Various Methods of Accelerated Curing for Precast Concrete Applications, and Their Impact on Short and Long Term Compressive Strength

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ABSRACT:

Precast concrete is advantageous for several reasons: shrinkage and creep can be reduced, dead-load deflections can be controlled, quality control is improved, material availability can be improved and erection methods are similar to that for steel and thus total construction time is significantly reduced. One of the key properties of concrete that makes precasting economically feasible is its ability, under the proper conditions, to gain compressive strength extremely rapidly. The focus of this paper is a description of the various methods currently available for accelerating the curing of concrete, particularly for precast concrete applications.

Two distinct methods for accelerating the curing process exist: 1) the use of physical processes, and 2) the use of admixtures to act as catalysts for the hydration process, resulting in the achievement of high compressive strengths in relatively short periods of time. Typical physical processes used to accelerate the curing process are generally combinations of the following: increases in curing temperature, introduction of moisture to curing environment. Numerous methods exist, including conductive/convective heating, electrical resistance heating, and steam curing (low and high pressure).

The use of admixtures in order to accelerate the curing process can be further subdivided into the use of mineral and chemical admixtures. Calcium Chloride has proven to be an extremely effective accelerator; however, due to corrosion concerns, its use in concrete with embedded metal is not recommended. The most common mineral admixture used as an accelerator is microsilica, or silica fume. While fly ash is frequently used in order to improve other properties of concrete, it has a retarding effect on the initial set and early strength gain of concrete, and should not be used for accelerated curing purposes. Some chemical admixtures, such as high-range water reducers (HRWR), or superplasticizers, have been used as indirect accelerators, primarily due to their ability to reduce the water demand for a given mix.

Although a number of methods currently exist for the acceleration of the curing process, most precast manufacturers maintain relatively simple operations, and due to logistical and economic constraints, only employ one or two of the methods described herein. Despite recent advances in the use of admixtures, the primary method of accelerated curing in the precast industry today still seems to be the use of elevated curing temperatures, which are achieved through various means. The one thing that most precast manufacturers have in common, however, is that

they all use type III portland cement whenever possible.

INTRODUCTION:

As building development throughout the world continues, the desire to construct cheaper structures on sites that are more difficult to build on, in shorter periods of time, all while providing improved performance will always be desirable in order to maximize both product economy and quality. As such, the construction industry is constantly searching for ways to improve their product. One means to this end is, rather than relying on improving construction implementation mechanisms such as scheduling, installation techniques, and quality control, is focusing on the industry's improved knowledge and development of materials and their behavior.

One result of such motivation by the construction and engineering industry was the advent of prestressed concrete. This product was developed in order to take advantage of the desirable properties of concrete and steel, chiefly compressive and tensile strength, respectively, in order to achieve structural solutions that were not previously possible. For many projects, the use of prestressed concrete is more desirable than reinforced concrete or steel for numerous reasons.

Prestressed concrete takes the concept of reinforced concrete one step further, in order to truly maximize the efficiency of the materials. Rather than simply relying on reinforcing steel for tensile strength, prestressed concrete utilizes high-strength prestressing tendons in order to produce an initially favorable state of stress within the prestressed concrete member. The result is a more efficient section, capable of bridging extremely long spans, that is less prone to cracking and exhibits improved durability. These improved performance characteristics of prestressed concrete have made it an extremely popular product in many aspects of heavy construction, including in roads and bridges, in marine environments, in sanitation systems, and even in buildings.

Due to the labor-intensive nature of prestressed concrete, improved production efficiency and quality control are both essential for the economical implementation of this product. For many projects, the best way to achieve this is through the use of precast concrete elements. Precasting prestressed concrete members eliminates many of the environmental and logistical problems associated with cast-in-place prestressed concrete, while taking advantage of the efficiency of factory-like operations and maintaining very strict quality control in order to produce a superior finished product. One of the most important characteristics of concrete that enables the use of precast members to be economically feasible is its ability, when under the right conditions, to gain strength extremely rapidly.

Ever since the inception of precast concrete, the ability to accelerate the curing process of concrete in order to increase a manufacturer's rate of production has been of critical importance. By achieving high strength in a short period of time, many production advantages are gained. First, concrete elements can be removed from their forms very early after placement; currently, a 24-hour turnover period for most precast elements is standard (Corcoran, 2004). Second, rapidly curing concrete means that manufacturers require less space reserved for the explicit purpose of curing. This also lends itself to a diminished reliance on production for inventory, due to an increased ability to produce, on short notice, specific products for specific projects. Numerous methods have been used in order to achieve such ends, with varying degrees of success.

The focus of this paper is the analysis of the various methods employed in the precast industry for the purpose of accelerating the curing process of concrete, and their effects on the short and long term compressive strength of concrete. These various methods of accelerated curing can be divided into three main categories: physical processes, mineral admixtures, and chemical admixtures. First, research and development of various accelerated curing methods will be presented, followed by a brief discussion of current methods predominantly employed by commercial precast manufacturers.

