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CURING OF PORTLAND CEMENT CONCRETE

I. GENERAL

The term "curing" of concrete deals with the processes or methods of care and attendance to promote and aid the hydration of the cement in concrete. There has been much research and many papers have been written on this subject. A large number of English references on the curing of concrete have been reviewed and a general discussion concerning the chemical and physical aspects of curing concrete is presented with the objective of determining how concrete may best be cured, how much curing is needed and when curing should be initiated. Unfortunately there is no simple straightforward answer to these questions, but when the basic chemical and physical aspects of curing concrete are understood, more definite practical recommendations can be made for specific situations. In general, the subject of curing of concrete should concern itself with everything that happens to a batch of concrete from the time the mixing water is added since the physico-chemical process of hydrating cement begin at this time.

II. PHYSICO-CHEMICAL ASPECTS OF CURING

Important Chemical Compounds

Blanks and Kennedy ( )* define Portland cement as the product obtained by pulverizing clinker consisting essentially of hydraulic calcium silicates and aluminates. These finely pulverized calcium silicates and

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* Numbers in parenthesis refer to corresponding items in the Bibliography.

aluminates are highly reactive and combine readily with water to form a paste, which in a matter of time hardens to form a strong, dense, artificial stone. Concrete, of course, is a conglomerate stone composed of aggregate bonded together by the hardened paste. This hardening process of the paste is a highly complex chemical reaction which depends on moisture, heat, time and the qualitative and quantitative chemical composition of the cement. The exact nature of these reactions and the composition of the hydrated compounds is very controversial; however, a brief summary of the present consensus of opinion is given below. The most significant compounds in cement which affect its strength properties after hardening are tricalcium silicate ($3CaO \cdot SiO_2$), dicalcium silicate ($2CaO \cdot SiO_2$) and tricalcium aluminate ($3CaO \cdot Al_2O_3$).

At present there are two theories which describe the "setting" and hardening of portland cement. The first is the crystalline theory and ascribes the development of strength to the growth of interlocking crystals. The second and more popular theory considers the cement paste to be a supersaturated solution of hydrated compounds which eventually coagulates to form an amorphous mass called gel. It is generally agreed, that both of these theories apply to portland cement. Under normal curing at air temperature the early strength and "final set" of cement is usually attributed to the crystalline products of hydrated tricalcium aluminate ($3CaO \cdot Al_2O_3$). The continual strength gain and the greater portion of strength is usually attributed to the formation of amorphous hydrates by the tricalcium and dicalcium silicates ($3CaO \cdot SiO_2$ and $2CaO \cdot SiO_2$ respectively) in accordance with the gel theory.

Hydration and Hydrolysis

When water is first added to portland cement the tricalcium aluminates ($3CaO \cdot Al_2O_3$) and silicates ($3CaO \cdot SiO_2$) begin to react immediately. The tricalcium silicate breaks down (hydrolyzes) to form more dicalcium silicate ($2CaO \cdot SiO_2$) and releases calcium hydroxide $Ca(OH)_2$ which dissolves in the uncombined or free water. When this solution becomes supersaturated, the calcium hydroxide begins to precipitate out as crystals and this builds up a semi-ridge crystalline structure which causes the "initial set" of concrete. During this same period of time the tricalcium aluminate is also hydrating and forming aluminate crystals which build up more gradually (if properly retarded by gypsum, $CaSO_4 \cdot 2H_2O$) to produce the "final set" in the cement.

After the initial and final set the rate of reaction in the cement is slowed down. However, the dicalcium silicate originally present in the cement and that resulting from the hydrolysis of the tricalcium silicates continues to combine with water to form amorphous compounds. These amorphous compounds form a supersaturated solution in the water-filled voids of the capillaries and eventually coagulate to form a mass called gel. This gel is usually considered to account for the greater portion of concrete strength.

Exposure Conditions

As in any chemical reaction, the conditions of the atmosphere in which the reaction is taking place has an extremely important influence on the final chemical product. The most important variables here are the moisture and temperature conditions. From the preceding discussion it can be seen that water is necessary for the curing (hydration) of the cement. As soon as the cement is deprived of a certain amount of its water no further significant hardening of the paste can be realized (see Figure 1). Concrete can be rejuvenated by re-saturating it with water, but this is usually extremely difficult (if not impossible) to accomplish. T. C. Powers ( ) indicates that the minimum amount of water required to bring cement to its ultimate degree of hydration is about 0.44 grams of water per gram of cement, plus the curing water that must be added to keep the paste saturated. <u>For maximum hydration concrete must be kept saturated</u> because hydration products can only form in the water-filled capillaries in the paste. Simply sealing concrete against evaporation (as in membrane curing) will not assure <u>full</u> hydration since cement paste is self-desiccating, that is, it uses up some of the capillary water and this must be replaced for maximum hydration. Even storing samples in water vapor will not assure maximum hydration, because some water will usually evaporate even under these conditions and certain capillaries will become emptied. Several common conditions which can cause concrete to be deprived of its capillary water are as follows:

(1.) Self-desiccation of cement paste sealed against evaporation (as in membrane curing).

(2.) Normal evaporation at room temperature when exposed to dry or even moist air.

(3.) Evaporation or boiling when exposed to high temperatures and/or low pressures (as in improperly controlled steam

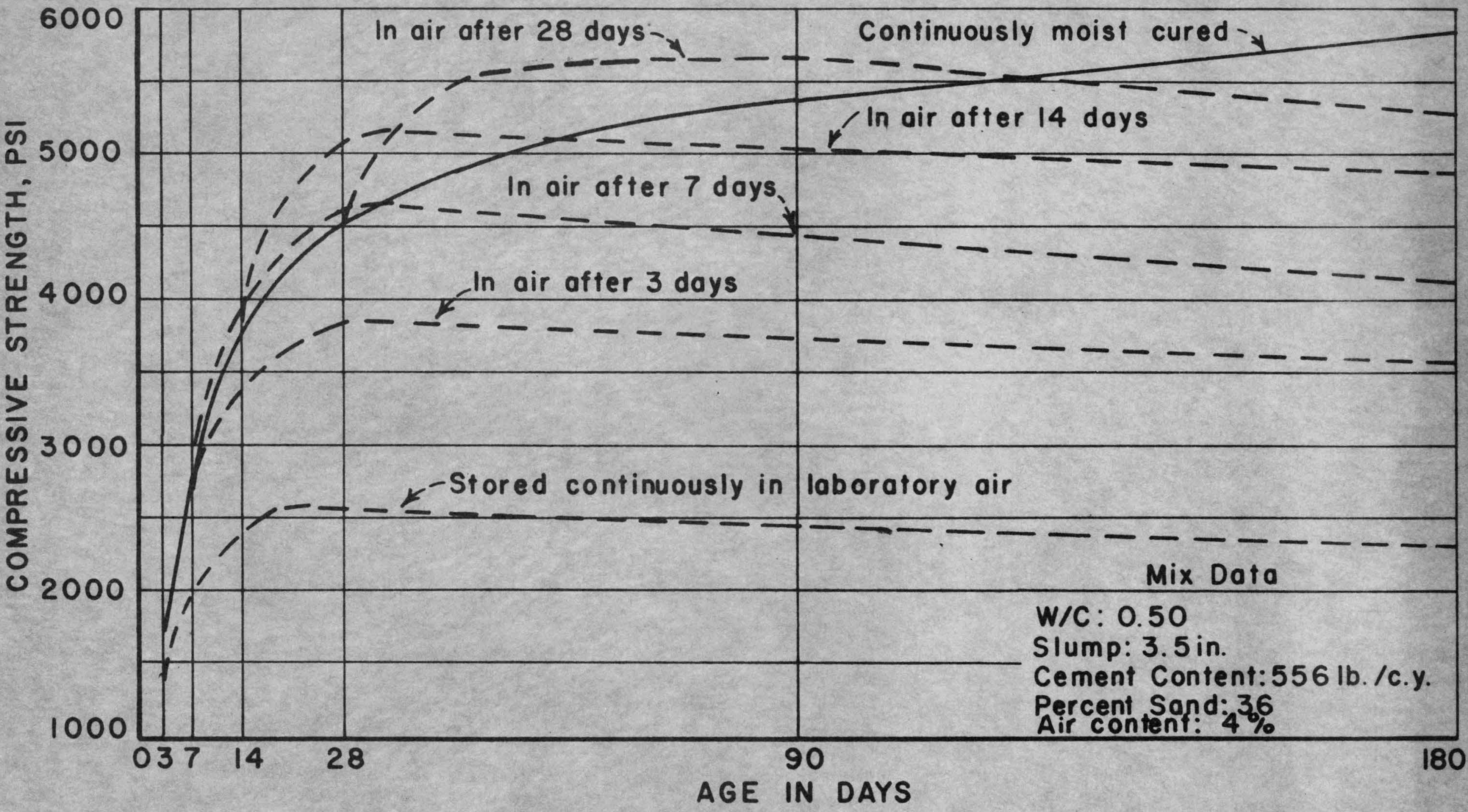


Fig. 1 — Compressive strength of concrete dried in laboratory air after preliminary moist curing (Data by Walter H. Price, ACI Journal, Feb. 1951)

