be added to the mix as a retarder. Conventional retarders for portland cement are not effective in slowing or controlling the set of regulated set cement. Where it is practical, the setting action can be effectively controlled by adjusting the mix temperature.

All exposed surfaces of newly placed, regulated-set portland cement concrete should be protected from moisture loss. Chlorinated rubber, butadiene styrene, or styrene acrylate sealing and curing compounds, as well as polyethylene sheets or wet burlap are recommended for this purpose.

When mixing mortars or concretes containing regulated-set cement, it has been found that excessive accumulations of hardened material in the mixers and processing equipment can be avoided when certain batching sequences and practices are followed. For example, it will usually be beneficial if at least a portion of the mix water and some of the sand or aggregate for the following batch is added to the mixer immediately following the discharge of the previous batch.

The best utilization of the fast strength development characteristics of this cement is possible when the concrete or mortar is prepared in a continuous mixer with as low a water-cement ratio and as high a mix temperature and cement content as will permit proper placement, consolidation, and finishing of the concrete. It is usually not possible to place and finish the concrete as early as possible because of the short setting time.

CHAPTER 3-EFFECT OF VARIATIONS IN ACCELERATED-CURING CYCLES

3.1-General

The application of steam at atmospheric pressure to the curing chamber is one of the oldest and most widely used methods of accelerated curing of concrete. Reference to this technique can be found in literature dating to 1912.

Under ideal conditions the curing of concrete by steam at atmospheric pressure (low-pressure accelerated curing) has the advantage over other methods of accelerated curing in that the curing environment of the concrete is near saturation in regard to moisture. Evaporation of water from the product is minimized, which is especially important where demolded or partially demolded products (block, pipe, etc.) are involved.

Although the steam curing of masonry units, pipe, and precast or prestressed concrete products follows the same basic rules, curing procedures are different for each. As an example, masonry units are of small mass and have a relatively large area-mass ratio. Heat transfer and evaporation will be fast. Pipe and precast products may be cured in a form where evaporation is minimum, or may be of such large mass that heat transfer is slow, and large temperature gradients and resultant stresses may exist between the center and the outside of the mass. Therefore, the curing of each type of concrete product is discussed in a separate section of this chapter.

3.2-Curing for concrete masonry units

As in the curing cycle for all concrete products, an adequate supply of moisture is essential to insure hydration of the cement. During steaming, ample moisture is generally provided through steam condensation. Lack of adequate moisture may result in reduced strengths and plastic cracking.

The most distinguishing feature of concrete masonry units is the use of zero-slump, nonplastic concrete in manufacturing the product. The concrete becomes plastic only through intense vibration and pressure employed.

Table 3.2 applies for the majority of those plants employing accelerated curing in conventional (atmospheric pres-

sure) steam-curing kilns. The first footnote, however, implies that the preset time need be increased by only 1 hr when ambient temperature is below 32 F (0 C). Research indicates that a longer period of time would be required to develop the same early strength as that achieved at 60 F (16 C). When ambient temperatures are below 32 F (0 C), the best practice would be to introduce the molded units into the kiln and slowly raise the temperature to at least 60 F (16 C) (in 1 to 1 1/2 hr). Then use the minimum preset time indicated in the table prior to increasing the temperature at the rate shown in the table. Research with lightweight aggregate block³ 3.1 indicates that it would take about 4 1/2 hr at 35 F (2 C) to achieve the strength that could be achieved in about 1/2 hr at 90 F (32 C) or in 1 hr at 70 F (21 C). The same research with sand and gravel aggregate block indicates that it would take 5 1/2 hr to achieve the same strength at 45 F (7 C) as could be achieved in 2 hr at 75 F (24 C).

3.2.1 Effect of variation in the curing cycle on compressive strength and other properties of concrete masonry-All portions of the curing cycle are completely interrelated. A change in one part of the curing cycle may cause adverse effects in another portion of the cycle. For example, the lack of an adequate preset period could be partially corrected by a slower rate of temperature rise, and conversely, a long preset period could be followed by a relatively rapid rate of temperature rise exceeding even the maximum of 60 F (16 C) per hr indicated.