GENERAL CURING PROCESS:

In order to maximize the efficiency of the curing process of concrete for precast applications, a general understanding of the hydration reaction is necessary. When combined with water, portland cement undergoes a chemical reaction known as hydration, the process responsible for the hardening of concrete. This process can be divided into three distinct stages.

Stage one of the curing process begins immediately upon the addition of water to the cement and aggregate that make up the dry concrete mix, and lasts until the onset of initial set, as determined by ASTM C403. Some manufacturers designate the end of this phase as being coincidental with the achievement of a compressive strength of 500 psi (Corcoran, 2004). During stage one, the chemical reaction between the Portland cement and the water begins; however, the development of measurable compressive strength gain is minimal. Depending on the particular mix design characteristics, this stage usually lasts for 3-4 hours.

Stage two, beginning at the onset of initial set, is characterized by a rapid rate of hydration, resulting in exothermic heat development as well as rapid compressive strength gain. The specific rates of strength gain and overall duration of stage two depend on the particular mix design and curing conditions. For typical precast applications, stage two of curing generally lasts six to eight hours, and the rate of compressive strength development can vary between 500 to 700 psi per hour. The efficacy of elevated curing temperatures regarding their ability to increase the rate of strength gain is greatest during stage two.

Finally, after a majority of the cementitious materials have reacted with water, stage three begins. During this time, less heat is generated by the hydration process, and a slower rate of strength development occurs, typically between 50 to 100 psi per hour. The application of elevated curing temperature has little effect on the rate of strength gain at this point (Pfeifer and Landgren, 1982).

Two basic approaches can be taken to affect the hydration process in order to achieve high early compressive strength in concrete. First, the environmental curing conditions can be altered in order to accelerate the process. The primary factor affecting the rate of hydration is the concrete curing temperature. Second, the cement composition can be specified in order to maximize the initial rate of compressive strength gain. This can be adjusted through the type of cement used, as well as through the use of both mineral and chemical admixtures. A combination of these various methods is usually employed in order to create the most economical accelerated curing process possible.

Cement Type:

Whenever rapid strength gain is of concern, such as in precast applications, type III portland cement should be used in order to maximize early strength achievement. type III portland cement is both chemically and physically similar to type I portland Cement; the primary difference is that type III portland cement particles have been ground finer. The use of type III cement, when combined with any of the numerous additional curing techniques described below, can result in the achievement of very high strengths in very short periods of time. Some plants routinely achieve compressive strengths of 8,300 psi in less than 24 hours (Corcoran, 2004).

PHYSICAL PROCESSES FOR ACCELERATED CURING:

The relationship between the rate of compressive strength gain in concrete and curing temperature has been long established. To an extent, an increased curing temperature will result in an increased rate of strength gain. Beyond a certain point, increases in temperature not only prove to be less efficient, but can actually be detrimental to the properties of the concrete. A typical maximum curing temperature used in commercial precast plants is 160 F (Corcoran, 2004).

Various methods of increasing the curing temperature of concrete have been employed in order to achieve high early strength. These methods include simple convection through the circulation of hot water or oil through formwork, or even through pipes inside the concrete members in the case of hollow elements, electric resistance heating, and both low and high pressure steam curing.

One of the drawbacks to an increased curing temperature is the increased rate of humidity loss to the surrounding environment, which can result in severe shrinkage and cracking. Another problem is the rapid change of temperature within concrete members, resulting in potentially large thermal stresses. In order to alleviate these problems, any method of increasing the curing temperature must also involve the provision of adequate humidity in order to prevent excessive moisture loss, as well as careful cyclic implementation of temperature increase and decrease, in order to prevent the development of thermal stresses (Heritage, 2000).

When using elevated temperatures in order to increase the curing rate of concrete, three main factors should be considered: rate of temperature rise, maximum curing temperature, and heating time. Traditionally, it has been thought that early strength gains are offset by lower 28-day strength. As such, specifications often restrict maximum curing temperatures to between 140 and 160 F. However, a study by Pfeifer and Landgren (1982) showed that the use of a maximum curing temperature of 180 F resulted in no significant decrease in 28-day strength when compared to concrete cured at maximum temperatures of 110 or 145 F. While this does not dispute the general relation of increased early strength gain to decreased long-term strength, it may indicate that current restrictions on maximum curing temperatures are too low.

A more recent study has reinforced the relation between increased early strength and decreased long-term strength. This report showed that increased curing temperatures resulting from direct electrical curing techniques, "increase the 1-day compressive strength, but reduce 28-day strength," (Heritage, 2000).