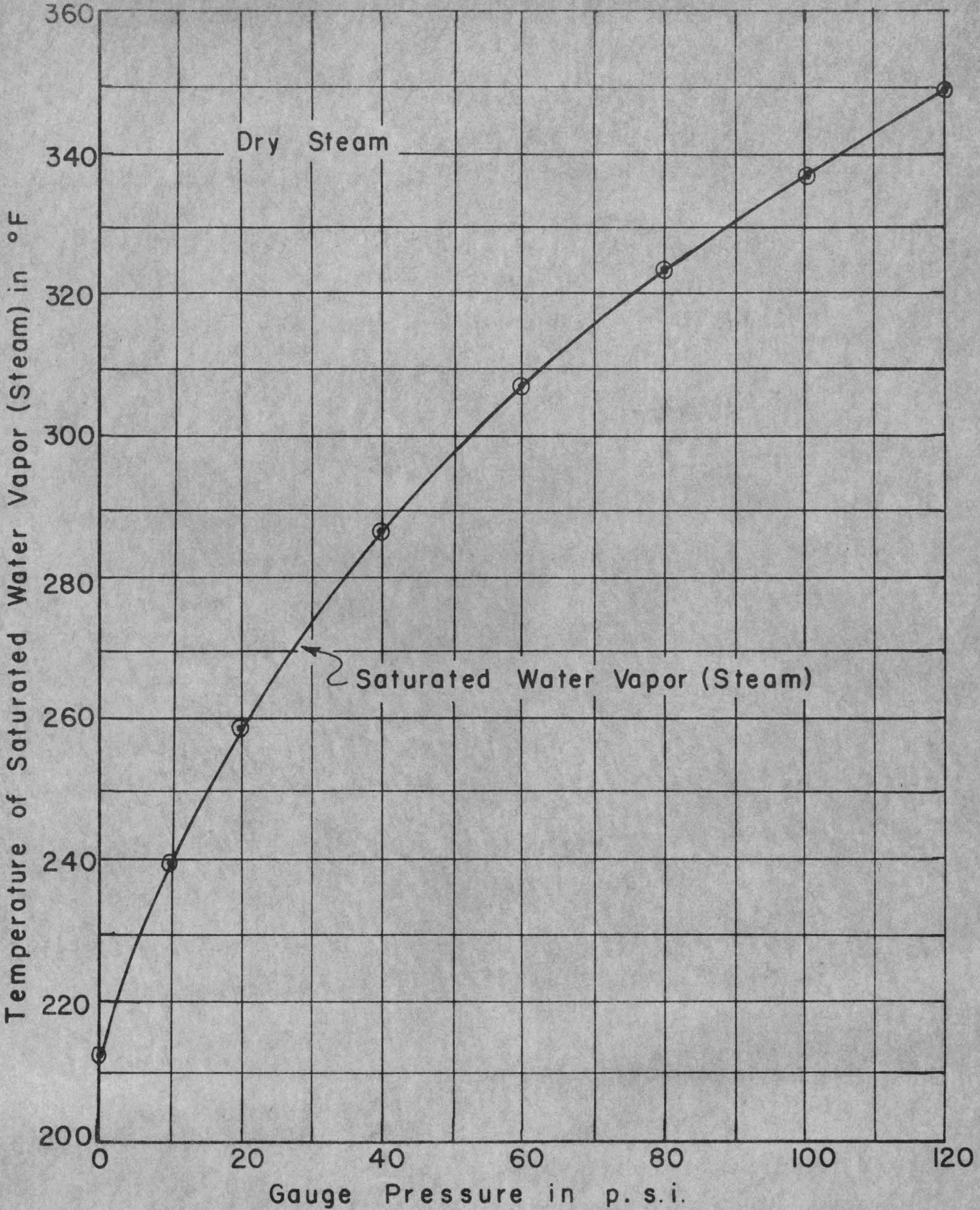


Fig. 2 – The temperature of saturated water vapor in degrees Fahrenheit corresponding to gauge pressure in p.s.i.

curing, see Figure 2).

(4.) Freezing of the water in the concrete.

Once hydration is completed Carlson ( ) points out that water is no longer needed, however the strength of concrete will be reduced by drying because of internal stresses produced in the gel by its shrinkage while the other constituents do not shrink.

The temperature of the atmosphere has a significant influence on the rate of the cement reaction. Nurse ( ) and Bergstrom ( ) indicate that the amount of hydration is a function of the product of the curing temperature times the exposure time (usually expressed in degree-hours). The curing temperature can influence the sequence in which the chemical products are formed as well as their character, and consequently the final structure of the crystalline-gel mass is affected. As an example, Blanks and Kennedy ( ) point out that when concrete is exposed to high temperatures during the first 24 hours, (such as in steam curing) the hydrated tricalcium silicates ($3CaO \cdot SiO_2$) also form crystalline products which supplement those of the tricalcium aluminate and it too contributes to the early strength and setting of the cement. This effect of temperature on the structure of the crystalline-gel mass can explain to some extent why the mechanical properties of concrete cured at high temperatures <u>will never</u> be the same as those of concrete cured at room temperatures even after both have achieved complete hydration chemically speaking. This point is further illustrated by the findings of steam curing researchers such as Price ( ) and Shideler and Chamberlin ( ) who concluded that while steam curing accelerated the early strength development in concrete it usually had an adverse effect upon the compressive strength at 28 days when compared with specimens continously fog cured (see Figures 9 and 10).

As a conclusion to this brief discussion of the physico-chemical aspects of curing concrete, it can be said that explanations to some of the apparent disagreements in the test results of various investigators of concrete and in the concrete construction experiences of various engineers often lies in the variable structure of the crystalline-gel mass as affected by different cements (chemically), different temperature and moisture conditions of curing, and different mixing temperatures.

III. IMPORTANT PHYSICAL PROPERTIES OF CEMENT PASTE, AGGREGATE AND CONCRETE

Two of the most obvious deficiencies of improperly cured concrete are usually inadequate strength (compressive and tensile) and durability. The durability of concrete depends upon its ability to resist chemical attack and to a large extent its tensile strength, since mechanical deterioration is a process of cracking and spalling resulting from tensile stresses and cracks induced by heating and cooling, freezing and thawing, wetting and drying, abrasion, etc. Consequently, it is desirable at this point to consider certain of the contrasting incompatible physical properties of cement paste and aggregate which combine to make up the properties of concrete.

The following table compares some typical values as follows:

	Siliceous Aggregate Particles	Cement Paste 28 day,w/c=.5	Concrete 28 day w/c=.5
Compressive Str., psi	30,000	5,000	3,000
Tensile Str., psi	3,000	550	275
Modulus of Elasticity, psi	12,000,000	2,000,000	4,500,000
Drying Shrinkage, in/in	0.0000(mil)	0.00600	0.00060
Coef. of Expansion, in/in-°F	0.0000061	0.0000065	0.0000065

Of particular interest are the relatively low tensile strength and the relatively large shrinkage value for the cement paste and the concrete as a whole. Both the compressive and tensile strength of the cement paste are a direct function of the curing which is dependent upon moisture, temperature and time. Anything that will induce tensile stresses in the cement paste (particularly at early ages), will usually produce severe cracking in the paste and concrete. Blakey and Beresford (   ) have classified some of these cracks as follows: (1) prehardening cracks caused by settlement of the plastic cement paste around rigid obstacles such as reinforcing bars or large pieces of aggregate, (2) shrinkage cracks in the matrix caused by the embedded rigid particles of aggregate and reinforcing which resist or restrain the shrinkage of and produce tensile stresses in the cement paste, (3) cracking due to externally applied load, and (4) shrinkage cracks caused by tensile stresses on the surface of concrete when the surface begins to dry and shrink while the interior concrete remains moist and dimensionally constant. In addition to these, rapid cooling of the exposed surface of "green" concrete causes it to contract while the warm interior remains expanded or of constant dimension and this too induces tensile stresses and sometimes cracks in the surface.

IV. PLACING AND FINISHING CONCRETE

Placing and finishing of concrete are two operations which have an extremely important effect on the final quality of portland cement concrete. Some of the significant factors in these initial curing operations are the temperature, timing and procedures used in placing and finishing. Klieger (   ) concluded that there is a temperature during the early life of concrete (including mixing, placing, and finishing) which may be considered optimum with regard to strength at later ages (see Figures 3 thru 6). He found that the 1, 3 and 7 day strengths increase with an increase in initial and curing temperature, however, lower strengths resulted at 3 months and 1 year. On the other hand, concrete placed and cured at low temperatures (as low as 25° F.) while showing lower strengths at early ages, show greater strengths at later ages. It can also be seen from Figures 3 and 4 that low mixing and placing temperatures allow lower water-cement ratios to be used. These conclusions were further substantiated by Timms and Withey (   ) and Price (   ) (see Figure 7).

Swayze (   ) found that the timing and method of finishing had a pronounced effect on the durability of concrete. The concrete should be well consolidated when placed and the final finishing should be delayed as long as is practicable. Blakey and Beresford (   ) found that re-trowelling concrete would heal prehardening cracks caused by settlement of the plastic cement matrix around rigid obstacles such as reinforcing steel and aggregate. Beresford and Mattison (   ) point out that this settlement and corresponding cracking may take up to 70 minutes (depending on mix), which suggests that trowelling or re-trowelling should be

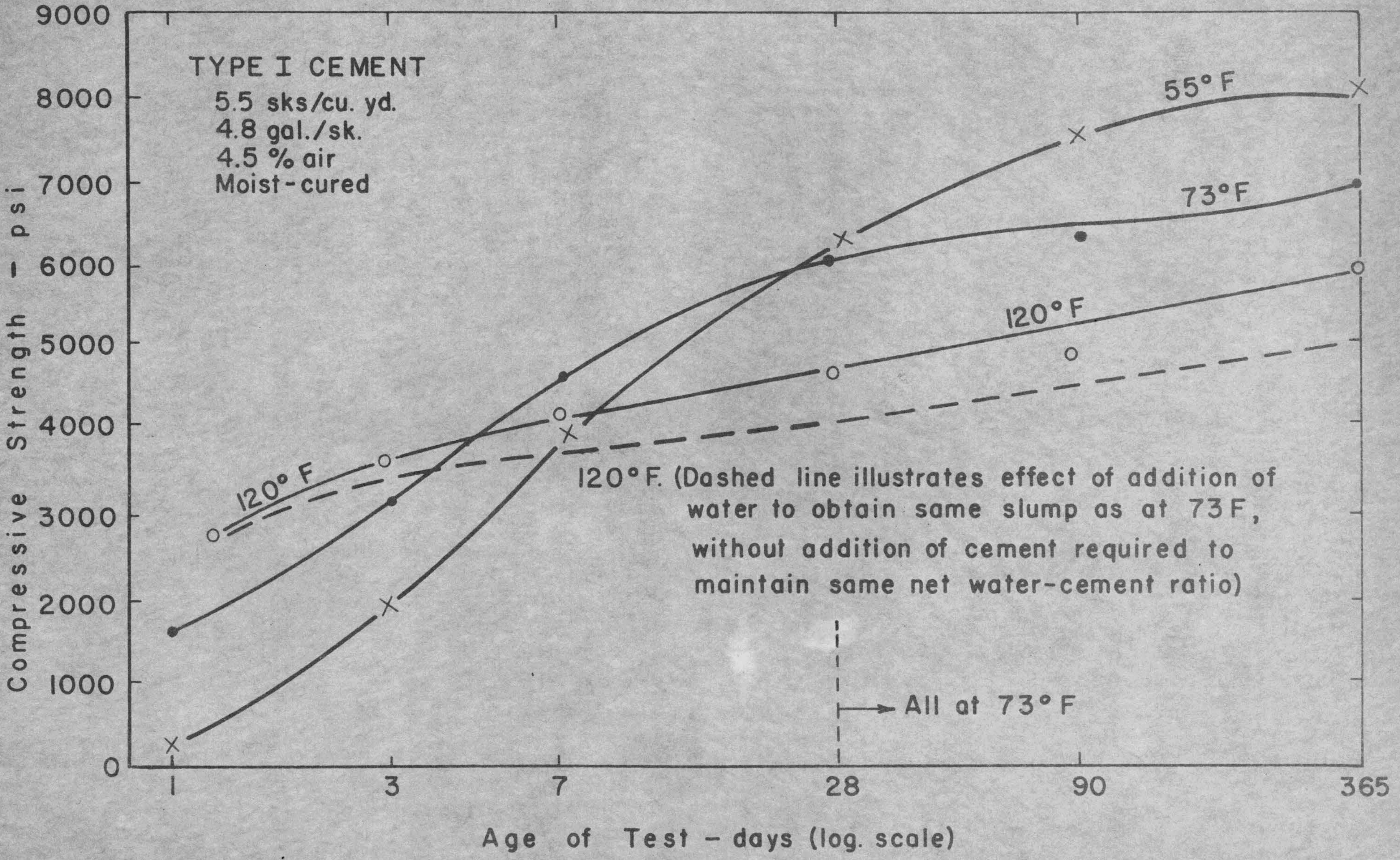


Fig. 3 —Effect of curing temperature and addition of water to maintain slump on the compressive strength (Data by Paul Klieger, ACI Journal, Oct. 1958)

