

Report 118

# An Appraisal of the Membrane Method of Curing Concrete Pavements

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MICHIGAN ENGINEERING EXPERIMENT STATION  
EAST LANSING, MICHIGAN

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### A MICHIGAN STATE COLLEGE BULLETIN

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INVESTIGATION CONDUCTED BY  
THE MICHIGAN STATE HIGHWAY DEPARTMENT

*In Co-operation with*

THE ENGINEERING EXPERIMENT STATION OF  
MICHIGAN STATE COLLEGE

MICHIGAN STATE COLLEGE  
MICHIGAN ENGINEERING EXPERIMENT STATION  
EAST LANSING

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## FOREWORD

The principal aim of this bulletin is to evaluate the membrane, or seal-coat, method of curing concrete pavements. In pursuing this aim, an approach differing somewhat from the conventional one was adopted at the outset. The authors felt that too little attention had been devoted in the past to a very important function of the curing operation—that of stress control by regulation of early temperature and moisture changes in the concrete slab. Throughout the present investigation, therefore, this regulatory function has received fully as much emphasis as the hydration needs of the cement.

The adoption of such a viewpoint implies further that a consideration of the effects of such factors as cement composition, hydration reactions, temperature and moisture changes, physical properties of the hardened cement paste, and subgrade characteristics on early stresses in the pavement slab is properly within the scope of the subject. All of these factors come into play during the setting and early hardening period, and profoundly influence the cracking tendency of the immature pavement.

This study was undertaken as a joint project of the Michigan State Highway Department, of which Charles M. Ziegler is State Highway Commissioner, and the Engineering Experiment Station of Michigan State College, which is under the direction of Dr. C. C. Dewitt. The project was under the general supervision of E. A. Finney, Director of the Highway Research Laboratory, which is located in the R. E. Olds Hall of Engineering on the campus of Michigan State College. The Research Laboratory is a functional unit of the State Highway Department's Testing and Research Division, headed by W. W. McLaughlin, Testing and Research Engineer.

Most of the experimental work of the present study was performed by the junior author in connection with graduate work in civil engineering leading to the degree of Master of Science at Michigan State College under a Fellowship established at the College by the Truscon Laboratories of Detroit, Michigan.

The authors are indebted to W. O. Fremont and L. D. Childs of the Research Laboratory for valuable discussion and helpful criticism of the section on warping stresses; and to William Martin and M. G. Brown of the same laboratory for their assistance in various phases of the experimental work. The cooperation of the Mechanical Engineering Department of the College in making available their testing equipment and the air-conditioning train used in the cabinet tests is also gratefully acknowledged.

# An Appraisal of the Membrane Method of Curing Concrete Pavements

*By C. C. RHODES and J. R. EVANS*

Since the early days of the second World War there has been a rapid growth in the use of membrane, or seal-coat, compounds for curing concrete pavements. The idea of curing concrete by sealing the surface against loss of the original mixing water was not new, but the exigencies of war created conditions particularly favorable for a method which utilized abundant, readily available materials and required a minimum of labor and supervision. In spite of its obvious advantages, however, many engineers and concrete technicians have taken the position that membrane curing should be considered only as a wartime substitute for the older methods of wet curing and should be abandoned as soon as it should again become feasible to do so.

Thus there has existed a need for a thorough evaluation of the membrane method to determine whether it should merit continued use as an alternate method of curing concrete pavements. Such has been the purpose of the present study, and the results obtained point to the conclusion that the use of membrane curing materials constitutes an acceptable method provided adequate means are employed to protect the concrete from the radiant heat of the sun during hot, clear weather in order that premature cracking be reduced to a minimum. Satisfactory temperature control may be accomplished by: 1) the use of white-pigmented compounds; 2) an initial 24-hour wet cure followed by spraying with water and application of either clear or white membrane; 3) the use of heat-insulating coverings in conjunction with membranes; or 4) shifting the construction work period so as to begin pouring operations later in the day.

Of these four methods of temperature control, probably the use of white pigments is the most practicable since it involves only a single operation and is immediately active in retarding temperature rise. Initial wet curing for 24 hours is very effective but is open to many of the objections applicable to wet curing for longer periods, and failure to thoroughly saturate the concrete prior to spraying with

membrane compound will generally result in discontinuous films and poor water retention. Insulation from the sun by dry coverings or shading requires strict attention and precise timing in order to prevent high temperatures in the slab during the first afternoon. Shifting the hours of daily work also presents practical problems, but there can be no doubt that such a measure would be highly effective in the mitigation of temperature cracking.

A complete appraisal of any curing method requires a clear understanding of the effects of conditions prevailing during the setting and early hardening period on the hydration of portland cement and the physical properties of the hardened paste. It seems worthwhile, therefore, to recall briefly a few facts of basic importance in the curing of concrete to form a background for the later interpretation of laboratory and field experiments performed in connection with the investigation.

## A PRELIMINARY REVIEW

### CLASSIFICATION OF CURING METHODS

Curing materials and methods may be classified functionally into three general groups:

- 1) Those which supply external moisture continuously at the surface during the curing period and tend to prevent the development of high temperatures in the concrete. This group of so-called "wet methods" includes ponding, spraying, and wetted coverings of all kinds, such as burlap, cotton mats, earth, sawdust, straw, and surface calcium chloride.

- 2) Those which retain the original mixing water within the concrete by sealing the surface and which do not supply additional moisture. Curing methods that prevent loss of water are the application of waterproof paper and liquid curing materials of all kinds, including bituminous solutions or emulsions, sodium silicate, and the resinous and waxy solutions which dry to form a moisture-retaining membrane at the surface of the concrete.

- 3) Hygroscopic accelerators added to the concrete mixture to retard evaporation and speed up the hydration process to take advantage of the high early moisture content of the fresh concrete. Calcium chloride integrally mixed with the concrete is an example of this type.