Regardless of the actual technique used to elevate concrete curing temperatures, and thus increase the rate of strength gain, two precautionary steps to prevent negative impacts of the process should be taken. First, "before any induced temperature increase is started, the time to the commencement of the initial set is required to allow the hardening phase to sufficiently resist thermally induced stresses," (Heritage et. Al, 2000). This delayed increase in temperature allows a minimum development of strength necessary to prevent cracking resulting from the formation of thermal stresses. In addition, the supplementation of heat prior to the initial set has been shown to be relatively ineffective in increasing the rate of strength gain (Pfeifer and Landgren, 1982). At this point, the rate of hydration is extremely slow, and is affected little by increased temperature.

An increased curing temperature also results in an increased rate of humidity loss to the environment. As such, "all efforts must be made to stop the evaporation of water from the surface of the sample by the use of a suitable covering," (Heritage et. Al, 2000). If the effect of humidity lost to the environment is not controlled during the accelerated curing process, the impact on long-term compressive strength can be detrimental (Mehta and Monteiro, 2001).

In addition, in order to maximize economic efficiency involved with energy use related to elevated curing temperatures, concrete members should be properly insulated during the curing process in order to minimize energy losses. Numerous studies have been conducted regarding energy efficient accelerated curing of concrete for precast applications (Pfeifer and Landgren, 1982; Polisner and Snell, 1985). The results of these studies indicate that the primary factors affecting efficient energy use during the curing process are the application of heat only during stage two of the curing process and adequate insulation of the concrete in order to prevent significant thermal losses.

Conduction/Convection Used for Accelerated Curing:

One of the most fundamental methods for rapidly increasing the curing temperature of concrete is through the employment of simple conduction/convection techniques. The temperature of the forms may be increased either electrically or by pumping hot oil or hot water through them (Gerwick, 1993). The direct contact between the concrete and the forms with an elevated temperature results in conductive heat transfer. By utilizing convection as well, in the form of flowing hot oil or water, the rate of thermal energy transfer is increased, thereby increasing the rate of curing temperature increase. As with all accelerated curing methods involving elevated temperatures, precautions should be taken to provide sufficient humidity to prevent drying of the concrete, and proper insulation of the formwork will result in a more energy efficient increase in curing temperature.

Electrical Resistance Curing:

Two primary types of accelerated curing processes involving elevated temperatures resulting from the dissipation of heat through electrical resistance have been attempted. One type of process involves the use of additional elements, such as special coils of wire, or even the reinforcement itself, as a means to generate heat through electric resistance (Heritage, 2000). By imposing an electrical current through reinforcing steel, or through additional wires, heat is generated inside the concrete as a result of the provided electrical resistance, resulting in an increased curing temperature. When steel forms are used, this method may also be used by applying electrical currents directly to the formwork, or by attaching electrical resistance elements to the forms.

More recently, an additional method of electrical resistance curing has been employed. Direct electrical curing, "is based on the fact that fresh concrete has an electrical resistivity of approximately 100 ohms-meter and, as such, can be heated ohmically when an alternating electric current is passed through it," (Heritage, 2000). With direct electrical curing, the electrical resistance of concrete itself is taken advantage of and additional wires for the purpose of electric resistance curing are unnecessary. In addition, a more even distribution of heat generation occurs when compared to the use of either reinforcement or additional wires as resistors.

It has been shown that the effects of increased water-cement ratio on compressive strength are less for concrete that has been electrically cured when compared to concrete that has been cured under standard conditions (Heritage, 2000). Figure 1 shows a relationship between compressive strength and water-cement ratio for both electrically cured and normally cured concrete. The electrically cured concrete exhibited a decrease in strength of approximately 28% when the water-cement ratio was increased from 0.55 to 0.7, while the normally cured concrete displayed a decrease in strength of approximately 83% for the same change.

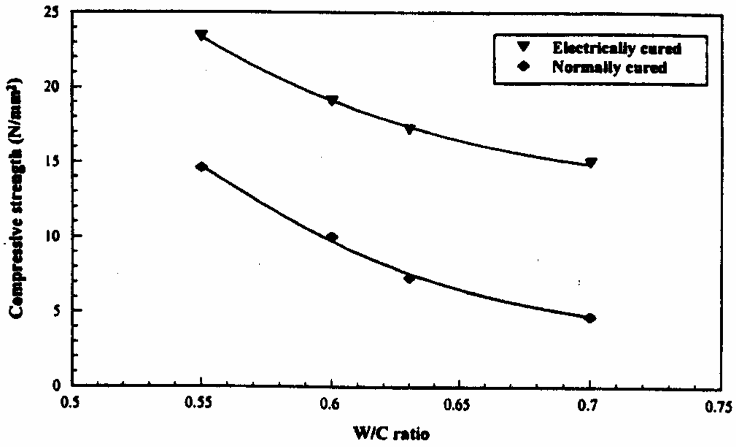

Figure 1 (Heritage, 2000)

It is unclear whether this effect is a result of the electrical curing process, or simply a result of the elevated curing temperature. Regardless, the implications of this result are significant, as a decreased water-cement ratio may be less important when employing accelerated curing processes, which is contrary to common practice. Additional research to determine the precise relationship between the decreased impact of water-cement ratio on the compressive strength and the method of curing temperature elevation is necessary.