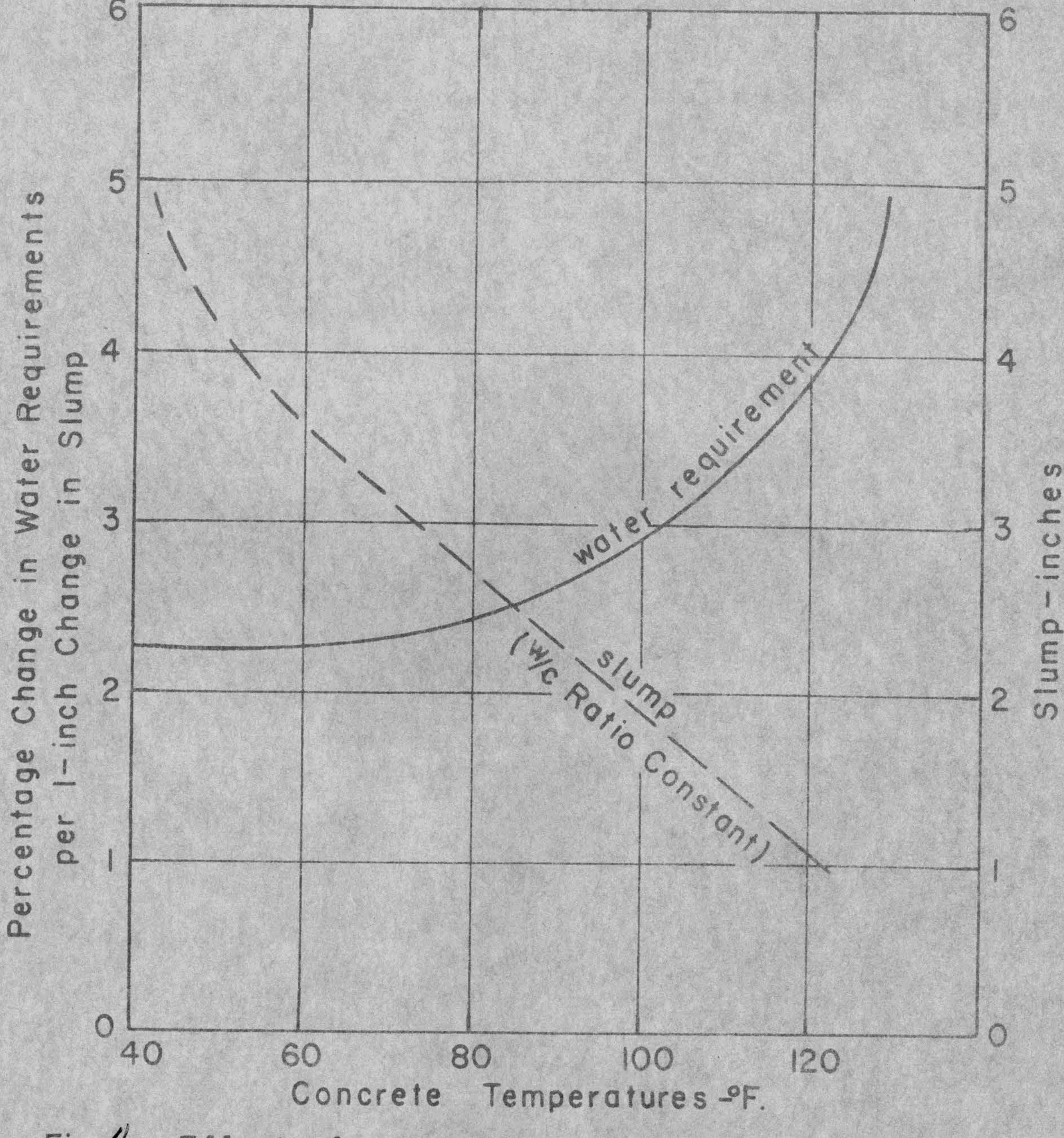


Fig. 4 - Effect of concrete temperature on slump and on water required to change slump.

Cement content: 5 1/2 sacks per cu. yd.; 4 1/2 ± 1/2 percent air; maximum size of aggregates, 1 1/2 in.; average of data for Types I and II cements.

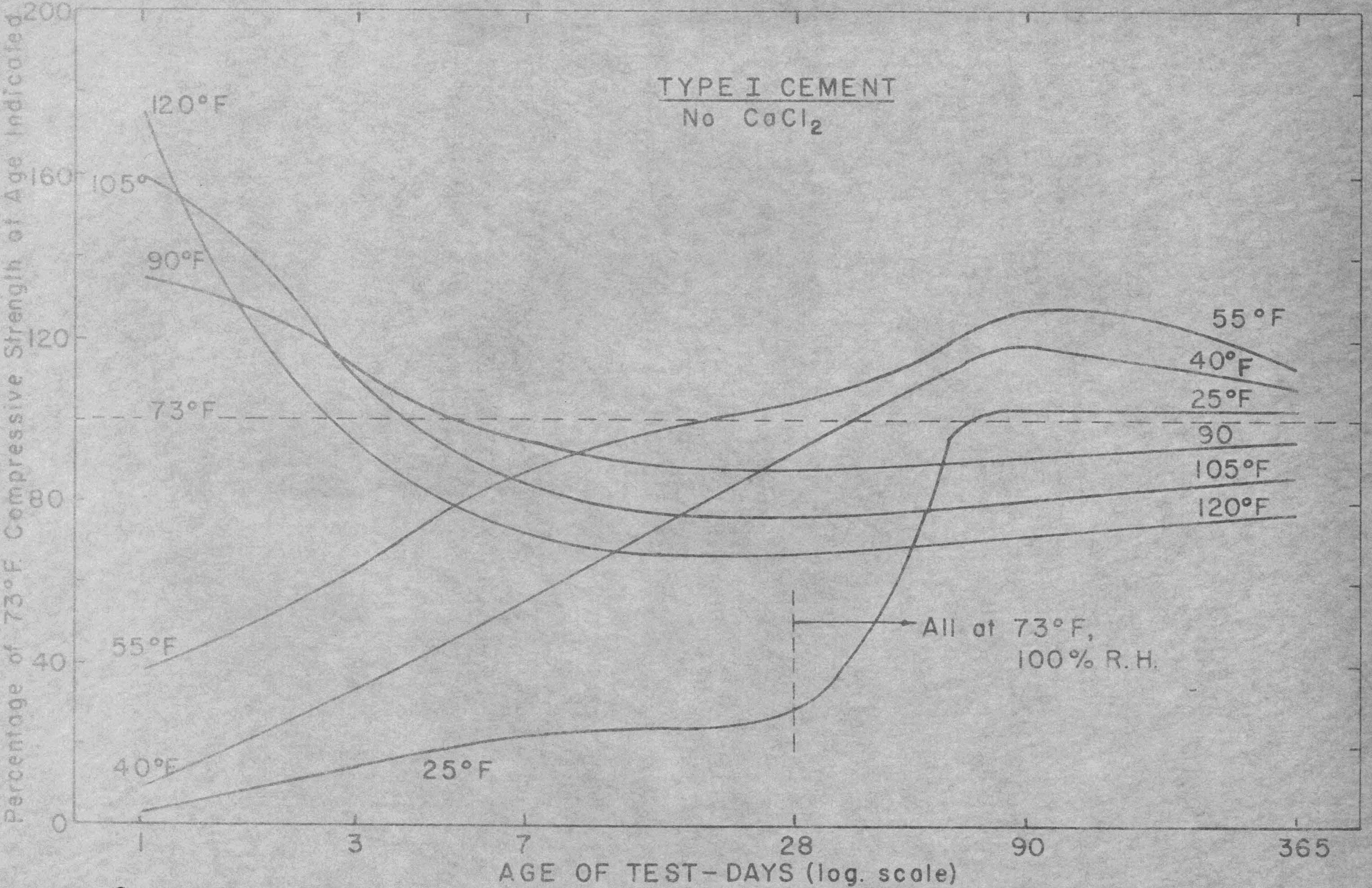


Fig 5 — Effect of temperature on compressive strength of Type I Cement. Air content, 4 1/2 ± 1/2 percent; (neutralized Vinsol resin solution added at mixer); cement content, 5 1/2 sacks per cu. yd. Net water-cement ratio is approximately equal. (Data by Paul Klieger, ACI Journal, Oct. 1958)

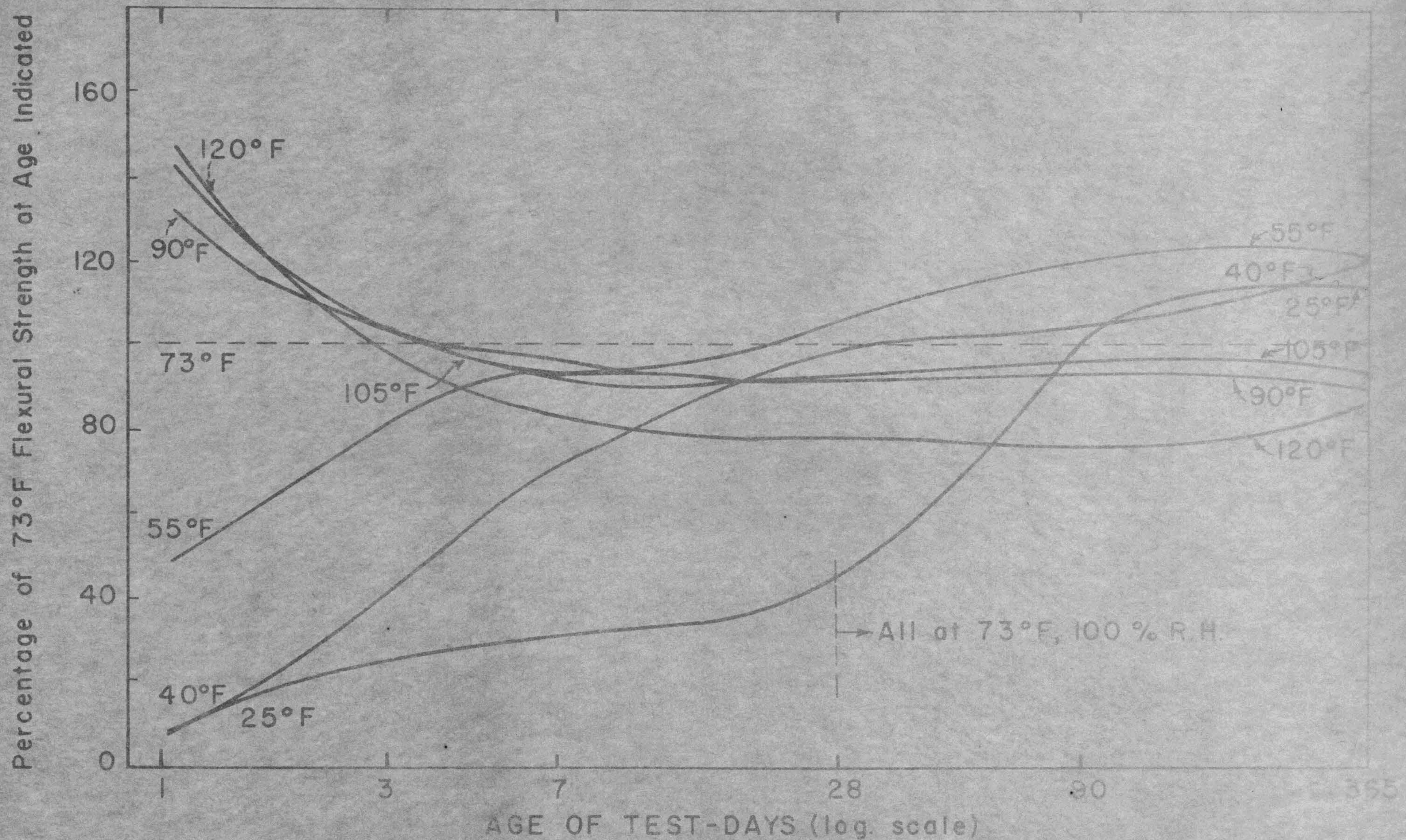


Fig. 6 -Effect of temperature on flexural strength of concrete made with Type I cement. Air content, 4 1/2 ± 1/2 percent (neutralized Vinsol resin solution added at mixer), cement content, 5 1/2 sacks per cu yd. Net water-cement ratio approximately equal. (Data by Paul Klieger, ACI Journal, Oct. 1958)

delayed at least this long. Vollick (   ) found that revibrating concrete 1 to 2 hours after placing increased the compressive strength an average of 13.8 percent. He further observed that revibration increases bleeding and improved the concrete's appearance which, along with the increased strength, suggest improved durability. Vollick also states that the delay period between placement and revibration of concrete that is necessary to increase strength can be increased and is less critical if a "set retarder" is used.