The type of curing being considered here falls in the second of the above three groups and consists in the application, usually by

spraying, of a varnish-like liquid to the surface of the concrete immediately after the free moisture has disappeared. The volatile solvents evaporate rapidly, leaving a film or membrane which seals the surface more or less effectively against further loss of mixing water. It goes without saying that the membrane thus formed should be continuous and as nearly impermeable to water vapor as possible, and that the curing compound should be applied just as soon as practicable after the finishing operation is completed. Most specifications require the addition of a fugitive dye to the liquid compound to facilitate uniform application by making the film more readily visible. This dye should fade after a few hours' exposure to sunlight, leaving a film which does not appreciably darken or discolor the concrete surface.

#### MOISTURE CONTENT VERSUS PHYSICAL PROPERTIES OF CONCRETE

It has been well established that a close relationship exists between the physical properties of concrete, such as strength, hardness, and volume, and the amount of water maintained within the concrete during the curing period. Lang (16), Gonnerman (9), Jackson and Kellermann (12), Morris (20), and others have clearly demonstrated that deficiency of water during the early stages of development is associated with low strength and the presence of adequate amounts of water is associated with high strength.

#### FIELD CURING EXPERIMENTS

Many attempts have been made to compare different curing methods on the basis of the performance of experimental pavement sections in the field. These attempts have not been entirely successful because of the many uncontrollable variables inherent in ordinary construction practice, particularly the weather and the time of day at which the concrete is placed, which tend to mask the difference in behavior directly traceable to the method of curing (14).

Nevertheless, one significant fact has emerged from experience and research in this field, namely that initial differences in effects produced by different methods of curing concrete pavements decrease with time and eventually disappear. This is true both in regard to the physical properties of the concrete itself (1, 18), and the average length of slab resulting from traverse cracking (13, 21, 29). After the curing operation is discontinued the progress of hydration is governed largely by prevailing climatological conditions and the prop-



erties of a given concrete approach the same limiting values regardless of the particular method of curing initially employed. Conservation of moisture through periods of high humidity and replenishment of moisture by occasional rainfall and moist subgrades will, in most regions of this country, insure adequate strengths at later ages.

It might be argued from the preceding that artificial curing of pavements is unnecessary, but in general this would not be true. Several years may be required to entirely obliterate the effects of initial curing, but the retention of sufficient moisture and suitable protection against large and rapid temperature change at the beginning will prevent surface crazing, minimize *premature* cracking, and assure the development of required working strengths at the end of 7 days. Concrete poured in the fall, or during cloudy, humid periods of spring and summer would suffer little from lack of artificial curing. Obviously construction operations cannot wait upon the weather to such an extent, and the function of the curing operation is to insure positive control of temperature and moisture immediately after placing the concrete.

#### MEMBRANE CURING

Most of the membranes employed in earlier work were of the bituminous type and, owing to their dark color, produced undesirable temperature effects through absorption of radiant heat from the sun. In studies reported to the Highway Research Board by Gonnerman (10), it was found that the average crack interval at ages between 28 days and 1 year for sections of pavement cured with bituminous membranes was about 40 feet less than the crack intervals for a group of other methods which included ponding, wet burlap, sodium silicate and surface calcium chloride. It was also noticed that temperature change was the dominant factor in volume changes of the concrete and that the temperature curve for the top surface of the concrete followed the general contour of the air temperature curve. It was observed further that nearly all test sections of pavement poured in the morning had a tendency to crack more than those poured in the afternoon, irrespective of curing method. This was attributed to the fact that concrete poured during the afternoon attained lower maximum temperatures during the day and contracted less at night; and to the fact that the concrete placed later in the day remained relatively plastic during the period of rapid temperature drop. Experimental sections cured with bituminous membranes were bene-

fitted more by cloudy days and late afternoon placing than those cured by other methods.

In another early report (17), these temperature effects were recognized and closer joint spacing was mentioned as a means of crack control in concrete pavements cured with bituminous membranes. The use of white coatings, such as whitewash, over bituminous membranes markedly reduced temperature rise in the concrete from this cause (3, 19).

Blanks, Meissner and Tuthill (2) have described the properties and use of several different types of curing compounds, enumerated the advantages and disadvantages of the method, and have shown that membrane curing is equivalent to 14-day initial water curing. These authors also found that the use of white-pigmented membranes considerably reduced the maximum temperature attained in concrete under intense sunlight and constituted a satisfactory means of temperature control when membranes were used.

## FUNDAMENTAL FACTORS IN CURING

The function of the curing operation is to provide favorable conditions for the development of maximum strength in the concrete with a minimum of volume change during the setting and early hardening period. There are two distinct aspects to the transformation of the cement paste from the plastic to the hardened state in a concrete pavement slab. The first has to do with the chemical reactions and end-products involved in the hydrolysis and hydration of the cement constituents. Here the influence of curing conditions is strongly felt through their ability to control, to a considerable degree, the nature, rate and extent of the initial chemical actions necessary for the laying down of the cementing material. The second aspect comprises the physical effects accompanying and following these chemical changes and their influence on the properties of the mass, such as strength, hardness, elasticity, volume and porosity. Here, again, curing conditions play an important part in balancing and regulating these physical changes so as to bring about the greatest possible strength and structural integrity of the concrete at early ages. Temperature-regulating ability thus constitutes a very considerable factor in the efficiency of any curing method.

### THE CHEMICAL ASPECT

The principal constituents of portland cement clinker are generally considered to be tricalcium silicate ( $C_3S$ ),<sup>1</sup> dicalcium silicate ( $C_2S$ ), tricalcium aluminate ( $C_3A$ ), and tetracalcium aluminoferrite ( $C_4AF$ ). The clinker also usually contains varying amounts of magnesium oxide and relatively small amounts of the oxides of sodium, potassium, manganese, phosphorous and titanium. The finished cement contains in addition a small amount of gypsum ( $CaSO_4 \cdot 2H_2O$ ), usually around 3 percent, which is ground with the clinker to retard the set. Each of the major compounds, including gypsum, exhibits characteristic properties which exert a marked effect on the behavior of the cement during and after the curing period.

