Some Generalizations in Theory and Technology of Acceleration of Concrete Hardening

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•THE VOLUME of data gained from theoretical and experimental research on accelerated hardening of concrete and in the practical application of this technique for the manufacture of precast reinforced-concrete products justifies discussion and generalization necessary for determination of the direction of further work.

Although chemical considerations are recognized as of great importance, especially under normal conditions, this paper deals mainly with physical phenomena occurring at elevated temperatures and mechanical changes which influence greatly the structure and properties of concrete. Some important technical and commercial problems connected with fabrication of reinforced-concrete units are also discussed.

PHYSICAL AND CHEMICAL PROCESSES AT AN EARLY STAGE IN THE HARDENING OF CEMENT AND CONCRETE

The early investigations carried out by Le Chatelier, Michaelis, Baikov and others dealt with the important questions of the physical and chemical phenomena of cement hardening. Their fundamental work contains the basic principles for further development of the theory of cement and concrete hardening.

More recently in many countries profound research was conducted in the field of physical and chemical processes of cement hardening. Much of this work, however, has been devoted to processes involved in hardening of cement at ambient air temperature or in the conditions of high-pressure steam curing. The most widespread method of accelerating hardening of concrete—heat treatment at temperatures ranging up to 100 C—has been less investigated. Some of the work analyzing physical and chemical processes induced by various methods of acceleration of cement and concrete hardening are of limited value. They often deal with some particular phenomenon, leaving aside the complex of problems as a whole. There is no generally accepted theory of hardening of cement. Moreover, hypotheses suggested and theoretical work available do not adequately reveal the complicated mechanism of hardening concrete. So it is necessary to elaborate a general theory of concrete hardening, not only to explain the processes involved but to control them.

Baikov, Dorsch, Calley, Malinin, Lopatnikova and others discussed such physical and chemical processes as hydration of cement, rise of cement-paste temperature due to heat of hydration, change of electrical conductivity, viscosity and plastic strength during setting and hardening of cement.

All these processes are interdependent and their development in time characterizes the kinetics of setting and hardening of concrete.

Adding water to cement initiates dissolution of clinker mineral components and hence saturation of the liquid phase. In a few minutes this process discontinues and for a long period thereafter the concentration of liquid phase remains stable. There is some rise in temperature and electrical conductivity of the paste associated with the early stage of dissolution of clinker minerals, which is followed by stabilization of these properties. Viscosity and plastic limit of cement at this stage also remain unchanged. This period lasts till the beginning of cement setting as determined by the Vicat method. Then hydration and the heat evolution accompanying it intensify, reaching their maxima later than the end of setting period as determined by the Vicat method. Electric resistance of cement paste initially decreases to its minimum (because of the saturation of liquid phase with lime) and after the setting period it begins to increase. Hence, the end of setting period cannot be exactly determined by the Vicat technique. It could be determined more accurately by increasing the load on the Vicat needle. In this case the end of needle penetration into cement paste will be delayed up to the moment of maximum development of cement hydration and its heat evolution. Among the phenomena observed in the setting period are not only an increase in viscosity of cement with the formation of coagulative structure and compaction of cement paste, but also cement strength development. If at the beginning of setting, strength of cement is measured in fractions of a kilogram, by the end of this period it achieves several kilograms per square centimeter.

By the actual end of cement setting, the structure of hardened cement paste is basically formed and molded units can retain their shape.

Up to this stage the structure of cement paste and concrete, owing to insufficient strength of crystalline skeleton of calcium sulfoaluminate and hydroaluminates, can be destroyed under vibration and additional compaction (i.e., the structure is still reversible under high dynamic influences). Later it becomes irreversible because of destruction of both feeble crystalline and gel components, and can withstand spontaneous deformations due to changes in temperature and moisture gradients, but it cannot withstand mechanical loads exceeding its strength.

Figure 1 shows the kinetics and the correlation of such physical and chemical phenomena as saturation of the liquid phase with lime when water is added to normal portland cement (curve 1), temperature change of the cement paste (curve 2), change of its electrical resistance (curve 3) and plastic limit gain (curve 4) plotted against different stages of cement setting as determined by the Vicat technique.