V. CURING METHODS

This section deals with the processes or methods of care and attendance to promote and aid the hydration of the cement in concrete. Basically, the practical objective of all these methods is to see that the concrete remains wet or moist for a given period of time (the amount of time depending upon the temperature and degree of hydration desired).

Water Curing

Powers (   ) points out that the best way to cure concrete for maximum hydration is to keep it completely saturated with water. To accomplish this in the field the relatively old methods of "ponding", wet sand and spraying are the most effective.

Ponding is very effective for curing flat slabs with a large level exposed surface area. The usual procedure is to build up a small levee of earth, two or more inches high, around the edge of the slab and then fill the enclosed "pond" with water which completely covers the concrete surface. This procedure should be initiated immediately after the concrete has obtained its final set (about 6 to 10 hours after pouring). The main disadvantage of this method is that a considerable supply of curing water is required initially and to maintain the pond for a week or two since evaporation losses can be sizeable.

Sprinlers and sprays are effective for almost any type concrete (slabs and structures), since they can be arranged to provide good coverage for various shapes. Here again the main disadvantage is that a considerable supply of curing water is required along with the sprinkling system of nozzles, pipes, storage tanks, etc. Very often canvas tents or covers are used with sprinklers and sprays to break up wind currents and reduce evaporation of the water.

Particular care must be taken to keep the concrete wet continuously. It has been found that intermittent wetting, or wetting and drying, at early ages is often more damaging than no curing at all.

Protective Covers

One of the most common curing methods used today is protective covers such as burlap mats, canvas, cotton mats, paper, straw, earth and coconut mats. These covers serve to protect the concrete surfact from air currents, hold absorbed water and reduce evaporation from the concrete surface. The most effective and usually preferred of these agents are burlap, cotton and canvas mats. Very often these mats. Very often these mats are used for the first few days and then are replaced by damp earth and straw covers. In any case, to be effective these covers must be kept continuously wet by hand or mechanically sprinkled with water. Of all these devices the heavy weight waterproof building paper is probably the least effective sine it does not absorb and hold water itself, but only reduces evaporation by protecting the concrete from direct exposure to wind, sun and atmospheric conditions. However field results using sisaldraft paper with sealed lapped joints and using polyethylene plastic sheets with lapped joints for 14-21 days have been found to give curing equal to 5-7 days of water curing. In any case the protective covers which are used should be placed on the concrete as soon as the surface becomes hard enough to resist damage. Usually this is after the initial set or about 3 to 5 hours after pouring.

Membrane Seals

The object of membrane curing is to seal the exposed surface of concrete with an impervious membrane of plastic, oil, asphalt, etc. in order to prevent the evaporation of the water which is necessary for the hydration of the cement. In addition, the membranes often have a white or light color so they will reflect a considerable amount of heat from the sun which keeps the concrete at a cooler and more favorable curing temperature.

Fresh concrete usually has enough water for hydration of the cement, however additional water must be supplied for low water-cement ratio concrete if it is desired to hydrate a maximum amount of the cement since the cement paste is self-desiccating (   ) and the amorphous hydration products can only form in the water filled capillaries. When most membrane seals are applied to concrete it is usually not possible to add additional curing water, consequently, this curing method will usually not produce the maximum degree of hydration. However, when membrane curing procedures are compared to other "field" curing methods this disadvantage does not seem to be apparent for Anon (   ) and Waters (   ) found membrane curing improved concrete compressive strengths when compared to wet-burlap and wet-hay curing respectively. The Bureau of Reclamation (   ) found that several of the compounds compared favorably with 14 day water curing.

Asphalt cut-back and emulsions have been sprayed on fresh concrete surfaces to seal in moisture since about 1928. Meissner and Smith (   ) found that while bituminous coating are effective curing agents they also disfigure the concrete and absorb heat due to the dark color. Gonnerman (   ) also noted the undesirable heat absorption which caused a greater daily temperature variation in the concrete and consequently greater volume change. It was found that this problem could be overcome by applying whitewash, stone dust, or other light colored substances to change the color of the black surface.

Coal tar and paraffin can also be applied in the form of cut-backs or emulsions to make a membrane seal. In addition to these, numerous other liquid membrane curing compounds are now appearing on the market. These compounds may contain a white, red or other color of pigment. The white pigmented compounds are effective in reflecting heat and reducing the range of temperature variation in the concrete. All of the colors make visual inspection for complete coverage easier. Waterproof paper and plastic sheets have also been found effective in sealing concrete. The results of Jagus and Sethi (   ) indicated that a solid plastic film was superior to other types.

Irrespective of the type membrane used, the general consensus of opinion as to the proper time of application of the membrane is fairly well summarized by Tremper ( ). He concluded that evaporation of water is beneficial during the period that the concrete is plastic and is bleeding due to the settlement of the solid particles. This period can last from 1 to 3 hours after pouring, depending upon the mix design and other conditions. However, at the conclusion of this period, further loss of water should be prevented to keep from impairing the quality of the concrete. In general, if the curing treatment is not applied by about 7 hours after pouring its value is largely lost.

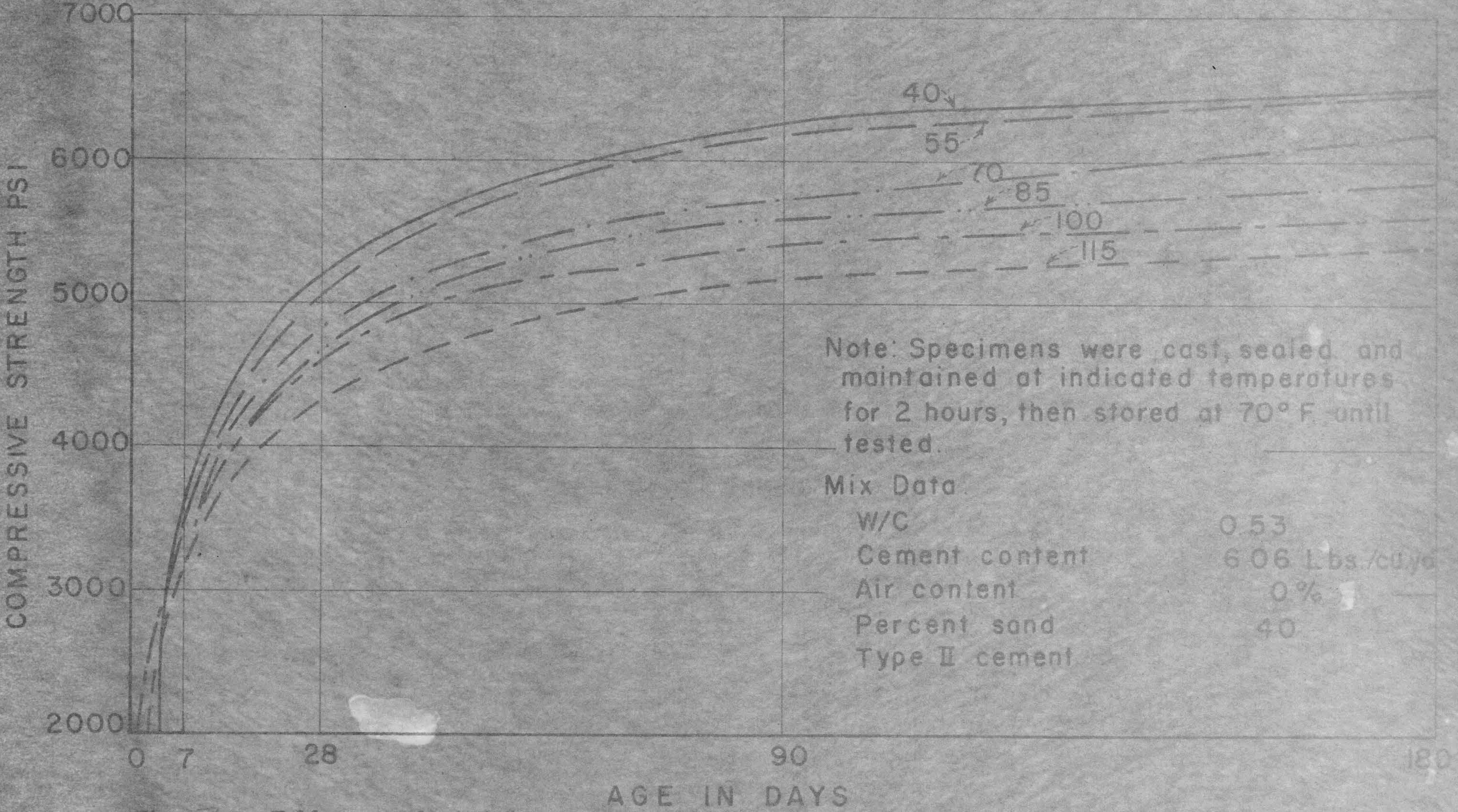
Steam Curing

The use of steam heat to accelerate the hydration of cement in concrete has been used effectively for a number of years. Steam is particularly advantageous because high temperatures and favorable moisture conditions are easily produced. In general, steam curing can be separated into two classifications, first, steam curing at atmospheric pressures where-by temperatures up to 212° F can be obtained while still maintaining a saturated water vapor exposure condition. If greater acceleration of hydration is desired, higher temperatures and favorable moisture conditions can be obtained by high pressure steam curing. As the temperature is increased above 212° F the exposure pressure must also be increased to prevent the vital curing water from evaporating or boiling from the concrete. Figure 2 shows the temperature of saturated water vapor corresponding to the required gage pressure.

Atmospheric Pressure. Nurse ( ) reports that the best and most commonly used process of steam curing at atmospheric pressure is to inject steam into the curing chamber with nozzles. The sudden lowering of temperature as the steam enters the chamber will always produce oversaturation of the air, and consequently, condensation will take place on the cooler concrete members. This has been found to be a very effective means of transferring heat evenly to the concrete.

Price ( ) found that concrete strengths at later ages are weakended by very rapid setting produced by high temperatures (Figure 7). Shideler and Chamberlin observed a similar phenomenon (see Figure 8) and recommended a delay of from two to six hours before commencing with steam curing. On the other hand, if onlyhigh strengths at early ages are to be considered, Nurse ( ) illustrated that this waiting period is not necessary (see Table 1).