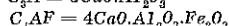
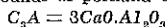
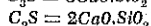
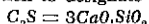
The constituent compounds of portland cement are all anhydrous initially, but all react with water to form the hydrated compounds which constitute the actual cementing material. The original anhydrous compounds, as such, cannot exist in equilibrium with water but form temporarily supersaturated and unstable solutions which gradually deposit excess solids and tend to reach a stable equilibrium with the hydrated compounds produced.

### The Setting and Hardening of Cement Pastes

The chemical reactions which take place after cement is mixed with water cause the plastic mass to assume a rigid structure within a comparatively short time. Two stages in the progress of this structural change, called *initial set* and *final set*, are determined empirically by standard procedures to define the time limits of the setting process for practical purposes. Heat is evolved rapidly during the early stages of hydration and, under ordinary conditions, initial set occurs while the temperature is rising rapidly and final set takes place at the time when the temperature reaches a maximum.

A simplified picture of the setting and hardening processes may be visualized as follows: When water is added to cement, the alumina-bearing compounds hydrate first, forming hydrated  $C_3A$  and calcium sulphoaluminate with the evolution of a considerable quantity of heat. The initial set is primarily the result of these reactions, although  $C_3S$  begins to hydrate fairly early and contributes to the stiffening of the

<sup>1</sup>The following abbreviated symbols now in general use will be used interchangeably with the conventional notation to designate the computed compounds of portland cement:



paste and the rise in temperature before final set takes place. If no gypsum were added to the cement to delay these initial reactions a *flash set* would usually result. The hydration of the alumina-bearing compounds is practically complete at 24 hours and the continued hydration of  $C_3S$  is responsible for the further development of early strength. At 7 days the hydration of  $C_3S$  is far advanced and at 28 days is nearly complete, but very little  $C_2S$  has hydrated during this time. The continued hydration of  $C_2S$ , however, is chiefly responsible for the gradual progression of strength at later ages. It is evident, therefore, that the chemical composition of the cement influences the rate at which water is fixed, or made non-evaporable, during the curing period.

All of these reactions overlap and are prolonged to a certain extent by the formation of increasingly impermeable shells of hydration products on the cement grains, and the increase in strength shown by mortars and concretes over a period of years is due not only to the continued hydration of  $C_2S$  but also to the gradual penetration of water to the cores of unhydrated material to hydrate remnants of the other cement compounds as well.

### THE PHYSICAL ASPECT

When water is mixed with cement in the proportion required for a plastic paste and the mixture is allowed to stand, sedimentation begins at once. The cement, with a specific gravity of more than three times that of water, settles and some of the free water rises to the surface. At the same time, water and cement are reacting at a rapid rate to produce the hydration products which constitute the cementing material. Within a comparatively short time solidification occurs and the final bulk volume of the paste is established except for relatively small changes due to continued hydration, wetting and drying, and variations in temperature.

Because of the manner in which the body of the paste is formed, it is apparent that the hardened paste is not a continuous solid but consists of a large number of small particles bound together in a porous structure. When the final reactions of hardening begin, the hydration products are deposited in the spaces of the structure and the capillaries are thus reduced in size, although their continuity is apparently not destroyed. The recent work of Powers and Brown-

yard (22)<sup>2</sup> indicates that the primary units of the hydration products, with the exception of calcium hydroxide, some clinker residues, and small amounts of other microcrystalline compounds, are of colloidal dimensions and form the gel which is the principal constituent of the hardened paste.

### Water in Hardened Portland Cement Pastes

During the setting and hardening processes the available water in the paste is redistributed and transformed by the chemical and physical forces acting upon it. A part becomes chemically combined as water of crystallization, hydroxides, and as a constituent of the various colloidal hydrates. This water, called *water of constitution*, loses its identity as such and becomes an integral part of the solid phase. Another part of the water is absorbed or bound to the solid phase by surface forces. The field of such forces is extremely small, but they are intense enough to compress and densify a fluid, either gas or liquid, that comes within their range. The amount of water held in this way is insignificant if the specific surface of the solid phase is small, but may comprise a large portion of the total water held at ordinary temperatures and pressures when the specific surface is large, as it is for colloidal material. A third part of the water remains in the capillary spaces, neither chemically combined nor within the range of surface forces of the solid phase.

### Volume Relationships in the Hardened Paste

Starting with a freshly mixed paste which contains about one-third cement and two-thirds water by volume, the hydration reactions cause the solid phase to increase to a final volume of about two-thirds of the total. Since the water in the hydration products of the hardened paste occupies less space than when in the free state, an internal contraction occurs which leaves part of the capillary space empty and results in a decrease of vapor pressure of the remaining water.

The volume of capillary space thus emptied by self-desiccation represents the amount of water that must be added to keep the paste saturated. It has been found that the water lost from the pores of the paste through either self-desiccation or evaporation is very difficult, if not impossible, to replace once the continuity of moisture flow from an external source to the capillaries has been interrupted. If

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<sup>2</sup>For a detailed and thorough treatment of the physical properties of hardened portland cement pastes, the reader is referred to the series of papers by these authors which appeared in the *ACI Journal*, October 1946 through April 1947. Terms and notations used in their presentation have been adopted freely in the present discussion.

evaporation from the paste occurs, more water is lost from the capillaries and the vapor pressure of the remaining water is still further reduced until, at relative vapor pressures<sup>3</sup> below about 0.80 or .085, hydration practically ceases. On strong drying, evaporable water can be lost from both the capillaries and the gel simultaneously, but the loss of gel water is negligible in pasts of fairly high  $w/c$  at early ages (25). In the relationships given below, all of the water lost by self-desiccation and evaporation is assumed to come from the capillaries. Under conditions ordinarily encountered in concrete pavements during the initial curing period, no serious error is introduced by this assumption.