The use of electrical curing has also produced results which extend beyond the precasting industry. In the study previously mentioned, the electrical resistance of concrete was measured immediately prior to compressive strength testing, and a correlation between resistance and compressive strength was established, which is shown in Figure 2.

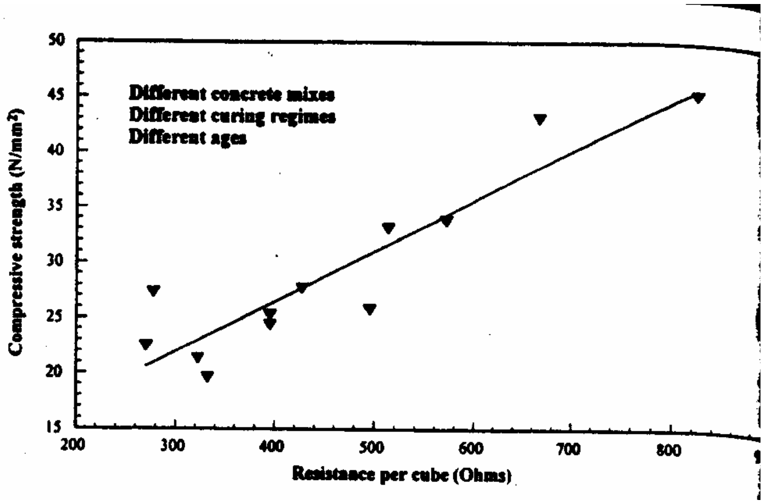

Figure 2 (Heritage, 2000)

As such, it was suggested that the use of electrical resistance measurement may be employed as a non-destructive technique for evaluating the compressive strength of concrete. However, "if resistance is to be used as a nondestructive test for geometrically different electrically cured specimens, calibration curves relating compressive strength and resistance, made of the same materials, are needed," (Heritage, 2000).

Low-Pressure Steam Curing:

Steam curing is a process in which elevated curing temperatures and the addition of moisture during the curing process are both used in order to accelerate the rate of strength gain. These methods can be applied simultaneously, with an increase in temperature as a direct result of steam injection, or individually, in which case an initial temperature elevation is achieved through some alternate means and is followed by an increase in humidity through steam injection. Low-pressure steam curing is frequently used in very dry climates and in applications when the controlling the loss of moisture is imperative (Gerwick, 1993).

The basic method of steam curing at atmospheric pressure, for the most part, follows the same stages present in any accelerated curing process involving elevated curing temperatures. First, an initial delay period, usually of three to four hours, is necessary for the concrete to attain its initial set. Next, a heating period, with a temperature rise of 40 to 60 F per hour, is employed in order to reach a maximum curing temperature, generally between 140 and 160 F. This is followed by a steaming period, typically lasting six hours while maintaining the maximum curing temperature. Next, a cooling period is employed, during which time it is sometimes necessary release the boundary constraints of the forms, prestressing tendons, etc., in order to prevent damage from the development of thermal stresses. In general, the concrete elements are still covered with the steam hoods, or with tarps, during this process. Finally, a stage unique to steam curing, an exposure period, is necessary. At this time, the steam hoods or tarps are removed, and the concrete surface is exposed to the natural environmental conditions (Gerwick, 1993). The combined use of high curing temperatures and moist curing conditions results in the attainment of very high early strength.

Numerous studies have been conducted regarding the effects of low-pressure steam curing on the various properties of concrete. It seems that the long term compressive strength of concrete is decreased slightly as a result of low-pressure steam curing. However, the significance of the decrease is not great enough to offset the tremendous benefits of the rapid gain in early strength. Figure 3 shows the typical relationship between low-pressure steam cured and standard moist-cured concrete with time. The long term availability of moisture during the curing process seems to have a more significant impact on the ultimate strength than the use of low-pressure steam curing.