The prime reason for taking care in planning the preset time (time-temperature related) and steaming rate is due to the different coefficients of thermal expansion of water, air, and the cement paste and aggregates in the mix. If the concrete does not have sufficient early strength to resist the expansive forces during heating, damage can result. Under conditions of mass production and rapid turnover in automated block plants it is possible to reduce the time required for preset and temperature rise periods if the concrete temperatures are elevated above ambient conditions at the time of mixing. There has not been sufficient research on this method with concrete block, but studies³ 2 indicate that elevating the temperature of the concrete mix through steam

Table 3.2-Accelerated curing cycles for concrete masonry units

Curing period	Time, hr	Temperature and rate of temperature change	
		deg F	deg C
Preset*			
Lightweight block	1 minimum	60-100	16-38
Normal weight block	2 minimum	60-100	16-38
Rate of rise		40-60 per hr	22-23 per hr
Maximum temperature	12 (minimum) for combined maximum temperature plus soaking periods†	180-190 150-165	82-88 66-74
Soaking (duration of time of initial set)		5 F per hr maximum average decline‡	2.8 C per hr maximum average decline‡

*Increase preset time 1 hr when ambient temperature is below 32 F (0C)

†When pozzolans are employed as part of the cementing medium, maximum temperatures of 200-210 F (93-99 C) should be investigated for both lightweight and normal weight aggregate units.

‡Soaking period--In steam curing, the time during which the live steam supply is shut off and the concrete products are exposed to the residual heat and moisture. The curing cycle may include a "soaking" or a constant "maximum temperature period," but need not include both. Soaking plus maximum temperature time should total 12 hr minimum. Soaking time may be reduced by an amount of time equal to the time at maximum temperature.

injection would considerably shorten the steam-curing time now commonly used.

3.2.2 Preset period for concrete masonry—As noted, a minimum preset time of 1 hr is suggested for lightweight block and 2 hr for normal weight block prior to applying steam. This recommendation is based on average conditions and may be restrictive in some cases and inadequate in others. For instance, with a coarse-textured, poorly compacted lightweight aggregate block it is entirely possible to begin raising temperatures in the kiln immediately without significant detriment to the concrete. The porosity allows the air and water to expand without causing internal tensile stresses. On the other hand, with the very high strength concrete block currently being produced for some architectural facing units and for high-rise, load-bearing construction, a preset time of 2 hr at 60 F (16 C) may not be adequate. With these units, which have strengths of 3500 to 6000 psi (24 to 41 MPa), it may be well to consider a minimum of 3 hr preset time at temperatures in excess of 60 F (16 C) and a minimum of 4 hr with temperatures between 40 and 60 F (4 and 16 C).

3.2.3 Temperature rise period for concrete masonry—As with the preset period, the temperature rise period or rate of temperature change should be tailored to the product and to its history prior to steaming. If the plant layout and facilities are such that long preset times are generally used, it is possible that for normal production units the rate of temperature rise could exceed that indicated in the table, that is, 60 F (33 C) per hr. However, with high-strength block 3500 to 6000 psi (24 to 41 MPa), the rate of temperature rise should probably not exceed 60 F (33 C) per hr, even if preset periods of 4 hr at temperatures above 60 F (16 C) are employed. In both the preset period and the temperature rise period, it is important that the relative humidity of the chamber surrounding the block be above 90 percent.

3.2.4 Steaming and soaking period for concrete masonry—The most common practice in the concrete masonry industry is to employ steaming and soaking periods of 12 or more hr of the normal 24 hr molding and curing process. It has been found that a combined steaming and soaking period of 12 hr is sufficient to produce the strength needed for purposes of product handling. If the steaming period is followed by a drying cycle, it is quite common to use less than 12 hr of steaming and soaking, followed by a drying period within the same kiln. It is generally considered good practice to employ drying temperatures under 250 F (121 C) unless plant tests are conducted to show that higher temperatures would not be detrimental. Some steaming and drying processes have employed drying temperatures as high as 450 F (232 C) without affecting the units; however, these high temperatures usually have damaged the roof and walls of the kilns.