As can be seen from Figure 1, inflection points on temperature and electrical resistance curves correspond to the first maximum value of dissolution of the clinker minerals (in terms of CaO content of liquid phase). Thus the physical nature of cement hydration reveals itself at a later, more intense stage of this process.

As far back as in the 30's investigations conducted in the USA, USSR, and other countries established certain correlation between mineral composition, rate of hydration, heat evolution, and activity of cement. It was determined that rise of temperature of the system, cement plus water, is associated with exothermic reactions of hydration. Application of exact methods and devices for measuring time-dependent heat evolution permitted determining values and kinetics of heat evolution for different mineral compositions of various types of cement. On the basis of these data some investigators attemped to establish a direct relationship between kinetics of hydration and heat evolution on the one hand and activity of cement or strength of concrete on the other.

Some investigators compared the curves of heat evolution of cements with the curves of strength development of concretes made with these cements. Moreover, some attempts to establish a mathematical relationship between heat evolution and strength of concrete were made. But the relationship between these characteristics is very complicated and far from being directly proportional.

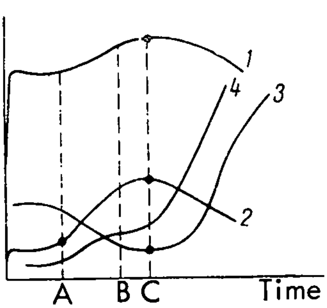

Figure 1. Curves of change of CaO concentration in the liquid phase (1), heat evolution (2), electrical resistance (3) and gain of cement paste strength at an early stage of hardening (4). A—start of setting; B—end of setting; C—true end of setting.

The attempts to achieve concrete strength required in an arbitrarily set period by control of the heat-evolution process failed because gain in concrete strength depends not merely on kinetics of cement hydration or heat evolution but on such factors as phase composition of hydration products, formation of hydrated cement paste structure and nature of methods of physical and mechanical treatment used.

It was proposed to determine concrete strength gain in heat treatment by the character of change in the specific electrical resistance curve. However, it should not be overlooked that there is no direct relationship between electrical resistance and strength of hardened concrete. In each particular case electrical resistance of material varies depending upon such factors as composition of cement, water content, density of concrete mixture, types of admixtures, temperature, etc. Thus it is impossible to read absolute values of concrete strength from changes of its electrical resistance. Data on electrical conductivity and specific resistance should be extensively used for research purposes, but these data cannot be relied upon as control points for automatic regulation of heat treatment of products.

On a level with other methods used in investigation of hardening processes of cement and concrete, those based on electrical conductivity provide a basis for judging the degree of dissolution of mineral constituents of cement, the rate of chemical reaction between cement and water, and the rate of formation of the hardened paste structure exhibiting rising specific resistance.

When considering the question of control of the processes of hardening it is necessary to take into account not only particular aspects of the phenomena but the whole complicated complex of physical and chemical phenomena and of fabrication technology.

It should be noted that the exothermic effect of cement hydration depends on the temperature conditions and may be either positive or negative. The negative effect of heat evolution is shown in undesirable stresses caused by temperature rise and in drying of the concrete when hardening. This negative effect is of great importance for heat treatment of reinforced concrete, especially in its initial stage when differences in thermal expansion factors of various concrete constituents give rise to major stresses leading sometimes to cracking. Exothermic heat developing during hardening following concreting of large, massive bodies should be somehow removed or redistributed in time.

On the other hand, heat evolution plays a very positive part in concrete hardening in cold weather. On these occasions it is advisable to use highly-exothermic cements with major heat evolution at early stages of concrete hardening.

Heat treatment of units as compared to normal hardening of cement and concrete brings about substantial complication of all the physical and chemical processes involved and gives rise to some new physical phenomena not yet fully investigated.