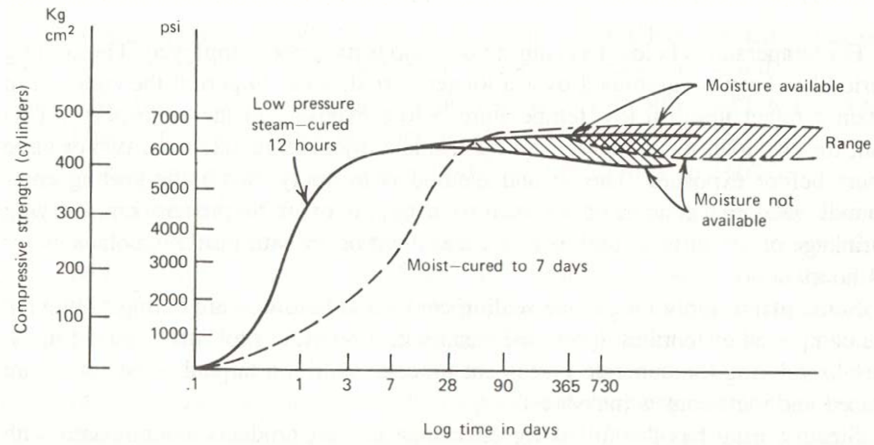

Figure 1.2. *Typical relationships between strengths at various ages and type of cure.*

Figure 3 (Gerwick, 1993)

High-Pressure Steam Curing (Autoclaving):

Although generally reserved for the production of concrete masonry units in the United States, high-pressure steam curing, also known as autoclaving, has been successfully employed in the production of prestressed precast concrete elements in Japan and Germany (Gerwick, 1993). During this process, the increase of curing temperature and humidity are combined with an increase in pressure; as such, elements in this manner must be cured in some type of enclosed vessel. This restriction limits the use of the technique to relatively small elements for typical applications.

One of the benefits of this technique is that extremely low water-cement ratios can be utilized in the initial mix design. In the case of concrete blocks, the elements are produced through extrusion machines, without the use of formwork, using no-slump concrete. By utilizing high-pressure steam curing, sufficient moisture necessary to complete the hydration process is introduced to the concrete elements (Polisner and Snell, 1985).

Some major concerns regarding the use of autoclaving do exist. Stress relaxation of pretensioned bars can be as much as 20% during autoclaving, and must be accounted for during the design phase (Gerwick, 1993). In addition, creep is accelerated during the curing process, also resulting in a loss of prestressing force. There does not seem to be any evidence that the addition of high pressure during the curing process has any detrimental impacts on the long term strength of the concrete, however.

MINERAL ADMIXTURES FOR ACCELERATING CURING:

Microsilica:

Microsilica, or silica fume, is an extremely reactive, pozzolanic material. In one study it was used as a cement replacement for the primary purpose of increasing overall concrete compressive strength (French et. Al, 1998). Not only did the results show an increase in long term strength, but they indicated an increase in concrete strength at all ages. Figure 4 demonstrates the relationship between compressive strength and time for the concrete with the addiction of microsilica compared to concrete without microsilica.

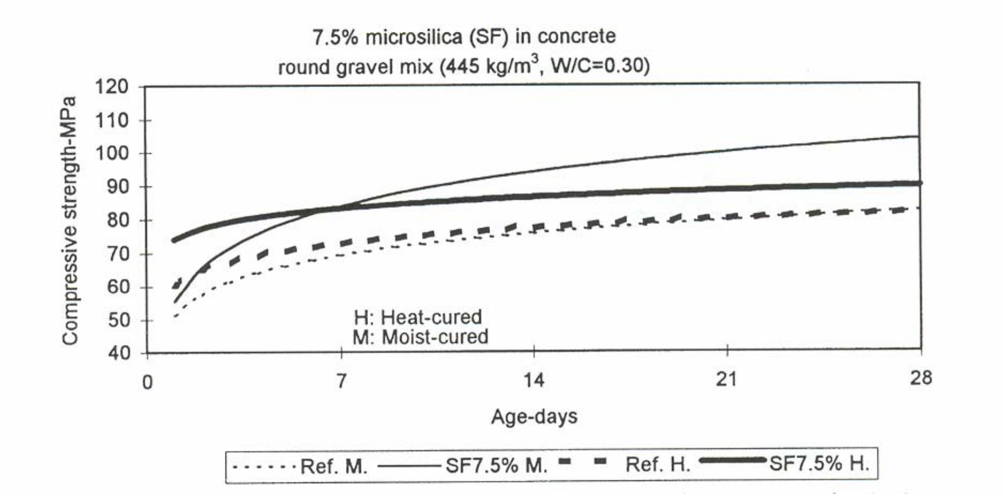

Figure 4 (French et al., 1998)

In these tests, 7.5% by weight of cement was replaced with microsilica. It can be seen that the combination of heat cured concrete with the addition of microsilica has much higher early strength than any of the other combinations. The primary mechanism to which the increased strength is attributed is not unique to the early stages of curing, however. "The inclusion of dry-densified form of microsilica increased cohesiveness and reduced segregation and bleeding of fresh concrete," (French et al., 1998). The use of the microsilica seemed to improve the transition zone characteristics of the concrete, increasing the bond strength between the aggregate and the matrix.