It has been found that the time taken to increase the concrete temperature from room temperature to the desired curing temperature has a definite effect on the strength of the final product. Saul ( ) found that when the time to raise the temperature to 95° C was 6 hours or more, the 28 day strengths of steam cured specimens approached those of moist cured concrete. On the other hand, when the time was less than 2 hours the strength was reduced by about 25%. Data taken by other researchers ( ) indicate that a rate of temperature rise of 120° F (67° C) per hour reduced the 28 days strength of steam cured concrete by about 35% when compared to moist cured concrete. A rate of temperature rise of 40° F (22° C) per hour produced strengths approaching those of moist cured concrete. There is evidence ( ) that a high rate of temperature rise (120° F per hour or more) and high steam curing temperatures (over 185° F) may actually cause a retrogression in strength at later ages.



Note: Specimens were cast, sealed and maintained at indicated temperatures for 2 hours, then stored at 70° F until tested.

Mix Data

W/C	0.53
Cement content	606 Lbs./cu.yd.
Air content	0%
Percent sand	40
Type II cement	

Fig. 7 — Effect of initial temperature on the compressive strength of concrete (Data by Walter H. Price, ACI Journal, Feb. 1951)

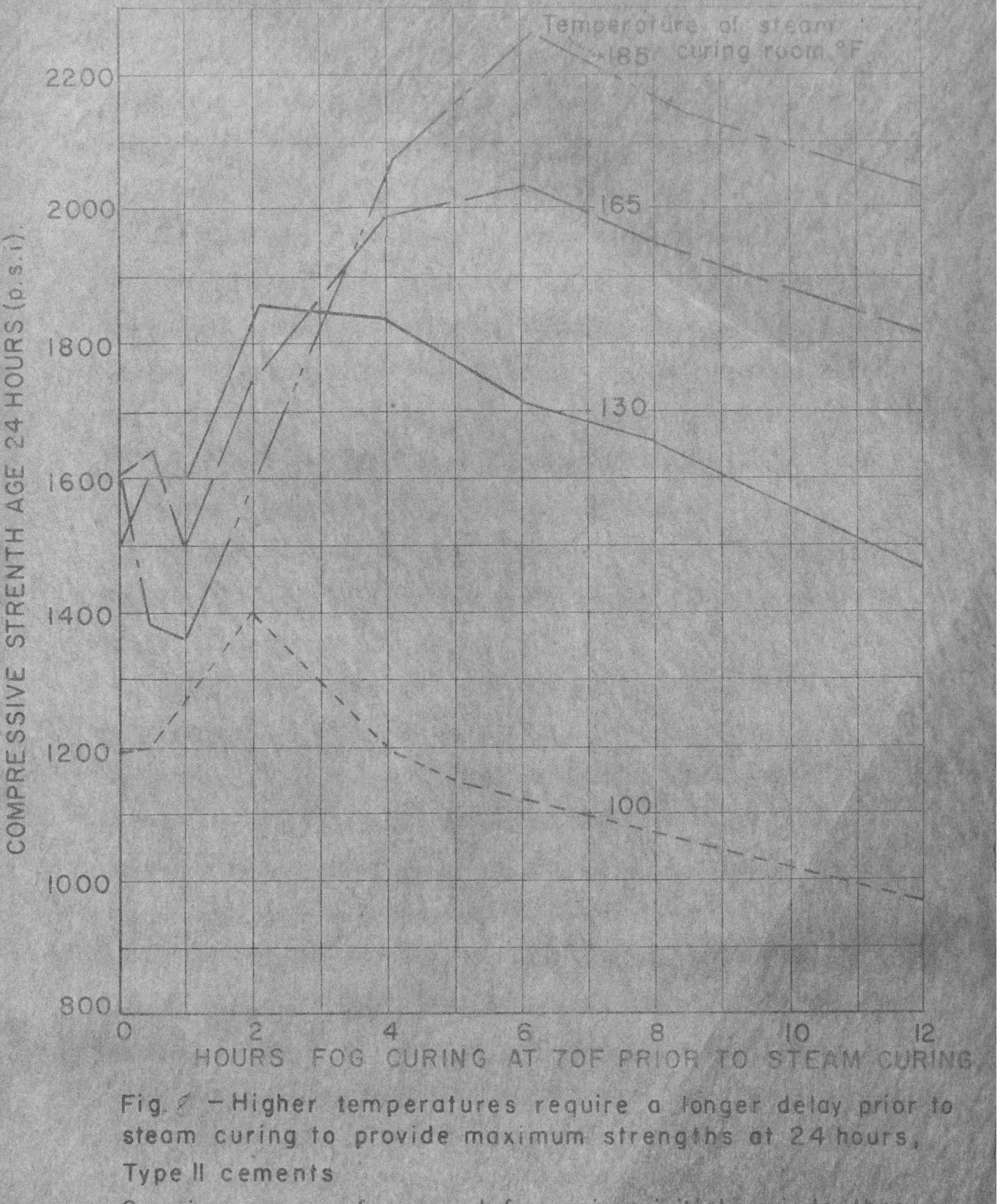


Fig. 8 – Higher temperatures require a longer delay prior to steam curing to provide maximum strengths at 24 hours, Type II cements

Specimens were fog cured for various initial periods, then steam cured to age 24 hours and tested. (Data by Shideler & Chamberlin, ACI Journal, Dec. 1949)

Research at Texas A. and M. College for four graduate theses (   ) indicate an initial holding time of 2-7 hours before application of steam; a rate of temperature rise not to exceed 60° per hour; a maximum temperature of 165°-185° F; a maximum of 24 hours exposure to the maximum temperature; and cooling at ambient temperatures give high early strength without retrogression at later ages using Type I cement and natural, non-reactive aggregates. Concrete cured under the most severe of these conditions does not continue to gain strength when removed from the curing chamber. The rate of temperature rise and the initial holding time appear to be the most critical variables. A very rapid rate of temperature rise actually causes retrogression in strength at later ages. The initial holding time should approximate the time of initial set and should not be delayed beyond the final set.

High Pressure. Concrete cured at temperatures above 212° F is outside the range of practicality for highway members and large building members at the present time due to economic reasons. However, on the basis of the data in this temperature range that was examined, it seems that the general principles which apply to the effect of temperature on moist cured and steam cured concrete at atmospheric pressures will apply here up to some unknown point. The unknown point being a temperature at which the chemical products of cement hydration change drastically. One of the disadvantages of high pressure steam curing is the costly curing pressure chamber required, however after the cycle of steam curing is completed the chamber can be used as a heated drying oven to hasten drying shrinkage of the concrete members so that they

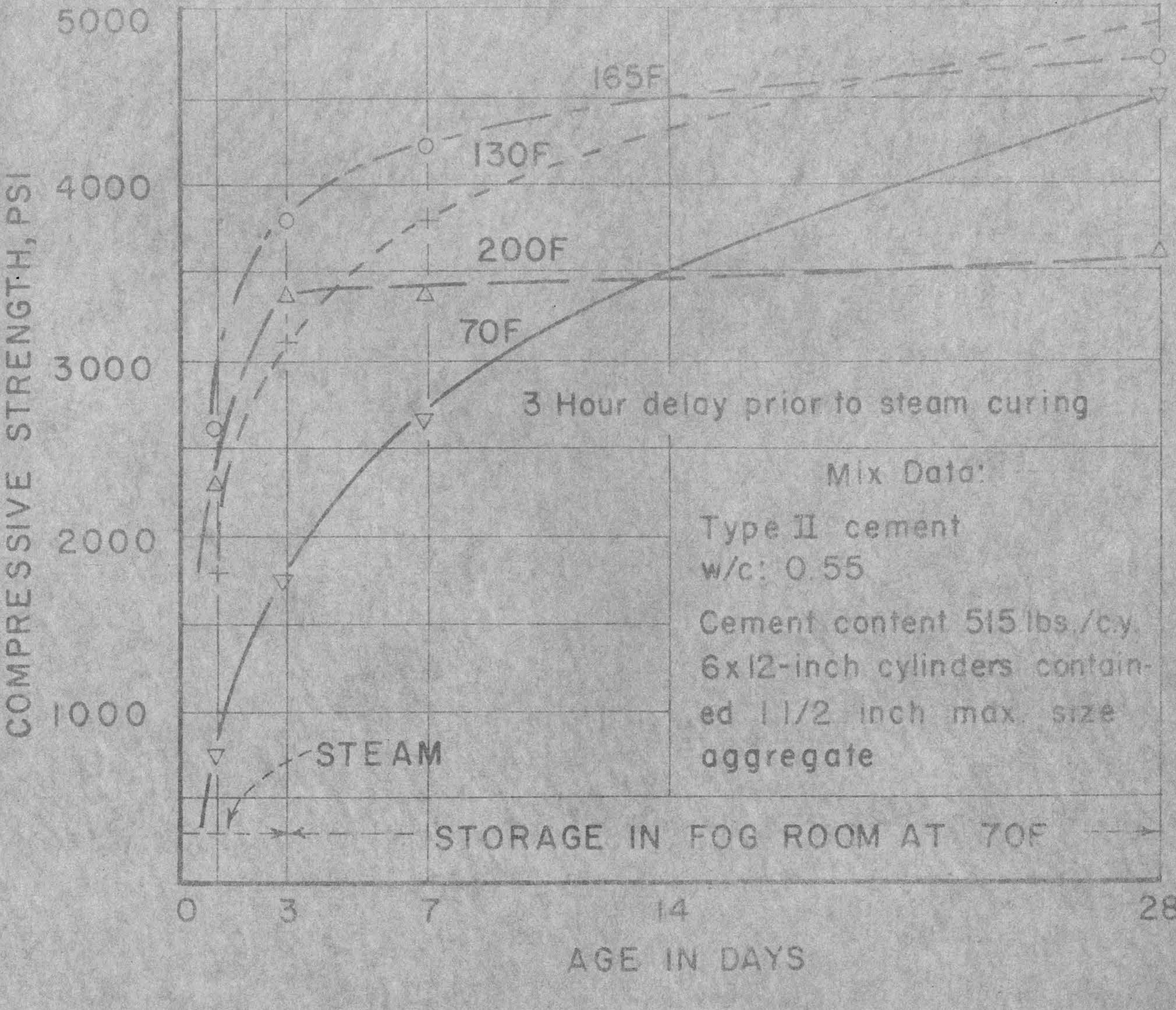


Fig. 9 – Compressive strength of specimens steam cured 3 days at various temperatures followed by moist curing at 70F (Data by Walter H. Price, ACI Journal, Feb. 1951)