Individual plant tests should be run to determine a reasonable drying cycle. The length of the drying cycle subsequent to the steam curing would be determined by the moisture content that is desired in the block. There is some information given in the literature^{3.3,3 4} with regard to drying times that may be expected for units manufactured with various aggregate types.

In the most extensive series of tests conducted on steam curing and drying of concrete masonry units at atmospheric pressure, W. H. Kuenning and C. C. Carlson,^{3.1} report in their summation that "it appears that block concretes have some tolerance for high temperature curing conditions which provide relative humidities in the kiln atmosphere that are less than 100 percent, but humidities lower than 90 percent cannot be used without some loss of strength." As a general guideline it is suggested that relative humidities as low as 90 percent can be tolerated without serious effects on the strength and other properties of concrete masonry units.

3.2.5 Conventional kilns and appurtenant facilities for steam curing concrete masonry—ACI 517 includes information with regard to equipment required, design of kilns, and the sizing of steam boilers. More extensive coverage is given on this subject by R. E. Copeland in an article published in 1971.^{3.5}

3.2.6 Continuous or automated curing systems currently employed in the concrete masonry industry—"Continuous" or perhaps more properly termed "automated curing systems" are claimed to have a number of advantages over conventional materials handling and curing systems. Some of the claimed advantages are lower operating costs, less plant space required, and lower initial investment. These systems are designed to eliminate forklift truck handling of racks or cured block, less fuel consumption, and shorter curing cycles. While it is claimed that these systems produce a better product, some of the relatively short curing times employed are open to question. Because of the variety in the different systems, it is not possible to discuss in detail the operation of these systems. The reader is referred to the manufacturer's literature for more information.

3.3-Curing concrete pipe

With few exceptions, concrete pipe is steam cured at atmospheric pressure. The particular methods, curing cycles, and temperatures employed depend on the type of manufacturing equipment used and the manner in which the concrete is placed and consolidated. For example, in some processes the molds are removed immediately after placement, while in others, all but a small portion are enclosed in the form during curing.

Another difference important to the curing is the amount of water in the mix. Consistencies for the various processes range from "earth-moist" to slumps in excess of several inches. Depending on these and other differences, curing cycles affect pipes made by the various methods in different ways and to differing degrees.

As in all curing systems, an adequate supply of moisture is essential to insure hydration of the cement. During accelerated curing, ample moisture is provided through steam condensation or by other means such as mist or water sprays. Pipe made of the drier mixes where the forms are stripped immediately, however, often require additional water during the preset and early temperature rise periods. Lack of adequate moisture at these times may lead to reduced strengths and plastic shrinkage cracking.

3.3.1 Delay or preset period—For optimum results, the preset period should be the same as the time required for initial set determined by ASTM C 403. These times are

generally 2 to 3 hr for Type I and III cements, and 4 or 5 hr for Type II and V at 70 F (21 C). Where concrete or ambient temperatures are significantly higher or lower, the time should be adjusted accordingly. During the preset period the ambient temperature of the curing enclosure should be kept as close as possible to the temperature of the concrete and mold.

The use of a shorter than optimum preset period can cause thermal expansion of the concrete before the structure of the material has attained sufficient strength to resist the internal stresses. As a result, cracks develop, usually microscopic but quite large in extreme cases, and the strength of the concrete is reduced. The drier earth-moist mixes used in machine pipe and the dry-cast process are able to withstand relatively short preset periods without damage because of their lower water content. At a total moisture content of 5 percent some mixes have shown no significant decrease in compressive strength with preset periods as short as 1 hr.

In centrifugated pipe where the moisture content of the interior surface is quite high, an insufficient preset period will lead to blistering and scaling of the surface. Also, where the fresh concrete is dependent on the mold for support, early application of heat may cause the mold to expand away from the concrete, resulting in slumps and cracks.