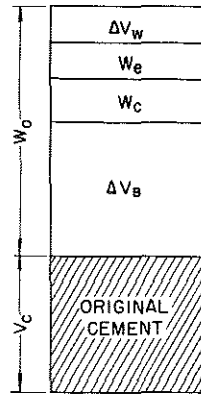


Fig. 1.

Figure 1 is a schematic diagram of volume relationships in cement pastes similar to one employed by Powers (26) to show how the capillaries become emptied by self-desiccation and evaporation. At any stage of hydration (under the conditions specified above),

$$w_e = w_o - \Delta V_B - \Delta v_w - w_e \dots\dots\dots (1)$$

where

- $w_o$  = water-filled capillary space,
- $w_o$  = original water content,
- $\Delta V_B$  = increase in volume of the solid phase,
- $\Delta v_w$  = contraction of the water in passing from the liquid to the solid phase, and
- $w_e$  = water lost by evaporation.

When the capillary space is completely emptied of water  $w_e = 0$  and, substituting this value in equation (1), the amount of water which must be lost by evaporation to bring about this condition is found to be

$$w_e = w_o - \Delta V_B - \Delta v_w \dots\dots\dots (2)$$

In the Powers-Brownyard (23) paper it was shown that

$$\Delta V_B = 1.74 w_n \dots\dots\dots (3)$$

and

$$\Delta v_w = 0.279 w_n \dots\dots\dots (4)$$

so that equation (2) becomes

$$w_e = w_o - 2.02 w_n \dots\dots\dots (5)$$

where  $w_n$  = non-evaporable water.

<sup>3</sup>Relative vapor pressure =  $p/p_s$  where  $p$  = existing vapor pressure, and  $p_s$  = saturation pressure at the same temperature.

From equation (5) it can be seen that the amount of water which must be lost to empty the capillaries of the paste and thus stifle hydration completely is a variable which depends on the original water-cement ratio and the extent of hydration of the cement.

In order to determine directly the loss of evaporable water required to stop hydration at any instant it would be necessary to have data giving values of  $w_n$  as a function of time, temperature, and  $w_0/c$ . Experiments in this laboratory on water fixation and the data of Gause and Tucker (6) on vapor pressures over sealed pastes indicate that  $w_n$  increases rapidly up to about 7 days from the time of mixing, especially during the first 3 or 4 days, and then levels off. The amount of non-evaporable water,  $w_n$ , in a completely hydrated paste varies from about 0.20 to 0.25 gram per gram of cement, depending on the particular characteristics of the individual cement.

As an example of the application of the equations given above, let us assume conservatively that a pavement mix of  $w_0/c = 0.44$  by weight has hydrated at 7 days to the extent that  $w_n$  does not exceed 0.17 of the weight of the cement. Equation (5) states in effect that more than 20 percent of the original mixing water can be lost by evaporation up to this point before hydration ceases entirely; for higher values of  $w_0/c$ , larger amounts can be lost. Moreover, it seems reasonable to conclude that if sufficient water were retained in the concrete to prevent complete emptying of the capillary space at the end of 7 days there would have been a satisfactory progress of hydration and development of strength in the interim, especially during the first 3 or 4 days.

### Freezing and Thawing of Cement Pastes

When the temperature of a saturated paste is continuously lowered below the normal freezing point of pure water in bulk, the evaporable water freezes progressively and a temperature of about  $-108^\circ$  F. is required to freeze all of it (23). The capillary water freezes first at temperatures down to about  $10^\circ$  F. and the gel water freezes from this point down to the minimum temperature of  $-108^\circ$  F. Thus the freezing point of the water in partially saturated pastes depends not only on the amount of dissolved substances but also on the degree of saturation; the drier the paste, the lower the freezing point of the evaporable water present. Conversely, on thawing the final melting point depends on the amount and distribution of evaporable water in the paste.

## SUMMARY AND DISCUSSION

In retrospect, the more significant facts and ideas of the foregoing discussion to be remembered in relation to the behavior of concrete pavements during the curing operation are given below. Some of these are stated specifically for the first time in the summary but may be derived directly from previous statements in the text.

First, initial differences in effects which may be produced by the use of various commonly accepted curing methods decrease with time and eventually disappear. Moisture from the subgrade and from rains and periods of high humidity brings about progressive hydration of the cement and increase in strength. Even in arid climates hydration is cumulative, since very little, if any, of the water of constitution is lost under the most extreme natural conditions to which concrete pavements may be subjected.

Second, in spite of these equalizing influences, however, initial curing by artificial means still is necessary in order to prevent surface crazing and premature cracking, and to assure adequate strengths at early ages under variable, and often adverse, weather conditions. Enough water must be maintained in the concrete during the first few days to function as a medium for the hydration reactions since the cement gel can be laid down only in water-filled capillary space. For pavement mixes it appears from a theoretical analysis that retention of about 80 percent of the original mixing water at 7 days should be sufficient to insure satisfactory progress of hydration during the 7-day curing period, and adequate strengths at the end of the period.

Third, the degree of saturation and extent of hydration determine the relative freezability of the water in the concrete. The evaporable water in a well-cured, comparatively dry concrete freezes at much lower temperatures than the water in a saturated, porous one. This fact has considerable bearing on the durability of concrete exposed to rigorous winters and on laboratory freezing and thawing tests for durability.

Fourth, the temperature-regulating function of the curing operation is a very important one. On hot days, high temperatures may be built up in the pavement slab through absorption of radiant heat. The rise in temperature due to this cause is augmented by heat liberated by the initial hydration reactions, and, for concrete poured in the morning on a hot day, final set takes place at about the time that maximum temperatures are attained in the concrete.