DEFORMATION OF CONCRETES IN HEAT TREATMENT

Insufficient attention in studies of concrete hardening has so far been given to the influence of thermal expansion and shrinkage of concrete in the process of heat treatment on the formation and strengthening of its structure. Problems connected with thermal expansion and shrinkage on the one hand and with the strength of concrete subjected to low- and high-pressure steam treatment have been explored recently in the laboratory of acceleration of concrete hardening at NIIZhB Institute by V. A. Fiodorov, E. N. Malinsky, L. A. Milinina, and the author.

It was found that both in normal conditions and in steaming at the temperatures ranging up to 100 C products of portland-cement hydration are identical. This could suggest the identity of structure and physical and mechanical characteristics of the hardened paste as well. Nevertheless we came to the firm conclusion that in heat treatment it is not phase composition of hydration products but mainly physical changes of structure called forth by thermal expansion of concrete components that influence qualities of hardened cement paste and concrete. Moreover, the influence of the temperature factor on fresh concrete is so great that at high-pressure steam treatment, in spite of substantial changes of phase composition and intensification of processes of cement hydration, structural disturbances bring material reduction of the effect that could be obtained through the active physical and chemical processes of hardening of binders. If formation of the hydrated cement paste structure depends on quality of cement composition and consistency of concrete, temperature and duration of hardening, it is rate of temperature rise and time of start of heating after concrete compaction that are the main determinants of the rate of destructive processes. Presence of forms and the degree to which they are sealed are of great influence too. It was noted that products heat-treated in forms—all other conditions being equal—are always better than those cured without forms.

Our experiments show that all this is connected with temperature-dependent destructive processes inherent in any method of heat treatment of concrete.

The extent of the destructive processes at various conditions of heat treatment can be judged by the results of investigation of temperature deformations, especially those occurring in the initial period of concrete hardening.

Maximum deformations of concrete at low- and high-pressure steam treatment depend mainly on temperature-rise rate and on level of temperature achieved during heating. Relatively rapid rise of temperature of concrete subjected to 2 hr precuring before start of heating results in expansion by 3-6 mm/m at steaming and 10-15 mm/m at high-pressure steam treatment.

Slow rise of temperature and increase of time of precuring bring substantial reduction of deformations—down to 1-1.2 mm/m at low-pressure steaming and to 2.3-2.5 mm/m at high-pressure steam treatment. These deformations correspond roughly to the linear coefficient of thermal expansion of the hardened concrete. Our investigations have revealed that if deformations of heat-treated concrete correspond to the coefficient of thermal expansion of the hardened concrete it may be heated without forms without substantial destruction of its structure.

A generalized diagram of deformation of various concretes in the process of heat treatment is shown in Figure 2.

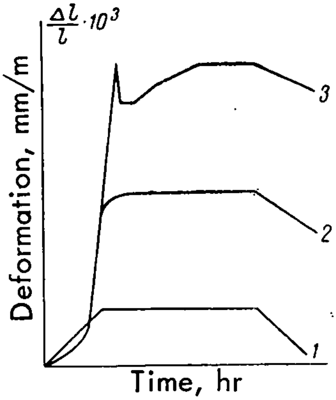

Figure 2. Deformations of various concretes in the process of heat treatment: 1—concrete precured for 24 hr; 2—concrete steamed at 60-80 C temperature after precuring for 2 hr; 3—concrete steamed at 8 atm after precuring for 2 hr.

Maximum deformations of concrete which gained sufficient strength prior to heat-treatment amount to 1-1.2 mm/m at low-pressure steaming and 2.3-2.5 mm/m at high-pressure steam treatment. These deformations may be described by the lower curve (curve 1). Concrete of insufficient strength when subjected to steaming at an early age has rather high maximum and residual expansion values (curve 2). When subjected to high-pressure steam treatment, its expansion is still more remarkable (curve 3). It should be noted that concrete specimens heated in closed forms attain higher strength than those heated without forms. This can be attributed to disturbance of structure of freshly prepared concrete specimens under thermal influences. The higher the initial strength of concrete specimens the lower the maximum thermal deformations induced by heat treatment and the higher the strength gained in formless heating. There exists a definite initial, so-called critical strength of concrete which, once gained, insures identical physical and mechanical properties of concretes heating and without forms.