Fly Ash:

Like microsilica, fly ash can be used as a cement replacement material. Fly ash is one of the byproducts formed by modern power plants; it is a coal-combustion byproduct, and is collected by electrostatic precipitators used to filter combustion gases.

Unlike mircrosilica, however, fly ash does not result in improved early strength of concrete. In fact, the results of the same study mentioned previously in which microsilica was shown to increase concrete strength show that the replacement of cement by fly ash resulted in decreased early strengths (French et al., 1998). For moist-cured specimens, the decrease in compressive strength was limited to relatively early ages, up to 180 days, while nearly all the specimens subjected to heat-curing exhibited lower compressive strengths at all ages (up to 365 days). While the use of fly ash may improve other properties of concrete, namely the plasticity of the mix (Corcoran, 2004), the discussion of which is beyond the scope of this paper, it should not be used as a curing accelerator.

CHEMICAL ADMIXTURES FOR ACCELERATING CURING:

Calcium:

Historically, the use of calcium, particularly in the form of calcium chloride, was thought to be an effective acceleration technique in concrete. However, numerous problems resulting from the inclusion of calcium-chloride in concrete mixes has resulted in its ban from use in concrete in several countries around the globe (Levitt, 1982). The inclusion of calcium chloride in reinforced and prestressed concrete can be extremely detrimental, as the chloride can contribute greatly to corrosion of the reinforcing steel.

Nonetheless, studies have shown that calcium chloride has a significant impact on early strength gain of concrete. The use of 1% of calcium chloride relative to the weight of cement in a mix has resulted in an increase of strength after 24 hours of 300% (Levitt, 1982). On the other hand, very small concentrations of calcium chloride, on the order of 0.0005-0.05% by weight of cement, can have a severe retarding effect on the hydration process. In applications in which metal is not embedded in concrete, the use of calcium chloride as an accelerator is still permitted. Additional suggestions regarding the use of calcium chloride as an accelerator include never using concentrations greater than 2% by cement weight, and being cautious when using it in concrete subjected to steam curing, if used in concrete containing dissimilar metals, in concrete slabs supported on permanent galvanized steel forms, and in colored concrete (Kosmatka and Panarese, 1988). Calcium chloride should not be used in prestressed concrete due to possible corrosion hazards, in concrete containing embedded aluminum, in concrete subjected to alkali-aggregate reaction or exposed to sulfates, in floor slabs intended to receive dry-shake metallic finishes, in hot weather, and in mass concrete (Kosmatka and Panarese, 1988). Regardless of these potential problems, the use of calcium chloride, usually specified by the contractor, still occurs with great frequency in the United States today.

Additional forms of calcium that have been used, although not as effectively, in order to accelerate curing are calcium formate and sodium nitrite. These forms of calcium also tend to be extremely sensitive to the chemistry of the portland cement. One example is that of tri-calcium aluminate, as previously mentioned, with which the acceleration effect is less significant as the C_3A content rises above 8% (Levitt, 1982).

High-Range Water Reducers (Super Plasticizers):

Although not technically characterized as accelerators, high-range water reducing (HRWR) admixtures contribute to, "large increases in early concrete strengths under both normal and accelerated curing conditions," (Hester, 1978). The use of these admixtures results in either increased concrete workability while maintaining a target strength level, or increased strength while maintaining a desired workability.

In general, a water-reducing admixture results in reduced water demands for a given mix. Traditional water reducing admixtures consisted of lignosulfonic acids, hydroxylated carboxylic acids, or processed carbohydrates; these have been shown to provide up to approximately a 10% reduction in mix water requirements while maintaining the same workability (Hester, 1978). More recently, HRWR admixtures have been employed that are composed of, "organic polymers, either sulphonated melamine or sulphonated naphthalene formaldehyde condensates,…and may readily reduce the mix water content of up to 20-25% while maintaining the desired slump," (Hester, 1978). In addition, corrosion concerns are not associated with the use of HRWR admixtures, as they do not contain added chlorides.

In order to maximize the benefits of HRWR admixtures, additional mix design features, including mixing sequence, admixture dosage, aggregate grading, and cement type should be considered. In general, the effects of HRWR admixtures are improved when some delay between blending of mix water and the addition of the admixture is employed; a 30-60 second delay has been recommended as a minimum (Hester, 1978).

In terms of precast applications, the admixture dosage is especially important. Tests have shown that, "ultimately, incrementally greater admixture dosages cease to contribute to further strength development. Indeed, they may contribute to severe retardation," (Hester, 1978).

Another mix characteristic which affects the efficiency of HRWR admixtures, and to an extent rate of strength gain, is the maximum aggregate size for cement rich concretes, which are generally used in precast applications. Decreasing the maximum aggregrate size results is an increased aggregate surface area, which corresponds to an increased mortar-aggregate bond strength and an improved transition zone, resulting in increased overall strength. For cement lean mixes (below 517 lb/yd3), it is necessary to increase the proportion of fine aggregate in order to achieve similar levels of strength (Hester, 1978).