Fifth, the chemical composition and physical properties of the cement determine to a large extent how the behavior of the pavement slab will be influenced during the first few hours or days by the type of curing employed and the care with which the operation is carried out. Cements high in  $C_3S$ ,  $C_3A$ , and  $C_4AF$ , cements from slowly cooled clinkers, and finely ground cements hydrate more rapidly, set more quickly, and liberate more heat, especially during the first few hours, than cements of other types. The amount of gypsum added to the clinker to retard the set also greatly influences the strength and volume change characteristics of the cement. Obviously curing water is consumed more rapidly in the initial stages by cements of the first category mentioned above and such cements are able to take more advantage of the relatively high free water content of the freshly-mixed concrete. Furthermore, such cements would not be as susceptible to drying in the later stages of the curing period, and shorter curing periods would be sufficient to attain minimum strength requirements.

It is equally apparent, however, that these same cements, because of their accelerated hydration rate, aggravate all those undesirable effects associated with volume change during the early life of the pavement. More heat is built up during the first day with a resulting increase in contraction on cooling at night, and autogenous volume changes are more rapid. These disadvantages may outweigh the advantages of higher early strength and may explain why, under otherwise comparable conditions, some pavements show cracking at a comparatively early age and others do not.

\* \* \*

There has been an increasing tendency in the more recent investigations to place greater emphasis on the role that curing plays in the control of volume changes during the early hardening period (15, 28). At this stage, when strength is lowest, many phenomena occur within the concrete which tend to produce volume changes of varying direction and magnitude. At the same time, hydration is proceeding and strength and elastic modulus are developing at different rates at the top and bottom of the slab due to the temperature gradient. Stresses induced by these processes, if not properly controlled, can cause cracking at a very early age.

Sufficient quantitative data upon which to base an evaluation of the effect of curing conditions on the above-mentioned processes are

at present lacking. A considerable portion of the experimental work about to be described has been devoted to the study of this phase of the curing problem.

## LABORATORY STUDIES

For reasons apparent from the preceding discussion, experimental work in the laboratory was confined to a study of the physical properties and behavior of the concrete during the first 7 days only, with particular attention to those changes occurring during the first 24 hours after mixing. The major portion of the laboratory work consisted of two studies: the first to determine the effect of change in moisture condition at several different temperature levels on volume changes and the rate of development of strength and elastic modulus; the second to afford a direct comparison of the membrane method with a standard wet method of curing with respect to warping, or curling, of concrete slabs under radiant heat.

## CABINET TESTS

### Description of Tests

By storing concrete specimens at three different temperatures in air maintained at three different humidities and in water, a series of moisture contents and corresponding values of strength, elastic modulus, and length were obtained at successive ages from 8 hours to 7 days. Temperatures of 75°, 100° and 120° F. were selected because it was desired to study particularly the behavior of concrete in the summer temperature range. At each of these temperatures a separate group of specimens was stored in water and in air maintained as nearly as possible at relative humidities of 10, 50 and 100 percent. The only significant deviation from these nominal values was at the 75-degree temperature where the minimum humidity attainable with the apparatus was 30 percent.

For each temperature and relative humidity still further differentiation of moisture content was obtained by coating two groups of each series of specimens with a commercial membrane curing compound at coverage rates of 200 and 100 square feet per gallon, respectively. The use of membrane coatings in this instance was prompted solely by the desire to secure a more uniform distribution of moisture within the specimens at different moisture contents, and it must be strongly emphasized that, because of the conditions of

application and storage, these experiments do not in any sense constitute a water-retention test of the curing material employed.

Possibly the most unusual feature of the tests is the early age at which measurements of the hardened concrete were begun. Originally the testing schedule called for the removal of specimens from the molds and taking of initial measurements 6 hours after mixing, followed by successive measurements at 6-hour intervals through the first 24 hours. Although this procedure had been followed in previous experiments of a similar nature and is entirely feasible, the demands of the continuing schedule made it advisable to alter the procedure so that measurements were taken at 8, 16 and 24 hours, and 2, 3 and 7 days from the time of mixing.

Because of the large number of specimens involved, more than 1000 in all, 3- by 3- by 15-inch beams were used for the determination of flexural strength, elastic modulus, and length, and 3- by 6-inch cylinders for compressive strength tests. Triplicate specimens were molded for each test, making a total of 54 for each condition of storage. Thus, for a given temperature and humidity, 18 beams and 18 cylinders comprising one specimen for each of the six ages and three rates of coverage were molded on the first day, and the same procedure repeated on two succeeding days to give three replica specimens for each test. Specimens to be water-cured at each temperature were cast separately and one extra specimen for specific gravity determination and three with thermocouples embedded in the center to determine temperatures at the time of test also were molded each day.

Air-entraining concrete of 3- to 4-inch slump was used exclusively, the desired air content of 3 to 6 percent being obtained with few exceptions by the addition of 0.01 percent of neutralized Vinsol resin by weight of the cement. The mix was designed on the basis of a cement factor of 5.5 bags per cubic yard of concrete, using the mortar voids method of proportioning. A local brand of Type I cement and natural sand and gravel of 1-inch maximum size, all meeting Michigan State Highway Department specifications, were used in the mix. Details of materials, mix proportions and the procedure followed in making, storing and testing the specimens may be found in the APPENDIX.