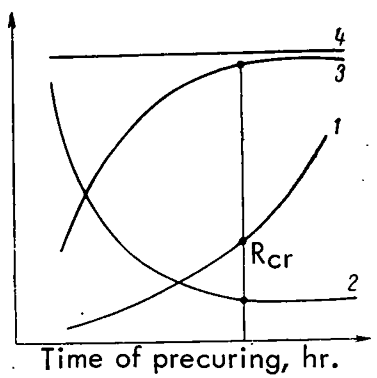

Figure 3. Influence of concrete precuring on its strength and deformation in the process of heat treatment: 1—concrete strength before heat-treatment (steaming); 2—maximum expansion deformations at high pressure steam treatment, mm/m; 3—strength of concrete high-pressure steam treatment without forms; 4—strength of concrete high-pressure steam treatment in forms or after long precuring; R_{cr}—R critical.

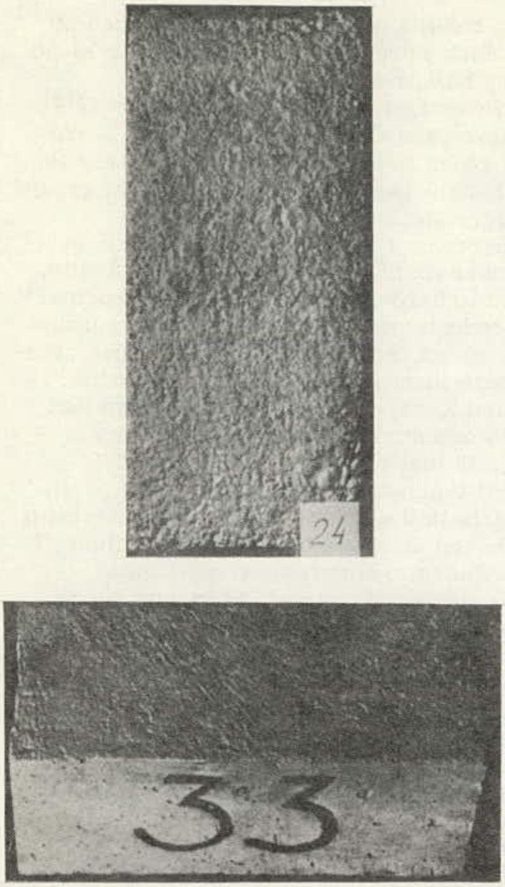

Figure 4. Test specimens of expanded clay concrete steamed at high-pressure steam treatment: No. 24—after 2 hr precuring at 15 C; No. 33—after 12 hr precuring at 15 C.

The influence exerted by precuring of concrete on its strength and deformations induced by heat treatment is shown in Figure 3.

After the concrete had gained critical strength (curve 1) of the order of 7-8 kg/sq cm, for example, its maximum deformations in 2 + 4 + 2 hr steaming at 8 atmos (gage) become permanent and independent on any further precuring (curve 2).

To each regime of heat-treatment conditions there is a corresponding definite critical strength of concrete preventing destructive changes in its structure.

As shown in Figure 3 (curve 3), when concrete with less than critical strength is subjected to formless high-pressure steam treatment, deterioration of its structure is more pronounced than when it is given high-pressure steam treatment in forms. Heat treatment of units in rigid forms brings about compaction of concrete. This prevents disturbance of contacts between concrete components and hence prevents cracking. Thus conditions favorable for tightening of contacts between concrete constituents and coalescing of newly formed crystalline hydrates (i.e., for compacting of submicrostructure) are created.

Figure 4 shows photographs of specimens after high-pressure steam treatment with 2 + 4 + 2 hr regime at 8 atmos (gage) without forms. Specimen 24 was precured for 2 hr. Specimen 33 before high-pressure steam treatment gained critical strength of 7-8 kg/sq cm. In the process of high-pressure steam treatment this specimen did not undergo structural changes of any importance despite the fact that it was steamed without forms.