The chemical composition of a cement also can affect the efficacy of HRWR admixtures. It has been shown that HRWR admixtures contribute more to strength development when used with cements that are lower in C_3A, have finer grinds, and when used with greater cement contents (Hester, 1978). Therefore, the combination of admixtures used in order to accelerate the curing process should be carefully examined, as the use of high amounts of tri-calcium aluminates with HRWR admixtures may result in decreased effectiveness.

When compared with standard concrete mixes, the inclusion of HRWR admixtures has showed a marked increase in early strength gain when exposed to a variety of curing temperatures. Figure 5 clearly demonstrates the relationship observed between compressive strength and time for a HRWR mix compared to a normal mix, for two different maximum curing temperatures (Hester, 1978). In both cases, the HRWR mix displays significantly greater strength than the plain mix. The early strength achieved as a result of the greater maximum curing temperature is nearly double that of the lower temperature, and the initial rate of strength gain is significantly greater as well.

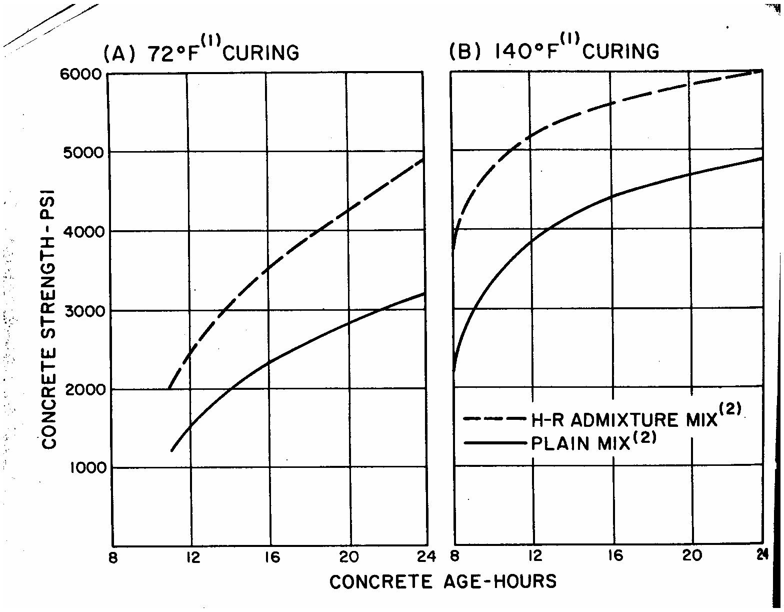

Figure 5 (Hester, 1978)

Another study in which a concrete mix design was developed for precast applications shows similar effects of using HRWR admixtures on the early strength of concrete (Pfeifer, 1982). Numerous tests were used in order to determine the result of various traditional water-reducing admixtures as well as HRWR admixtures. The results show that traditional water-reducing admixtures may decrease the water demand by approximately 10%, while the inclusion of HRWR admixtures can result in a reduction in water demand of up to 24% (Pfeifer, 1982). These results agree closely with those presented by Hester (1978).

Self-Consolidating Concrete:

A similar product involving the use of highly advanced HRWR admixtures is self-consolidating, or self-compacting concrete (SCC). Initially developed in Japan in the 1980s in response to a lack of skilled laborers for placing traditional concrete, "SCC is a highly workable concrete that can flow through densely reinforced or geometrically complex structural elements under its own weight and adequately fill voids without segregation or excessive bleeding without the need for vibration to consolidate it," (Lanier et al., 2003). The development of this product has the potential to significantly alter the current precast concrete industry. Regarding accelerated curing, the use of SCC has primarily an indirect potential impact.

The use of SCC can greatly reduce the time required for placing concrete. To an extent, this can possibly reduce the need for accelerated curing (Lanier et al., 2003). While it is unlikely that the need for accelerated curing will be eliminated altogether, it is possible that the process will require less energy, and thus become more economical. The use of SCC is one of the newest innovations in the precast concrete industry, and will likely have the biggest effect on the evolution of the industry in the near future.

PREDOMINANT ACCELERATED CURING METHODS CURRENTLY EMPLOYED IN INDUSTRY: (telephone interview with James Corcoran)

As the previous discussion has shown, numerous accelerated curing methods currently exist which can be easily implemented on a commercial basis. However, the actual accelerating methods predominantly employed by commercial precasters are greatly influenced by logistical limitations, local material and labor costs, product demand, and ultimately, economic efficiency (Corcoran, 2004).