Immediately after finishing, all specimens except those to be water-cured were weighed and placed on racks in a walk-in cabinet main-

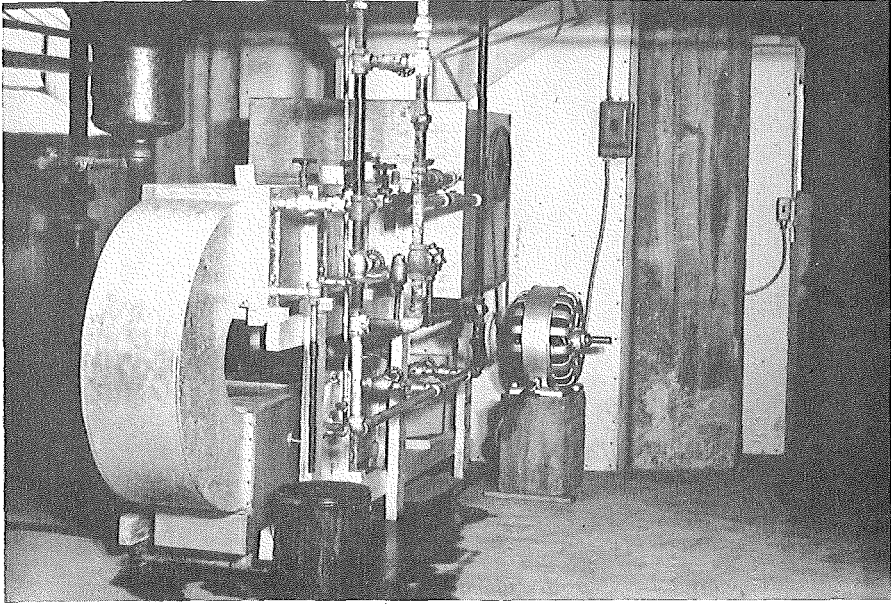


Fig. 2. Air-conditioning unit and storage cabinet (in background) for concrete specimens.

tained at the specified temperature and humidity. The air of the cabinet was conditioned by continuous circulation through an external train of heating coils, cooling coils, and water spray connected to vents near the ceiling and floor of the cabinet. Conditioned air was introduced at the top and withdrawn from the bottom; in this way it was possible to provide a uniform vertical flow at all points of the horizontal section by a series of baffles and vents suitably arranged near the ceiling just below the point of entrance of the air. Relative humidity was maintained within  $\pm 5$  percent and temperature within  $\pm 2^\circ$  F. of the nominal values. A photograph of the cabinet showing the air-conditioning train and blower is reproduced in Fig. 2.

Specimens to be cured in water were covered with wet burlap at room temperature for the first 8 hours, then stripped, measured and placed in water at the specified temperature for the balance of the test period.

Measurements were made on all beams remaining at each age just before breaking the test beams, so that moisture, length, and dynamic modulus values represent the average of 18 specimens at 8 hours, 15 specimens at 16 hours, 12 at 24 hours, and so on. Length was

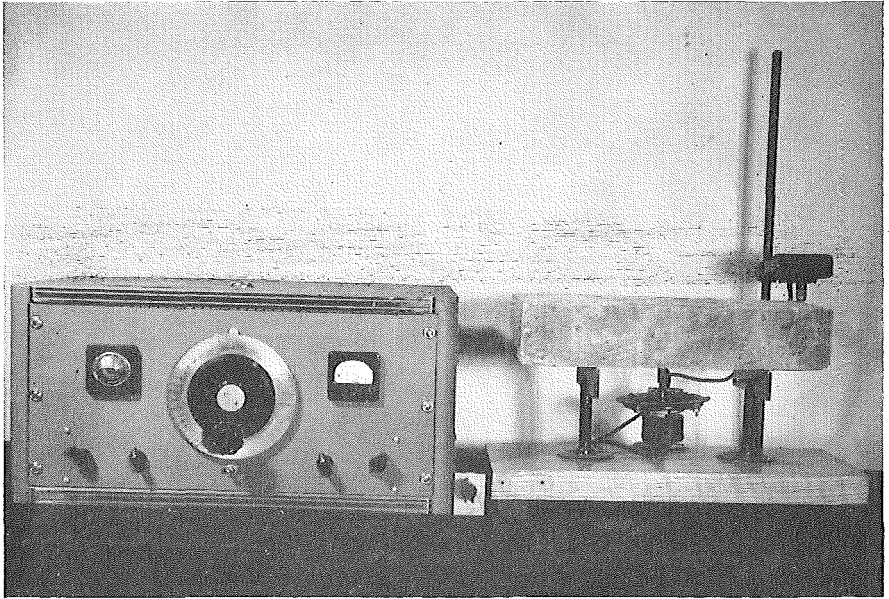


Fig. 3. Sonic apparatus used in determining dynamic modulus of elasticity.

measured by an autoclave comparator which had been extended to accommodate a 15-inch beam, and dynamic modulus of elasticity by the sonic apparatus shown in Fig. 3. Flexural strengths were determined by the third point method of loading using a 12-inch span.

It was not possible to use conventional methods of capping the concrete cylinders for compressive strength tests because of time limitations at the early ages involved. Pieces of  $\frac{1}{8}$ -inch rubber gasket material were placed on the top and bottom surfaces of the cylinders in lieu of plaster of paris or neat cement caps. A series of preliminary tests showed that this procedure resulted in a reduction of the indicated strength of about 20 percent at 7 days, but gave a better concordance between replica specimens than the plaster of paris method of capping.

All beams and cylinders were tested in the condition existing at the time with respect to both temperature and moisture, no effort being made to obtain a uniform moisture content by saturation prior to test. From previous observation it appeared that little was to be gained in consistency of results by presaturation and it was desired to determine the characteristics of the concrete at the time and under the conditions specified.