Equality of strength characteristics of cube specimens after high-pressure steam treatment in and not in forms is indicative of the same correlation. Specimen 24 evidences substantial destruction of concrete structure. Strength of some specimens heat-treated without forms was 2-3 times lower than that of identical specimens subjected to heat treatment in closed forms.

This prompts a very important practical conclusion that low- and high-pressure steaming and electrical curing of the products should be carried out in closed forms or after precuring to some critical strength.

Correlation between deformation and strength of concrete thus ascertained scientifically explains general phenomena of hardening of concrete and provides a clue to the understanding of some peculiarities of concrete hardening under conditions of heat treatment.

ON THE STRUCTURE OF HYDRATION PRODUCTS OF CONCRETE CURVED NORMALLY

Following Le Chatelier's (and in this respect, Baikov's) theory many investigators in their work on hardening of cement and concrete under normal temperature conditions point out that unstable gels gradually turn into crystalline intergrowths.

It is interesting to consider in this connection results of petrographical studies of concretes made with various portland cements which were allowed to harden for 16-20 years in different humidity conditions without any heat treatment.

For example, V. N. Young and V. V. Lapin investigated concrete specimens immersed for 20 years in seawater; B. G. Skramtayev and O. M. Astreyeva and L. Ya. Lopatnikova studied specimens stored for 16-17 years in humid air; and the author in collaboration with O. M. Astreyeva studied specimens buried for 18 years in the ground and subjected to seasonal variations of temperature and humidity.

As stated by all these workers, up to 30-40 percent of portland cement did not react with water. Unhydrated particles of cement clinker included crystals of alite, belite, and calcium aluminoferrites. Concretes allowed to harden for 16-20 years at normal temperatures along with crystalline hydration products contain an overwhelming quantity of an isotropic gel-like mass. Hydration products in the form of fine fibrous crystals filling pores or voids in the cement paste were identified as calcium hydroxide. Latest research based on electron microscopy and X-ray examination has shown that calcium hydrosilicate in its initial stage consists of submicrocrystallites of such infinitesimal size that their behavior is identical with that of gel.

It may be assumed consequently that at normal temperatures around cement particles there accumulate gradually hydration products in the form of a gel-like mass with inclusions of microcrystalline calcium hydroxide and an enveloping film of calcium hydrosilicate. Gradual compaction of gels contributes to concrete strength gain.

Thus we can conclude that contributions to the theory of concrete hardening being elaborated by certain scientists are not in agreement with the actual nature of hydration products.

The crystallization theory of hardening of such multiphase binders as portland cement consisting of up to 75 percent calcium silicates should be revised.

The structure of hydrated cement paste is determined mainly by gel-like calcium hydrosilicates formed in hydration of portland cement, and the technical qualities of concretes are determined by changes which these hydrosilicates undergo with time.

Such portland cement hydration products as calcium hydrosilicates which are present for an indefinitely long time in gel-like form are responsible for the strength of cement paste and concrete. These hydrosilicates and not minor hydration products should be the subject of main concern in theoretical research of cement hardening.

HIGH-EARLY-STRENGTH CEMENTS AND CONCRETES

To accelerate the hardening of concrete, high-early-strength cements and concrete mixtures of as low a consistency as possible with low water-cement ratios should be used. These recommendations are generally accepted. Increases in the production of high-early-strength cements and investigations of ways of further improvement of their qualities are being made in all countries. Additional acceleration of concrete hardening, depending on qualities of cements and concretes used and on degree of acceleration required for various methods, is achieved in the following ways:

1. Mechanically, e.g., by positive agitation with mixture; efficient compaction of concrete mixtures by loaded, repeated and multifrequency vibration; by vibratory pressing or rolling of the products, etc.
2. Chemically, e.g., by addition of chemical admixtures accelerating hardening; prehydration of cements; treatment with gases (silicon tetrafluoride, carbon dioxide).
3. Physically, chiefly by heat treatment (low- and high-pressure steam treatment, electrical curing, curing with hot gases, immersion in water and oil, etc.).

In view of the trend toward assembly-line highly-mechanized plant fabrication of concrete products, it is desirable to reduce the hardening time down to several hours (or even minutes).