Concrete Technology Corporation (CTC) is a technologically current precast concrete manufacturer in Tacoma, Washington, and their practices are a good example of standard practices typically observed in many plants today. CTC employs a combination of physical processes and chemical admixtures as curing acceleration tools. The use of increased curing temperatures is the predominant method by which CTC accelerates curing, and is occasionally supplemented with the use of microsilica and superplasticizers.

Like many precast manufacturers, CTC is subject to the limitations of their batch provider, as well as their on-site storage capabilities. As such, the expenses associated with additional chemical and mineral admixtures outweigh the potential benefits. However, in order to take advantage of the effect of chemical composition on curing rate, CTC advocates the use of type III portland cement whenever possible. By producing a type III portland cement that is very similar to types I and II portland cement in terms of chemical composition, the primary difference being the increased Blaine fineness, CTC is usually able to meet their clients' needs with the faster curing cement type. When high-strength (>8,000 psi overnight) concrete is required, the addition of microsilica, usually at approximately 50 lb/yd^3, is common. While this does increase the rate of strength gain, it is usually employed to increase long term strength, rather than to directly increase the short term rate of strength gain. In addition, although HRWR admixtures have a positive impact on an accelerated curing process, they are generally used for other purposes. CTC uses any additional storage space for additional admixtures, such as air-entraining admixtures, the importance of which is greater than the effects of accelerating admixtures.

CTC relies on three types of elevated curing temperatures as their primary means of accelerated curing. The most basic method involves the placement of forms directly over pipes, through which hot water is pumped during the curing process. This conductive/convective technique, while effective, provides the least amount of control and automation. The next step up involves the use of forced-air, gas-fired heaters. This method of accelerated curing provides a bit more control during the curing process. In addition, one byproduct of the gas-fired heaters is moisture, which is very beneficial. For both of these methods described above, continual monitoring of the internal temperature of the concrete, through thermocouples attached to the reinforcing, is essential. In addition, formwork is completely covered with tarps for the purpose of both insulation and moisture-loss prevention.

The most precisely controlled method of accelerated curing used by CTC involves electrical resistance heating of the forms themselves. In this case, electrical elements are attached to the steel forms, and the entire process is automated. A temperature cycle is programmed, and based on the electronic monitoring of thermocouples, this time located at the form/concrete interface, the electric current is continuously adjusted. With such a process, the target temperature can usually be maintained throughout an entire curing cycle within a few degrees.

The general curing process employed by CTC closely follows the general process previously described. After the placement of concrete until the initial set has occurred, minimal energy is used, just enough to maintain the temperature at that of initial placement. After the onset of the initial set, the temperature is increased through one of the three methods described above, generally at a rate of 20 F per hour, to a maximum curing temperature of 160 F in the case of electric curing, and 140 F in the case of gas-fired or hot-water curing. This maximum curing temperature is maintained overnight, for a period of approximately six hours. Formwork is generally stripped before a significant reduction in curing temperature (below 120 F) has occurred; this is to prevent problems with shrinkage associated with decreasing temperatures. However, before the release of prestressing forces or the handling of any freshly cured members, concrete cylinders that have been match-cured under conditions identical to those for the main members are tested in order to ensure that a minimum compressive strength has been achieved.

For most applications, CTC uses water-cement ratios of approximately 0.30, and even as low as 0.28 when HRWR are employed. In addition, the use of curing compounds is sometimes employed for high surface area elements, such as wall panels. However, due to the relatively cheap costs of electricity and the high relative humidity in the Pacific Northwest, CTC is able to rely on achieving high early strength in their precast concrete products primarily through the employment of increased curing temperature.

SUMMARY AND CONCLUSIONS:

The major methods that exist for the purpose of accelerating the curing process of concrete can be divided into two categories: physical processes and admixtures. Like most chemical reactions, the rate at which hydration occurs is very susceptible to temperature changes; with increased temperatures, the rate significantly increases. In concrete, this translates to the achievement of high early strengths; many precast manufacturers routinely achieve compressive strengths of 8,300 psi in less than 24 hours, primarily through the use of elevated curing temperatures. The relationship between concrete strength gain and curing temperature has long been known. The implementation of elevated curing temperatures is a relatively straight forward process, and can be achieved without the need for a great deal of research and development. As a result, this is the primary method currently employed by commercial precast manufacturers.

With recent advances in material technology, a number of admixtures (mineral and chemical) can be used, both directly and indirectly, as accelerating agents. However, compared with increased curing temperatures, the use of admixtures as accelerators can introduce numerous potential problems and difficulties.

Until the behavior of admixtures and their effects on other properties of concrete are readily understood, their use as primary accelerating agents in the commercial precast industry will likely remain relatively sparse. A 24-hour turnaround period is standard in today’s industry; as such, there is not an immediate need for the further improvement of accelerating methods. Until some significant incentive or motivation is provided, such as significant increases in energy costs and decreases in admixture costs, currently employed curing methods involving elevated curing temperatures will likely continue to prevail.

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