3- by 3- by 15-in. beams

Curing conditions			8 Hours				16 Hours				24 Hours				2 Days				3 Days				7 Days			
Temp. °F.	Rel. Hum. %	Seal sq. ft. per gal.	Moist. loss %	Dyn. Mod. 10 <sup>6</sup> psi	Flex. Str. psi	Moist. loss %	Length change %	Dyn. Mod. 10 <sup>6</sup> psi	Flex. Str. psi	Moist. loss %	Length change %	Dyn. Mod. 10 <sup>6</sup> psi	Flex. Str. psi	Moist. loss %	Length change %	Dyn. Mod. 10 <sup>6</sup> psi	Flex. Str. psi	Moist. loss %	Length change %	Dyn. Mod. 10 <sup>6</sup> psi	Flex. Str. psi	Moist. loss %	Length change %	Dyn. Mod. 10 <sup>6</sup> psi	Flex. Str. psi	
75	30	0	12.1	.27	7	28.6	-.007	1.58	59	49.7	-.009	3.42	146	58.0	-.013	4.28	191	60.5	-.014	4.42	185	65.2	-.024	4.25	248	
		200	10.0	.35	12	14.3	+.002	2.39	117	19.7	-.002	4.28	257	24.7	-.004	5.50	393	27.1	-.005	6.51	421	34.5	-.010	7.33	430	
		100	11.5	.29	14	14.7	+.008	2.59	114	17.2	+.004	4.34	275	20.3	+.006	6.04	423	22.7	+.008	6.44	569	27.9	-.001	7.47	512	
	50	0	10.1	.56	21	30.3	+.002	1.91	104	43.3	+.001	3.15	153	49.1	-.003	4.15	239	51.2	-.006	4.26	224	55.0	-.013	4.63	299	
		200	6.6	.42	25	14.8	+.005	2.36	154	21.2	+.005	4.09	252	27.4	+.003	5.33	337	29.9	+.002	5.62	418	37.0	-.006	5.84	557	
		100	6.8	.42	29	12.8	+.005	2.47	170	14.9	+.005	4.32	309	17.5	+.003	5.43	465	19.6	-.001	6.13	503	24.7	-.003	6.32	568	
	95	0	8.7	.35	22	13.6	.000	2.43	116	17.9	+.001	4.58	276	22.3	+.001	6.03	407	24.2	.000	6.82	395	28.9	.000	7.40	420	
		200	8.2	.35	22	12.6	+.004	2.58	120	14.5	+.003	5.32	331	16.1	+.004	6.20	442	17.2	+.005	6.80	456	20.2	+.004	7.33	552	
		100	7.5	.38	21	11.8	+.003	2.62	150	12.8	+.002	5.26	346	14.1	+.003	6.10	406	14.8	+.005	6.77	495	18.3	+.002	7.18	638	
in water*	0	11.3	.47	16	11.3	+.008	2.47	127	11.0	+.015	4.09	250	9.3	+.011	5.81	427	8.5	+.013	6.24	532	6.7	+.014	7.52	757		
100	14	0	18.5	.96	60	50.0	+.001	2.71	150	58.5	-.006	3.01	156	63.8	-.014	3.65	187	66.5	-.015	3.81	218	71.6	-.023	3.92	243	
		200	8.3	1.30	74	24.0	+.002	3.62	250	35.8	-.002	4.32	275	43.5	-.007	5.15	323	49.0	-.011	5.13	320	57.0	-.023	5.12	373	
		100	8.3	.87	63	17.3	+.006	4.22	266	27.8	+.002	4.50	330	34.8	-.002	5.58	419	38.7	-.005	5.48	401	49.3	-.018	5.60	412	
	50	0	13.4	1.47	76	36.6	-.003	2.93	220	45.4	-.005	3.71	302	51.6	-.009	4.28	310	54.1	-.006	4.24	310	58.5	-.016	4.27	351	
		200	9.7	1.85	88	20.1	-.001	3.48	321	26.3	-.005	4.48	429	35.0	-.008	5.41	459	37.8	-.010	5.58	433	45.9	-.018	5.47	456	
		100	9.6	1.75	95	16.3	+.003	4.06	274	19.8	+.001	4.57	399	25.8	.000	5.35	536	28.2	-.001	5.73	478	36.2	-.009	5.65	551	
	95	0	9.9	1.88	66	16.8	+.007	4.53	269	21.0	+.001	5.34	344	24.4	+.001	6.28	377	26.6	-.001	6.62	429	31.5	-.005	6.77	467	
		200	6.8	1.75	94	11.7	+.005	4.53	321	13.6	+.003	5.37	421	16.4	+.003	6.49	475	18.3	+.001	6.82	486	22.9	-.002	7.08	579	
		100	7.3	1.84	80	11.9	+.003	4.35	293	13.1	+.003	5.34	343	14.6	+.002	6.43	526	16.0	+.002	7.14	557	19.5	-.005	7.26	572	
in water*	0	7.2	.50	20	6.9	+.009	3.46	177	5.9	+.009	4.63	294	5.1	+.012	6.08	467	3.6	+.010	6.81	462	0.0	+.007	7.53	581		
120	10	0	22.0	1.59	90	52.1	-.002	3.14	163	62.3	-.007	3.44	176	69.0	-.012	3.83	230	68.3	-.017	3.68	259	71.7	-.023	3.67	280	
		200	8.9	1.90	102	28.4	-.001	3.85	205	40.4	-.006	4.74	292	49.6	-.012	4.98	293	56.4	-.019	4.94	328	63.7	-.025	4.33	438	
		100	8.4	1.58	100	23.4	+.006	3.88	260	32.1	+.004	4.98	316	41.0	-.001	5.62	332	46.5	-.008	5.66	360	52.8	-.013	5.79	430	
	50	0	17.1	2.37	136	40.6	-.004	3.99	227	47.4	-.008	4.18	247	54.0	-.012	4.23	267	56.7	-.015	4.24	277	62.7	-.022	4.30	302	
		200	8.5	2.77	156	22.9	-.006	4.51	315	30.3	-.010	4.96	347	39.1	-.014	5.07	349	43.3	-.017	5.01	352	53.2	-.021	4.85	390	
		100	8.0	3.05	130	18.1	-.004	4.38	335	23.7	-.007	5.03	400	31.0	-.011	5.37	360	34.9	-.014	5.34	378	44.7	-.021	5.24	381	
	95	0	10.3	2.68	138	18.4	-.001	4.60	246	23.9	-.003	5.28	310	29.3	-.004	5.75	381	32.1	-.005	5.90	355	34.4	-.010	6.12	459	
		200	7.1	2.50	150	14.1	+.001	4.63	269	17.9	+.001	5.33	332	21.8	-.002	6.24	386	24.6	-.006	6.43	444	28.7	-.013	6.82	493	
		100	6.6	2.53	131	12.5	+.003	4.62	283	15.1	+.002	5.43	347	18.2	-.002	6.09	461	19.7	-.001	6.40	487	23.1	-.006	6.78	551	
in water*	0	9.8	.34	24	9.2	-.001	4.93	209	9.1	+.005	5.99	362	8.9	+.005	6.99	439	8.5	+.003	7.07	509	7.0	+.006	7.53	633		

\*All water-cured specimens covered with wet burlap at room temperature during the first 8 hours.