To achieve maximum acceleration of the hardening of concrete it is usually necessary to apply simultaneously several or all of the above methods and to elaborate new, more efficient techniques.

In our opinion, precasting plants should be supplied with high-early-strength cements of several grades meeting the demands of various techniques. First of all, high-early-strength, high (≥ 60 percent) alite content portland cement, with a fineness not less than 5000 sq cm/g, is indispensable. Alite crystals in portland cement clinker should be oblong in shape, not larger than 15-30 μ in size. If destined for fabrication of concrete and reinforced concrete units without or with slightest heat treatment, such cement should have high (≥ 10 percent) tricalcium aluminate content. At 24-hr age, compressive strength of this cement when subjected to the standard mortar test is not less than 300 kg/sq cm.

For plant fabrication of concrete products with moderate heat treatment, high-early-strength cement with 50-60 percent alite and 6-9 percent tricalcium aluminate is required. Fineness of grinding of such cement may be of the order of 3500-4000 sq cm/g. Modern cements of improved quality satisfy these requirements but they are not always efficient for heat treatment.

As was found by us as far back as the early 30's, blast-furnace slag cements are most efficient for heat treatment. Experience in the use of such cements for heat-treated concretes was gained in the Soviet Union. Now the cement industry is expanding the production of high-early-strength and high-strength grades of blast-furnace slag cements. Economically these cements are a good choice for all those cases when concrete units are subjected to long or rigid (at up to 100 C temperatures) heat treatment. As a rule, high-temperature curing of products made of concrete with blast-furnace slag cement results in an increase of their working strength.

Concrete mixtures with low water-cement ratios are often used as a means of raising strength of concrete and accelerating its hardening.

In this connection it may be advisable to try to determine the extent to which additional expenditures of cement in various methods of heat treatment are commercially justified. Problems of concrete mixture proportions and compaction should likewise be considered.

Improved methods of agitation with activation of concrete and mortar mixtures produced improve their strength development and characteristics. Prolonged and repeated vibration resulting in destruction of initially loose structures and in appearance of new, more compact ones can, according to the literature, accelerate hardening and raise 24-hr strength of concrete by 100 percent.

Wide application of dual-frequency vibrators producing more than 12,000 oscillations per min can insure up to 50 percent increase in 24-hr concrete strength in comparison with that achieved by lower frequency (3000 oscillations per min) vibration.

Attention should therefore be given not only to the problems of improving the techniques of heat treatment of products and qualities of cements but also to those of raising efficiency of mixture production and compaction with modern plants and equipment.

As problems of harshness of concrete mixtures used in precasting plants are debatable, it is desirable to discuss it here because prolonged and repeated vibration raises costs and complicates the technology of precast product fabrication.

SCOPE OF APPLICATION AND ECONOMICS OF CONCRETE HEAT TREATMENT

Industrialization of construction calls for shortening the time necessary for plant fabrication of concrete and reinforced-concrete products and for their gaining strength and other properties.

But it is only in a few cases that use of high-early-strength cements, harsh heavily compacted mixtures and even accelerating admixtures can insure production of concrete of the required strength in short times corresponding to economically optimal rates of production of precasting plants.

Therefore in precasting plants and yards the necessity of applying various methods of heat treatment of heavy and lightweight concrete products is often assumed despite the fact that this treatment raises cost of production by 5-10 percent and even causes some deterioration of concrete quality. When heat treatment is used, the technological process of concrete product fabrication becomes independent of climatic factors. This is especially important for the USSR, where large-scale construction is carried out in the North and East, in the Urals, and in other regions where temperatures of +20 C required for application of high-early-strength cements in natural conditions prevail for not more than two or three months of the year.

Nowadays structural members of heavy, light, and cellular concretes are produced in large quantities in plant conditions. For example, in 1963 precasting plants and yards in the USSR fabricated more than 44×10^6 cu m of concrete and reinforced concrete products.

In fabrication of these members various methods of heat treatment and atmospheric pressure steaming are used for acceleration of concrete hardening. High pressure steam-treatment and electrical curing are used to a lesser extent.