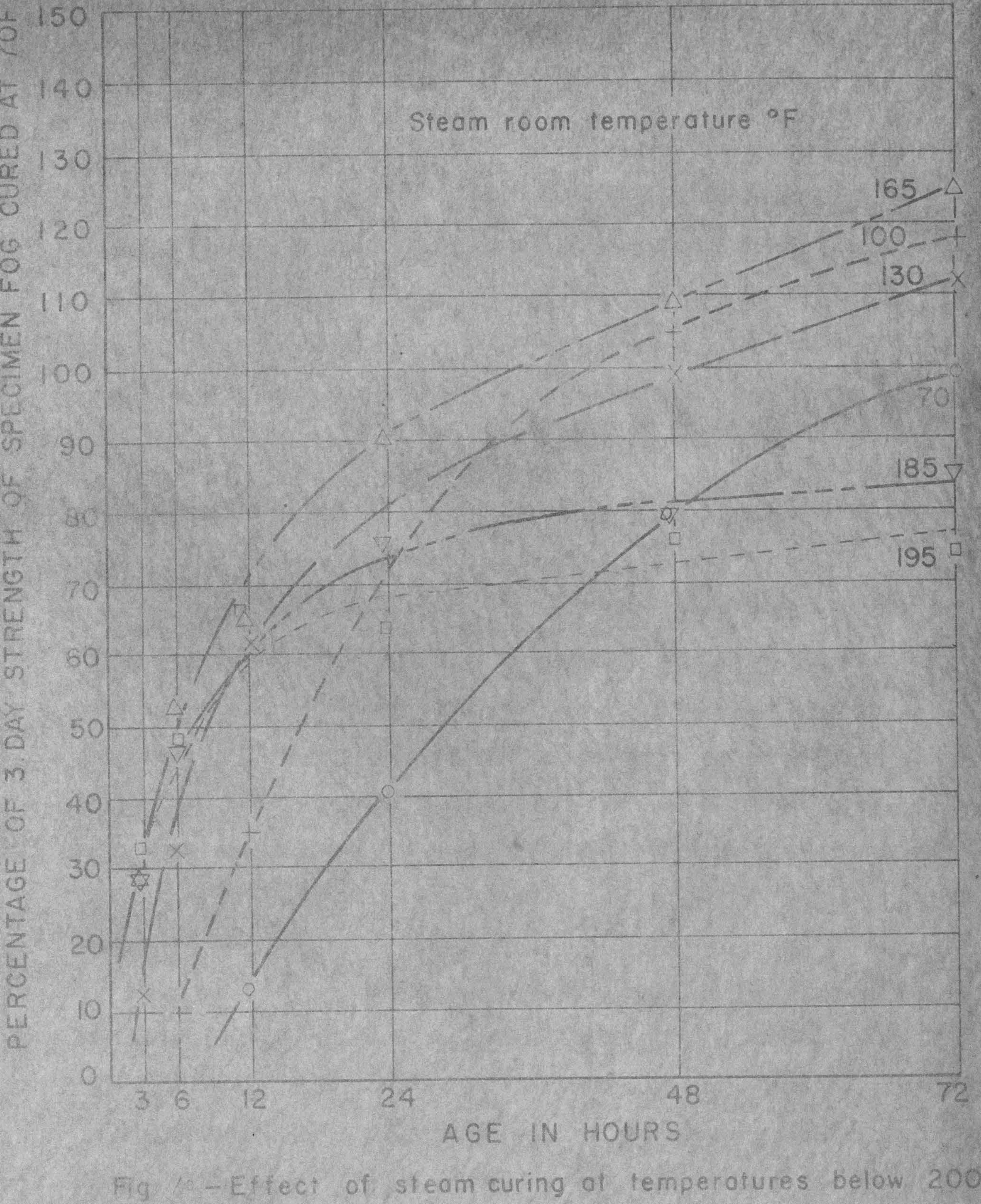


Fig 10 — Effect of steam curing at temperatures below 200F on the compressive strength of concrete at early stages, Type I cement.

Steam curing started immediately after specimens were cast. Compressive strength at 3 days of specimens fog cured at 70F was 2250 p.s.i. (Data by Shideler & Chamberlin, ACI Journal, Dec. 1949) will be more dimensionally stable. This is true even for members that will be exposed to moisture, because the second, third, etc., expansion and shrinking cycles due to alternate wetting and drying periods were shown by Pickett ( ) to be much less than the initial shrinkage. This procedure is often used on concrete blocks but severe cracking will probably result if applied to large unstressed members.

Chemical Agents

Certain chemicals are often added to concrete to either accelerate or retard the setting and curing.

Accelerators. Chemicals known to accelerate the reaction of cements are calcium chloride, soluble carbonates, silicates, aluminous cements and certain organic compounds. Calcium chloride is the most convenient and commonly used accelerator. Sodium silicate (sometimes called silicate of soda and "water glass") has also received considerable use. At the present time there is inadequate information available concerning the effect of chemical accelerators, other than calcium chloride, on concrete.

Price ( ) found that at temperatures around 40° F the strength of concrete was improved at all ages by adding calcium chloride ($CaCl_2$). The strength improved as the amount of calcium chloride increased, for the proportions included in the scope of this study. His data indicated, however, that there is little advantage in using more than 3 percent (by weight of cement) as there was very little increase in strength realized by increasing the amount of calcium chloride from 2 percent to 3 percent. As the placing temperature increased the percentage of calcium chloride should be decreased for optimum results. Further conclusions were that less than ½ percent usually retards sets, however, it reacts differently with different cements.

Figures 11 and 12 show some of the results of Klieger ( ). These figures indicate that at low placing and curing temperatures calcium chloride produces a proportionally greater increase in strength than at high temperatures. For both flexural and compressive strengths, the increases caused by calcium chloride decreased with an increase in age. At later ages the compressive strength was always equal to or greater than those for concrete without calcium chloride. Later-age flexural strengths, on the other hand, were reduced by as much as 10 percent when calcium chloride was used. The beneficial effects of the accelerator for the low temperature curing early-age concretes are relatively more important than the small detrimental decreases in flexural strength at later ages.

Clemmer ( ) found that lower water-cement ratios can be used because calcium chloride increases the workability of concrete. Vollmer ( ) arrived at substantially the same conclusions even when the accelerator was used with vinsol resin as an air entraining agent.

Other notable effects of calcium chloride was that it decreases bleeding, increases the rate of heat evolution at early ages, lowers freezing point of concrete slightly, and lowers resistance of concrete to sulfate attack.

Data collected by Rapp ( ) and Sloane, McCoughy, Foster, Wilder and Shreve ( ) indicates that calcium chloride accelerates the hydration of dicalcium silicate ($2C_aO \ . \ SiO_2$) and tetracalcium ferro-aluminate

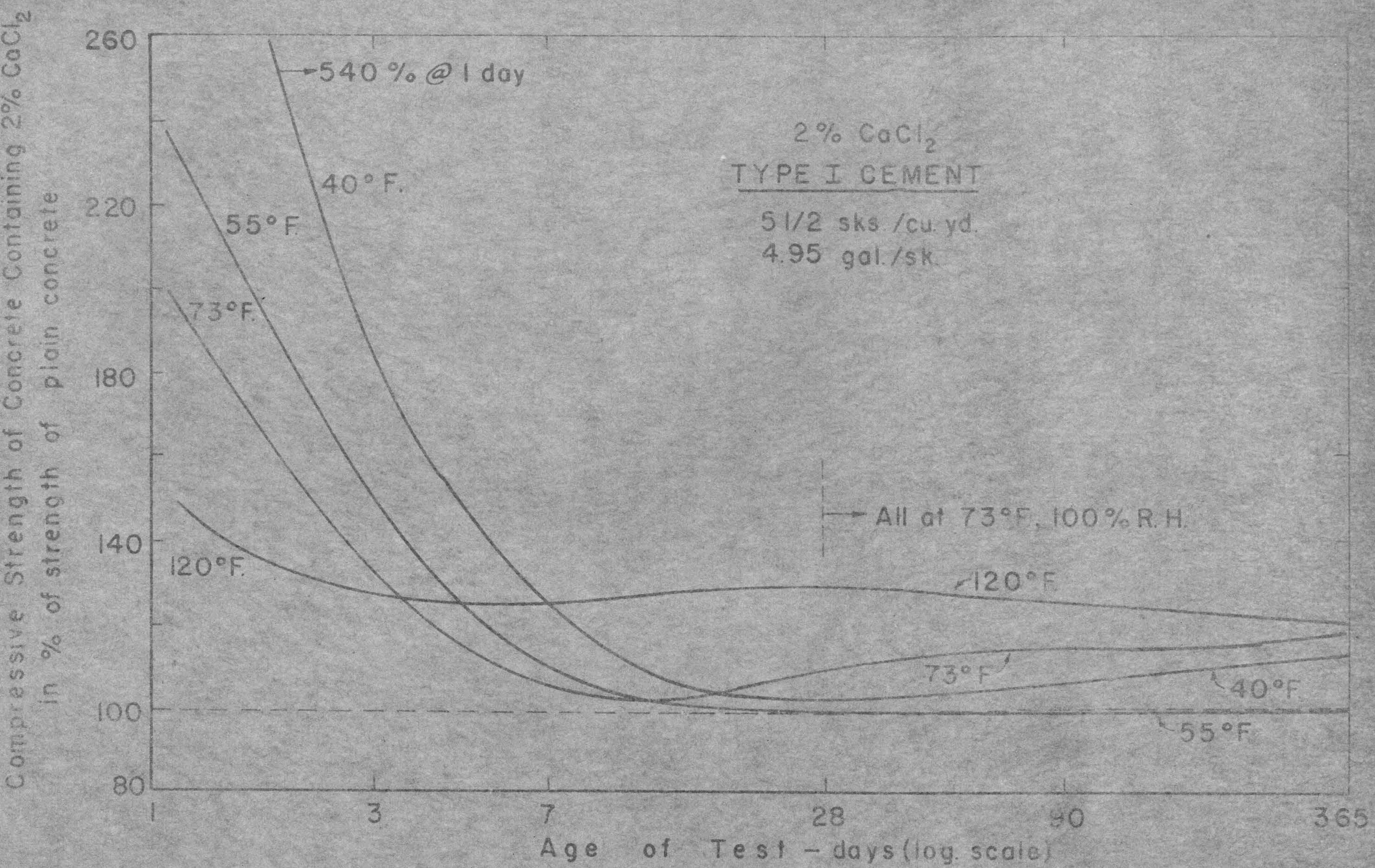


Fig. 11 - Effect of calcium chloride on compressive strength development of concrete made with Type I cement
Air content, 4 1/2 ± 1/2 percent (neutralized Vinsol resin solution added at mixer) (Data by Paul Klieger, ACI Journal, Oct. 1958)