Too long a preset period is generally not as harmful as one that is too short. Although some reduction of strength will occur, it is usually not significant. Pipe in which large surface areas are exposed, however, are susceptible to plastic shrinkage cracking if evaporation rates are high. This vulnerability is particularly high in centrifugated pipe where the water has been forced out of the concrete and there is little if any bleeding capacity left. Where such conditions are prevalent, fog sprays are used to keep the ambient humidity as high as practical. Refer to ACI 308 for more detailed information concerning plastic shrinkage cracking.

3.3.2 Temperature rise period for concrete pipe-Following the preset period, the temperature of the curing enclosure should gradually be raised to the desired curing temperature. Controlling the rate of temperature rise is important to avoid damage to the pipe. Should the temperature be raised too rapidly, stresses will develop because of the temperature gradients. Cast pipe cured with the inner and outer molds in place are particularly susceptible. The steel molds expand before the concrete has an opportunity to do so, resulting in longitudinal cracking. Large-diameter pipe are more vulnerable than the small-diameter pipe. Whereas small-diameter cast pipe have successfully withstood changes in temperature of 60 F (33 C) per hr, it is often necessary to limit the rate of temperature rise of a larger diameter pipe to temperature changes of 35 F (19 C) per hr to avoid cracking.

The point of application of heat and moisture is also important. Care should be taken to avoid localized overheating of the product and the distribution should be arranged so as to minimize expansion of the molds.

3.3.3 Accelerated curing period for concrete pipe-Generally, the higher the curing temperatures, the lower the 28-day strengths. The maximum temperature used should be the lowest possible consistent with production requirements. The reduction of the maximum accelerated curing

temperature from 140 to 120 F (60 to 49 C) may not significantly reduce early compressive strengths.

When the accelerated curing time required is in excess of 12 hr, it is common to interrupt the curing to strip and reuse the forms. American Water Works Association standards^{3.6} require at least 6 hr before this interruption, but in practice it is generally longer to insure adequate stripping strengths. There appear to be no noticeable effects on the strength or other qualities, but further studies are required to determine the exact significance of interrupted curing cycles.

Large variations in temperature during accelerated curing due to the intermittent application of heat should be avoided. While the product can usually withstand thermal shocks relatively well, proportional controllers should be employed wherever possible to minimize temperature variations, particularly with larger pipe and also toward the end of the cycle.

3.3.4 Cooling period for concrete pipe-There is no research to indicate to what extent rapid cooling of concrete after curing is detrimental. Under extreme temperature conditions, cracking during cooling has been reported where the pipe was restrained by the mold and large temperature gradients occurred. A controlled cooling period, however, is both practical and beneficial to the extent that thermal shock is minimized.

3.4-Curing of precast and/or prestressed concrete products

In the curing of precast and/or prestressed concrete products, all factors are interrelated. A change in one part of the operation may affect the others. The optimum curing cycle can generally be determined only by trial. Also, the size of the structural member may affect the optimum steam-curing cycle. As an example, small masses become heated faster than larger masses; however, a large mass of concrete will generate and retain more of its own heat through hydration. Such a large mass will reach a higher internal temperature than indicated by the ambient temperature. The water-cement ratio employed will also affect the steam-curing cycle. Low water-cement ratio concrete generally requires a shorter preset period. In some cases for members with high volume-to-surface ratios, the heat of hydration is all the heat that is needed to cure the product. In all cases, it is a significant contributor to the curing heat. The insulation and coverings used to protect and insulate the forms and fresh concrete must be designed for maximum thermal efficiency. This insulation should minimize air leakage and moisture loss.

Since the heat of hydration is a significant contributor to curing-cycle efficiency, the internal concrete temperature rather than the ambient air temperature should be monitored to realize this quantity of heat.

3.4.1 Preset period-The preset period can be defined as the duration of time after the concrete has been batched until initial set is obtained. During this period, heat is not normally applied unless it is necessary for maintaining the initial temperature. The preset period should be established by determining the initial setting time of the concrete in accordance with procedures in ASTM C 403. It appears that energy conservation and optimum early-age strengths can be achieved by