Heavy concrete structural members as a rule are steamed at 60-100 C temperatures. High-pressure steam treatment is applied for fabrication of cellular and silicate concrete products. Units made of heavy (for load-carrying elements) and cellular (for heat-insulating layer) concrete—for instance, roof slabs "KAP"—sometimes undergo high-pressure steam treatment. Lightweight concrete units, both concrete and reinforced, like heavy concrete products are cured chiefly by steaming.

As in the USSR, in the USA and European countries heavy and lightweight concrete products are subjected to steaming at temperatures up to 100 C (as a rule at 70-80 C). Only USA and Canadian precasting plants apply high-pressure (8-10 atm) steam treatment in fabrication of heavy and lightweight concrete masonry units. Cellular concrete units are steam cured in autoclaves at 8-12 atm pressure in all the countries (Sweden, USA, Denmark, France, Poland, etc.).

Electrical curing of reinforced concrete units is used on a limited scale. Design calculations and practice of electrical curing of the products at plants show definite promise of improving production economics as compared to steaming.

Economic aspects of the application of various heat treatment methods are rarely discussed in technical literature. Articles published in the USA show that in production of heavy and lightweight concrete masonry units high-pressure steam treatment is not less profitable than low pressure treatment. This can be attributed to the fact that, owing to partial substitution of ground quartz sand for portland cement and to acceleration of hardening, cost of production with high-pressure steam treatment is lower than with low-pressure steaming, in spite of the 25-30 percent increase in initial capital cost of the high pressure plants.

In considering high-pressure (8-12 atm) steam treatment it is necessary to take into account the fact that, though it secures rapid development of strength up to the values specified for high-grade concretes, it brings some deterioration because of low frost resistance. This cannot be overlooked in determining the type of products to be subjected to high-pressure steam treatment.

Despite the importance of this problem, up to now there has been no generally accepted method of economic evaluation of the various heat-treatment techniques in comparison to curing in natural conditions.

Economic expediency of one or another method of heat treatment can be determined by:

1. Comparing design characteristics of several plants of equal capacity using low- and high-pressure steam treatment, electrical curing and natural curing of concrete products.
2. Investigating economic indexes characterizing operation of existing precasting plants.

In the absence of such economic studies comprehensive analysis of the economics of various heat treatment techniques is infeasible. In the future economics of accelerated hardening of concrete should be paid most serious attention.

Economic analysis should not only point out relative commercial advantages and fields of application of various methods of accelerated hardening of concrete, but also solve a more general problem of finding the technical and economical optimum of shortening heat treatment time. An interesting technical and economic research program in connection with special engineering design problems was conducted by F. F. Porozhenko at "Giprostroyindustria" Institute.

Based on findings of the Laboratory of Accelerated Hardening of Concrete at the NIIZhB Institute, "Giprostroyindustria" calculated economics of different steaming times (in the range of 4-12 hr) for intermittent assembly-line fabrication of precast reinforced-concrete products. In this study such factors as additional cement expenditure, more frequent reuse of steel forms, deficiency of concrete strength, and all other costs of precasting plants operating in two shifts were taken into account. Moreover, additional investment for expansion of the cement industry necessitated by increase in cement consumption at accelerated steam treatment was taken into account.

For small-series stand production and mechanized continuous assembly-line technology the economic profitability of shortened heat curing time is still more pronounced.

As an example, economic efficiency of short-time electrical curing of wall slabs compared to steaming on casting stands at Gorky and Vladivostok home-building plants may be cited.

Practical application of theoretically ideal schemes of intermittent and continuous assembly-line production methods is often accompanied by difficulties connected with maintaining optimum temperature conditions at different stages of concrete hardening and with preparation and compaction of activated concrete mixtures. Prolonged and repeated vibration at the stage of reversible structural changes—especially when very harsh mixtures are used—not only decreases plant capacity but deteriorates labor conditions. This is why design engineers are bound to find an optimum compromise with due account of all technical and economic factors of production.

Technical and economic studies reveal that very often fabrication technology assuring optimum qualities of concrete does not meet the requirements of economy and ease of production.