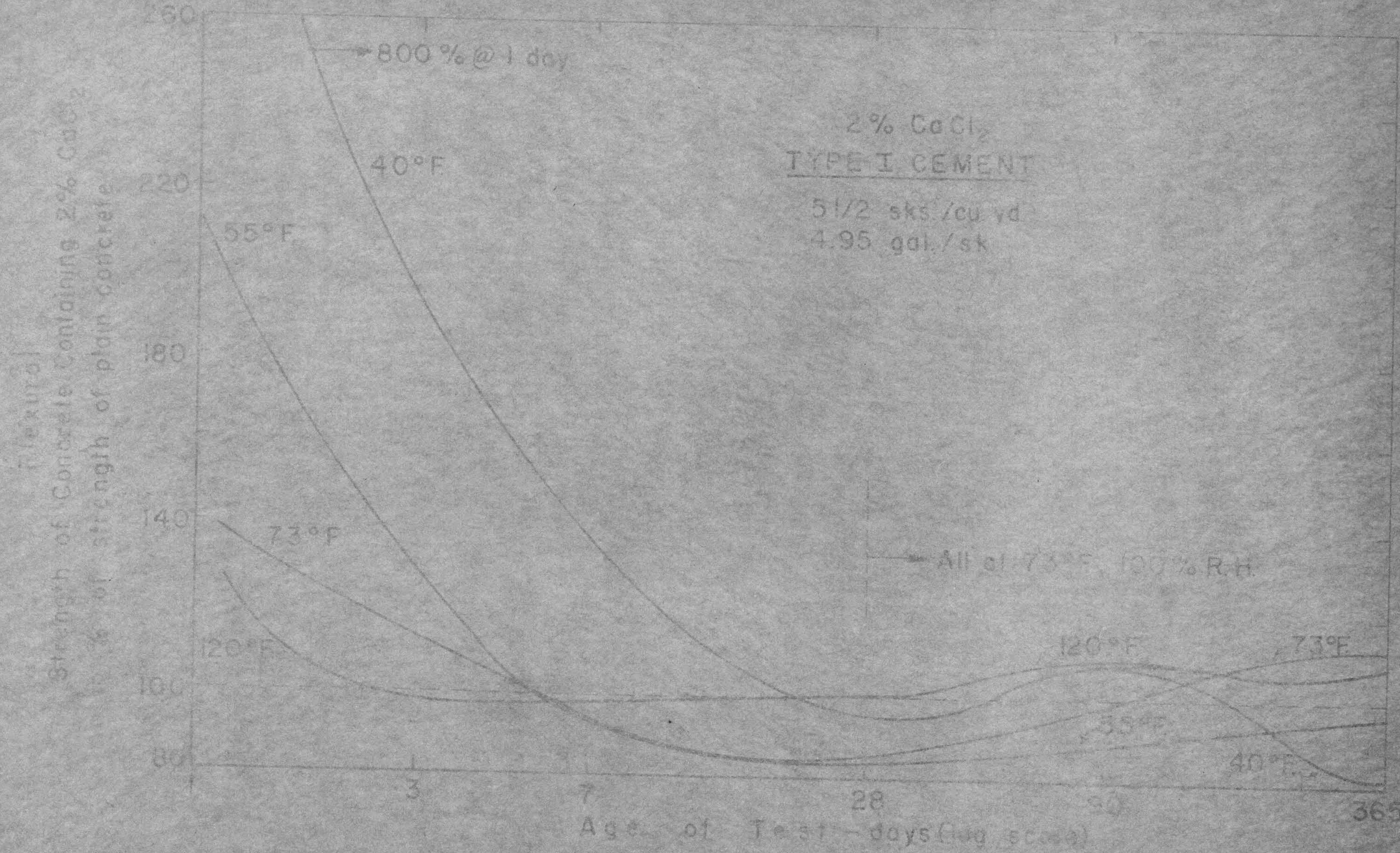


Fig. 2 Effect of calcium chloride on flexural strength development of concretes made with Type I cement.
Air content, 4 1/2 ± 1/2 percent (neutralized Vinsol resin solution added at mixer). (Data by Paul Klieger, ACI Journal, Oct. 1958)

($4CaO \,.\, Al_2O_3 \,.\, Fe_2O_3$). It appears to have little effect on tricalcium silicate ($3CaO. \, SiO_2$) and a retarding influence on the hydration of tricalcium aluminate ($3CaO \,.\, Al_2O_3$). Rapp reported that the accelerator decreased the time of set of 11 commercial cements and increased the flow and strength of the resulting concretes at ages up to 90 days.

Sodium silicate can also be used as a concrete curing agent. The solution of sodium silicate is usually applied to the surface of fresh concrete as soon as possible after pouring. Remler (   ) found that it reacts with free lime and forms a hard insoluble calcium silicate on the surface of the concrete. This compound acts as a sealing membrane which prevents evaporation of the necessary curing water. In addition to sealing in the water the insoluble calcium silicate will harden the concrete surface considerably.

<u>Retarders</u>. The principle uses of retarders in ordinary concrete are to counteract the set-accelerating effect of high temperature during hot weather, to prevent the tendency of some cements to false set, and to delay stiffening of concrete for difficult and time consuming conditions of placing. Gypsum ($CaSO_4 \,.\, 2\,H_2O$) is the most widely used set retarder and a long standing practice of the cement industry is to add gypsum as an integral part of portland cement to control the time of set. The tricalcium aluminate ($3C_aO \,.\, Al_2O_3$) constituent in cement will react very rapidly with water (when unretarded) and produce calcium aluminate crystals which build up a rigid crystalline structure causing an undesirable quick set. Gypsum slows up this reaction because/when it is dissolved in the water the

solubility of the tricalcium aluminate is greatly reduced and, consequently, the quick set is prevented.

A wide variety of commercial chemicals and formulations are proposed to have a retarding effect on the setting time of cement. Unless experience has been had with a particular retarder its use should not be attempted without competent technical advice or preferably advanced experiments to determine its effect on the setting time and other properties of a given concrete mix.

Water Reducers. Following are selected excerpts from a summary by Bruce Foster of an A.S.T.M. symposium, EFFECT OF WATER-REDUCING AND SET-RETARDING ADMIXTURES ON PROPERTIES OF CONCRETE:

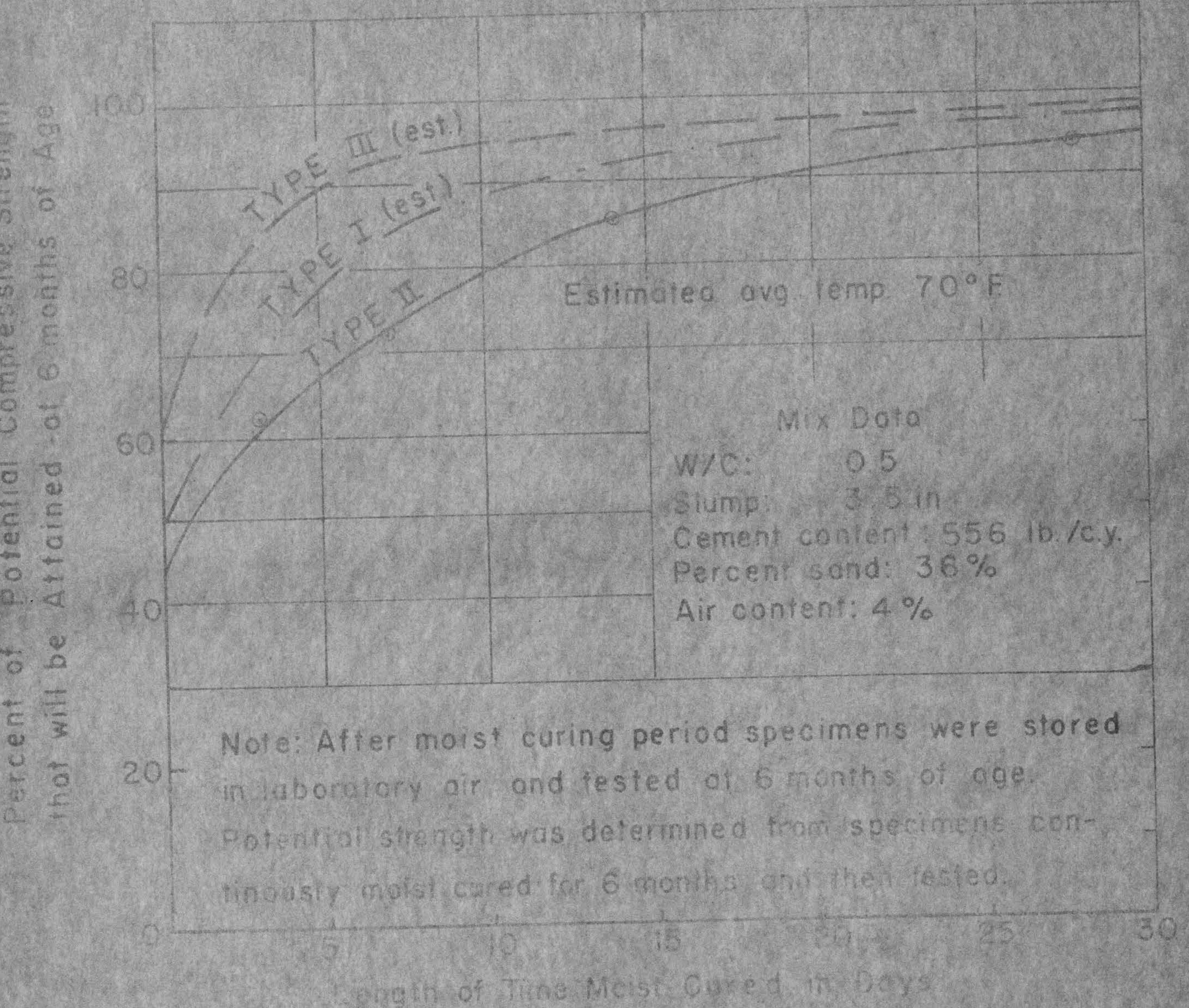
> "Water reducing admixtures...........classified into four categories:
>
> "(1) Lignosulphonic acids and their salts, (2) modifications are derivatives of lignosulphonic acids and their salts, (3) hydroxylated carboxylic acids and their salts. In each of these, the primary component has both water-reducing and set-ratarding properties. These may be modified by the addition of other components to give various degrees of retardation, no appreciable change in setting time or acceleration, while at the same time preserving water-reducing properties.
>
> "The admixtures discussed in the symposium are surface active chemicals whose anions and molecules are adsorbed on the cement grains, giving them a negative charge. The presence of the adsorbate, and the charge, was pictured as resulting in (a) a reduction of the interfacial tension, (b) an increase in the elector-kinetic potential, and (c) a protective sheath of oriented water dipoles around each cement particle. The resulting reduction in natural flocculating tendency of the cement particles then leaves them with increased mobility, and the water freed from the restraining influence of a highly flocculated system becomes available to lubricate the mix. Less water is required, therefore, for a given consistency."

The effect of commercially available admixtures is to reduce the mixing water requirement from 5 to 15 percent depending upon a number of variables. The better admixes reduce the water requirement from 10-15 percent with nominal amounts of entrained air with a resulting increase in strength of 15-30 percent.

VI. CURING PERIOD

The length of time that concrete should be subjected to artificial curing procedures is highly controversial. While most engineers are trying to speed up or cut short the formal curing period for various economic reasons, they are also interested in obtaining a high quality material. In general there are two aspects to this problem. First, what is the optimum length of curing time desirable to obtain the highest percent of potential concrete strength consistent with maximum economy of cement and time? Secondly, at what age should concrete be subjected to design loads? This second aspect refers to the time required to develop certain strength properties after the formal curing period has been discontinued. This can usually be resolved for average conditions using laboratory results to predict strengths at later ages.

The first aspect, however, concerning the optimum length of curing time consistent with maximum economy considering both quantity of cement and time required is more involved. In Figure 1, Price illustrates the effect of various periods of preliminary moist curing on the comprehensive strength of concrete. If the relative values from this figure at 180 days of age are taken and plotted opposite the moist curing period, the effect of the length of moist curing period on the development of the potential compressive strength of the given



Mix Data
W/C: 0.5
Slump: 3.5 in.
Cement content: 556 lb./c.y.
Percent sand: 36%
Air content: 4%

Note: After moist curing period specimens were stored in laboratory air and tested at 6 months of age. Potential strength was determined from specimens continously moist cured for 6 months and then tested.