Therefore many seemingly advanced technological methods (vibratory fine grinding, repeated vibration, concrete pressing, vibratory stand rolling, carbonation, etc.) do not find practical application.

REFERENCES

1. Baikov, A. A. Portland Cement and Theory of Hardening of Hydraulic Cements. Sobranie trudov, tom 5, izdanie AN SSSR, 1948.
2. Bernal, J. D. Structure of Cement Hydration Products. Tretij mejdunarodnyj kongress po chimii tsementa, Gosstroyizdat, 1958.
3. Desov, A. E., and Nadolsky, V. I. Influence of Repeated Periodical Vibration of Hardening Concrete on Its Strength and Adherence to Reinforcing Steel. Technologija i svojstva tjajolyh betonov, Sbornik NIIGB, vypusk 29, Gosstroyizdat, 1962.
4. Dorsch, K. Hardening and Corrosion of Cements. ONTI NKTP, 1936.
5. Butt, Yu. M., and Timashev, V. V. Effect of Phase Composition of Portland Cement Clinkers on Binding Qualities of Cements. Trudy NII Tsementa, vypusk 17, Gosstroyizdat, 1962.
6. Ignatiev, K. S., and Nikiforov, M. I. Automation of Heat Treatment of Plain and Reinforced Concrete Products at Different Stages of Concrete Hardening. Beton i Zhelezobeton, No. 8, 1963.
7. Kalousek, G. L. Reactions of Cement Hydration at Raised Temperatures. Tretij Mejdunarodnyj kongress po chimii tsementa, Gosstroyizdat, 1958.
8. L'Hermite, R. Concrete Problems. Gosstroyizdat, 1958.
9. Calleja, J. New Techniques in the Study of Setting and Hardening of Hydraulic Materials. Jour. ACI, Proc., Vol. 48, pp. 525-536, 1952.
10. Malinin, Yu. S., and Klishanis, N. D. Investigation of the Process of Hydration of Tricalcium Silicate. Trudy NII Tsement, vypusk 17, Gosstroyizdat, 1962.
11. Mironov, S. A. New Method of Concrete Heat Treatment. Stroitel'naya promyshlennost, No. 3, 1963.
12. Mironov, S. A., and Malinina, L. A. Acceleration of Concrete Hardening. Gosstroyizdat, 1964.
13. Mironov, S. A., Malinina, L. A., and Malinsky, E. N. Method of Investigation of Various Concretes During High-Pressure Steam Treatment. Stroitel'nyye materially, No. 4, 1964.

14. Malinina, L. A., and Fiodorov, V. A. Deformations of Concretes in the Process of Steaming and in Subsequent Storage in Air-Dry Conditions. Izvestia AS i A SSSR, No. 1, 1962.
15. Mchedlov-Petrosian, O. P., Bunakov, A. G., and Latyshev, F. A. Choice of Technology of Automated Manufacture of Large-Size Structural Members. Stroitel'nyye materially, No. 8, 1961.
16. Powers, T. C., and Brownyard, T. Investigation of Physical Qualities of Hardening Portland Cement Paste. Chicago, 1948.
17. Powers, T. C. Physical Phenomena of Portland Cement Hydration. Jour. PCA Res. and Dev. Lab., Vol. 3, No. 1, 1961.
18. Rebinder, P. A. Formation and Mechanical Properties of Disperse Structures. On the Chemical and Physical Mechanics of Silicate Disperse Systems. Zhurnal V.Kh.O, No. 2, 1963.
19. Skramtayev, B. G., Astreyeva, O. M., and Lopatnikova, L. Ya. Structure of Cement Stone and Strength of Concrete at Slow Hardening. Zement, No. 5, 1955.
20. Nurse, R. W., and Taylor, H. F. Contribution to Discussion on Hydration of Cement at Normal Temperature. Tretij mejdunarodryj kongress po chimii tsementa, Gosstroyizdat, 1958.
21. Sheikin, A. E. Methods of Manufacture of High-Strength Concrete. Beton i Zhelezobeton, No. 4, 1957.