Fig. 17. Effect of length of moist curing period on the development the potential compressive strength of concrete.

concrete batch is more clearly revealed (see Figure 13). The curves for Type I and III cements on Figure 13 were estimated by using information from the Portland Cement Association ( ) and others. This figure indicates that under these conditions concrete made with Type III cement will obtain 90 percent of its practical strength potential with only 5 days of moist curing. (Note: it may take 28 days to achieve this strength, but only 5 days of moist curing). It is in Figure 13 will be affected by the size and shape of the concrete specimen (or member), and the temperature and humidity conditions of exposure both during and after the curing period. Higher temperatures will reduce the amount of curing time required to reach a given percentage of the potential strength but it will also decrease the potential. Lower temperatures will increase the curing time required to reach a given percentage of the potential and will also increase the potential. Exposure of the concrete to lower relative humidities after removal from the moist room will lower all of the curves in Figure 13. The specimens would dry out more rapidly and reach a lower percent of their potential strength capacity. Thus, a longer curing period would be required. A smaller size specimen (or member) will require more moist curing to obtain a given percent of strength potential for the same reason; it would dry out more rapidly than a larger one. It is interesting to note here that if the specimens (or members)are treated with a membrane seal after the moist curing period the effect of the size of specimen and relative humidity of later exposure largely eliminated.

VII. CONCLUSIONS

1. The mixing, placing and curing temperature have a great effect upon the strength properties of concrete. Low mixing and placing temperatures in the neighborhood of 40° F give the greatest potential ultimate strengths. Low curing temperatures give high potential ultimate strengths but high curing temperatures give high early strengths with small sacrifices in the potential ultimate strength. The strength sacrifice in summer work can be greatly alleviated with a cement dispersing, set retarding admix.

2. It is recommended that concrete temperatures at the time of mixing and placing be controlled between 40° and 90° F.

3. Chemical admixes for modifying the properties of the concrete are commercially available as quality controlled products to produce a set retarding effect for summer concrete work, a set and strength accelerator for winter concrete work, cement dispersion (sometimes called water reducers, or wetting agents), air entrainment etc.

Summer concrete work should require the use of a cement dispersing, set retarding admix for best results. Benefits can be gained at temperatures above 70° F and the admix is needed at temperatures above about 80-85° F. A.S.T.M. committee C-9, is working on a new method of test A.S.T.M.: C403-T "Tentative Method of Test for Time of Setting of Concrete Mixtures by Proctor Penetration Resistance Needles" which gives a reasonable method of determining the relative set retarding effect of various admixtures

Winter concrete work may require the use of an accelerator.

Calcium chloride is the most effective chemical available for this purpose. It accelerates the strength gain but does not provide an anti-freeze action. It is not recommended for use in steam curing or prestressed concrete work.

Entrained air up to about 5 percent for conventional concrete and 7-8 percent for lightweight concrete increases workability, decreases the water requirement and increases the durability of the concrete with no apparent harmful effects.

4. The commonly used curing methods can be ranked according to their ability to develop maximum concrete strengths when properly used as follows:

(1) Water curing

(2) Damp curing under protective covers such as burlap, canvas etc.

(3) Membrane seals to hold in moisture.Certain economic and/or field conditions may make a less ideal method of curing more desirable. For instance a lack of water, a remoteness of the job from water, vertical surfaces or other economic considerations may dictate the use of liquid or solid membranes.

Liquid membranes with white pigment added are more desirable than clear or dark colored membranes for curing pavements and bridge slabs in the summer months due to the good heat reflecting properties of these materials. Reduction in maximum concrete temperatures of 20-30° F have been reported.

5. Rapid cooling and/or drying of concrete are particularly detrimental to the concrete quality and may produce severe surface cracking. Large concrete members and large concrete surfaces are more vulnerable to this damage than smaller ones.

6. Revibration of concrete near the time of initial set and delayed inal finishing may increase the strength as much as 10-15 percent, it will increase the durability and correct early plastic cracking due to settlement etc.

7. Steam curing at atmospheric pressure can be especially beneficial to early strengths at some sacrifice to later strengths. Variables that should be controlled are the holding time before applying steam, the rate of temperature rise, the maximum temperature, the length of curing at maximum temperature and the rate of cooling.

BIBLIOGRAPHY

1. HIGHWAY RESEARCH BOARD, "Curing of Concrete 1925-1955," Bibliography 18, 1956.

2. ANON, "The Treatment of Road Surfaces With Bitumen Emulsions," Engineering, Vol. 135, No. 3518, June 16, 1933.

3. BERGSTROM, S. G., "Curing Temperature, Age and Strength of Concrete," Magazine of Concrete Research, No. 14, December 1953.

4. BERESFORD, F. D. AND MATTISON, E. N., "Presetting Cracks in Fluid Concrete," Constructional Review, Vol. 31, No. 9, September 1958.

5. BLAKEY, F. A. AND BERESFORD, F. D. "Cracksing of Concrete," Constructional Review, Vol. 32, No. 2, February 1959.

6. BLANKS, R. F. AND KENNEDY, H. L., The Technology of Cement and Concrete, Vol. I. John Wiley & Son, Inc., 1955.

7. CARLSON, R. W., "The Function of Water in Hardening Concrete." Highway Research Board, Proceedings, Vol. 16, 1936.

8. CLEMMER, HAROLD F. "Integral Use of Calcium Chloride Supplies High Early Strength." Concrete, Vol. 42, No. 12, December 1942.

9. GONNERMAN, H. F. "Report of Committee on Curing of Concrete Pavements Slabs." Highway Research Board, Proceedings, Vol. 13, pt. II, Ch. 3, 1933.

10. ACI COMMITTEE 212, "Admixtures for Concrete," ACI Journal, October 1954.

11. JAGUS, P. J. AND SETHI, K. L., "Use of Membranes for Curing of Concrete," Highway Research Abstracts May 1959, Vol. 20, No. 5. Indian Roads Congress (Jamnagar House, Mansingh Rd., New Delhi 2, India), Road Research

12. KLIEGER, PAUL, "Effect of Mixing and Curing Temperature on Concrete Strength," ACI Journal, June 1958.

13. MEISSNER, H. S. AND SMITH, S. E., "Curing Compounds--Summary of Tests Reported by Authors at A.C.I. Meeting February 22-24, 1938." Engineering News-Record, Vol. 120, March 10, 1938.

14. NURSE, R. W., "Steam Curing of Concrete," Magazine of Concrete Research, No. 2, June 1949.

15. OLIVIER-CINTRON, ELMER, "Effects of Variation in Rate of Temperature Rise, Curing Temperature and Size of Specimen on Selected Phisical Properties of Concrete Made with Type I Cement and Steam Cured at Atomospheric Pressure," A Master of Science Thesis, The A. & M. College of Texas.

16. ALDRIDGE, WELDON WAYNE, "Effects of Variations in Rate of Temperature Rise, Curing Temperature and Size of Specimen on Selected Physical Properties of Concrete Made With Type III Cement and Steam Cured at Atmospherice Pressure," A Master of Science Thesis, The A. & M. College of Texas, 1958.

17. BURLESON, KERRY E., "Early Effects of Low-Pressure Steam Curing on Some of the Physical Properties of Concrete", A Master of Science Thesis, The A. & M. College of Texas, 1958

18. BURLESON, KENNETH S., "Effects of Variations in Holding Time, Curing Temperature, and Treatment Period on Selected Physical Properties of Concrete Made With Type III Cement and Steam Cured at Atmospheric Pressure", A Master of Science Thesis, The A. & M. College of Texas, 1958

19. PICKETT, HERALD, "Effect of Aggregate on Shrinkage of Concrete and a Hypothesis Concerning Shrinkage," ACI Journal January 1956.

20. POWERS, T. C. "A Discussion of Cement Hydration in Relation to the Curing of Concrete." Highway Research Board, Proceedings, Vol. 27, 1947.

21. PRICE, WALTER H., "Factors Influencing Concrete Strength," ACI Journal, Feb. 1951.

22. RAPP, PAUL. "Progress Report on the Reaction of Calcium Chloride on Portland Cement." Highway Research Board, Proc., Vol. 13, Pt. I, 1934.

23. REMLER, R. F. "Curing Concrete Roads With Silicate of Soda." Public Works, Vol. 57, No. 3, April 1926.

24. SAUL, A. G. A., "Principles Underlying the Steam Curing of Concrete at Atmospheric Pressure," Magazine of Concrete Research No. 6, March 1951.

25. SHIDELER, JOSEPH J. AND CHAMBERLIN, WILBUR H. "Early Strength of Concrete as Affected by Steam Curing Temperatures." Journal of American Concrete Institute, Vol. 46, 46-18, December 1949.

26. SLOANE, R. C., MC COUGHY, W.J., FOSTER, WILDER D., AND SHREVE, CARL. "Effect of Calcium Chloride as an Admixture in Portland Cement Concrete." The Ohio State University, Eng. Exp. Sta., Bul. No. 61, 1931.

27. SWAYZE, MYRON A., "Finishing and Curing: A Key to Durable Concrete Surfaces," ACI Journal, Dec. 1950.

28. TIMMS, A. G., ROBINSON, D. L., GILKEY, H. J., CARLSON, ROY W. AND JOHNSON, W. R., BURNETT, C. E. AND VOLLMER, H. C., "Curing of Concrete," ACI Journal May 1952.

29. TREMPER, BAILEY. "Effect of Delay in Applying Concrete Curing Membrane." Roads and Streets, Vol. 96, No. 3, 1953.

30. VOLLICK, C. A., "Effects of Revibrating Concrete," Highway Research Abstracts June 1956, Vol. 28, No. 6. Journal of the American Concrete Institute (P.O. Box 4754 Redford Station, Detroit 19, Mich.), Vol. 29. 9; Proceedings Vol. 54, March 1958.

31. VOLLMER, H. C. "Effect of Calcium Chloride of the Water Requirements, Specific Weights and Compressive Strengths of Concretes Made with Plain and Treated Cements." Highway Research Board, Proc. Vol. 23, 1943.

32. PORTLAND CEMENT ASSOCIATION, Design and Control of Concrete Mixtures, 10th edition, 1952.

33. WATERS, CHARLES R., "Some Observations on Highway Work," Roads and Streets, Vol. 69, 1929.

34. SWAYZE, MYRON A., "Early Concrete Volume Changes and Their Control", ACI Journal, April 1942.

35. VOLLMER, H. C., "Influence of Various Curing Methods on Some Physical Properties of Portland Cement Concrete, "Highway Research Board Proceedings, Vol. 24, 1944.

36. DAVEY, N., "Influence of Temperature upon the Strength Development of Concrete", Building Research Technical Paper No. 14, Department of Scientific and Industrial Research (England), October 1933.

37. TIMMS, A. G. AND WHITHEY, N. H., "Temperature Effects on Compressive Strength of Concrete", ACI Journal, Jan-Feb. 1934.

38. BURNETT, G. E. AND SPINDLER, M. R., "Effect of Time of Application of Sealing Compound on the Quality of Concrete," ACI Journal November 1952.

39. RHODES, C. C. AND EVANS, J. R., "Appraisal of Membrane Method of Curing Concrete Pavements", Michigan Engineering Experiment Station Bulletin 108, 1949.

40. STANTON, T. E., "Field Tests-Concrete Curing (Series 1925)", Highway Research Abstracts No. 1, May 1931.

41. GILKEY, H. J., "The Moist Curing of Concrete", Engineering New Record, October 14, 1937.

42. TIMMS, A. G., "Effect of Duration of Moist Curing on the principle Properties of Concrete", Proceedings ASTM, Vol. 34, Pt. II 1834.
1934