TABLE 2—Summary of cabinet storage data  
3- by 6-in. cylinders

Curing conditions			8 Hours		16 Hours		24 Hours		2 Days		3 Days		7 Days	
Temperature °F.	Rel. Hum. %	Seal sq. ft. per gal.	Comp. Str. psi	Moist. loss %	Comp. Str. psi	Moist. loss %	Comp. Str. psi	Moist. loss %	Comp. Str. psi	Moist. loss %	Comp. Str. psi	Moist. loss %	Comp. Str. psi	Moist. loss %
75	30	0	39	15.8	174	52.5	438	63.2	548	66.8	626	68.6	903	71.7
		200	34	14.1	326	19.8	1170	24.8	1329	31.4	1805	33.5	2005	41.4
		100	37	14.7	428	17.5	965	20.5	1715	23.6	1805	25.9	2845	33.1
	50	0	78	18.7	326	48.8	580	57.0	749	60.6	803	61.1	994	63.6
		200	110	13.6	470	22.3	867	29.2	1266	34.4	1347	36.2	1778	41.1
		100	110	13.2	481	20.3	941	23.4	1486	27.2	1601	29.9	1920	34.3
	95	0	82	16.1	448	28.5	915	34.7	1119	37.2	1257	39.1	1636	42.3
		200	97	14.4	501	21.7	1092	24.2	1802	25.5	1845	26.7	2006	30.0
		100	90	14.2	597	18.7	1112	20.2	1552	20.3	2000	21.1	2175	23.7
	In water*	0	21	13.5	367	14.5	892	14.3	1330	13.6	1767	13.3	2130	10.9
100	14	0	261	21.4	467	60.7	651	65.9	641	72.3	705	73.4	726	77.1
		200	264	15.1	530	37.5	900	50.3	1145	57.8	1116	62.5	1154	70.8
		100	248	14.1	720	17.4	974	43.6	1287	51.2	1197	57.7	1463	68.3
	50	0	375	18.8	596	43.2	686	51.3	868	57.6	838	60.3	885	64.7
		200	561	15.1	725	27.7	994	35.3	1178	44.5	1170	47.1	1362	55.5
		100	467	15.1	835	23.5	1188	26.9	1189	32.8	1518	37.0	1873	45.3
	95	0	291	17.0	752	28.6	995	34.8	1165	38.0	1315	40.9	1553	44.7
		200	338	12.8	1040	20.7	1136	22.3	1554	25.3	1586	27.0	1827	30.6
		100	329	12.4	870	18.1	1345	19.2	1698	20.7	1823	21.7	2150	25.6
	In water*	0	29	12.1	517	11.9	863	11.4	1575	10.7	1797	9.9	2114	6.6
120	10	0	391	20.8	615	57.2	702	64.3	810	71.1	836	75.6	897	77.0
		200	494	13.4	728	47.3	1055	56.4	1057	64.5	1114	70.7	1134	75.6
		100	506	14.2	1006	36.9	1227	45.4	1302	50.8	1336	62.8	1459	70.6
	50	0	597	19.9	869	43.2	859	48.9	977	54.8	1053	57.3	1183	63.8
		200	830	12.4	973	28.6	1239	36.0	1508	41.5	1633	45.7	1793	54.8
		100	789	12.7	1128	20.8	1428	26.6	1760	31.8	1947	35.8	1913	44.3
	95	0	544	17.4	806	35.1	980	37.2	1174	41.4	1240	44.6	1305	49.2
		200	793	11.5	1055	23.3	1555	27.1	1780	32.1	1860	34.1	2105	39.5
		100	657	11.6	1104	21.6	1330	22.9	1730	25.4	2070	28.0	2100	32.8
	In water*	0	31	14.8	852	15.7	1200	14.7	1467	14.8	2011	14.7	1915	14.9

\*All water-cured specimens covered with wet burlap at room temperature during the first 8 hours.

## Discussion

As pointed out previously, the purpose of this group of tests was to obtain quantitative data on the behavior of air-entraining concrete under a variety of conditions regardless of curing method. Such data make possible an approximate evaluation of the effect of different curing methods on the basis of the particular set of conditions produced by each. Thus the several groups of specimens can be considered to represent elements of a concrete slab existing in a comparable state at different depths below the surface on a summer day.

The results of the cabinet study are presented in Tables 1 and 2 and the graphs of Figs. 4, 5 and 6. In these figures,  $p/p_s$  has the same significance as formerly and is equivalent to relative humidity. It will be seen at once that moisture losses at 7 days in most cases exceeded 20 percent of the original mixing water due to high initial losses before applying the membrane and to the high surface-mass ratio of the specimens. In most instances curing under water from 8 hours onward to 7 days was not sufficient to restore all of the moisture lost during the setting and hardening period prior to immersion. These factors limit somewhat the utilization of all the data, little information having been gained on the moisture-strength relationship in the region of 80 to 100 percent moisture retention at 7 days.

Even at the relatively large moisture losses observed, it can be seen from the graphs that the strength and modulus of elasticity of the concrete were not adversely affected to any appreciable extent until moisture losses of 20 to 25 percent were exceeded. This fact is particularly evident from a comparison of the graphs for 0.95  $p/p_s$  with those for water storage at the three temperatures and tends to confirm the deductions based on the theoretical analysis developed previously (page 13).

Length changes of beams cured in the cabinet were somewhat erratic, which was probably due in part to the non-uniform distribution of moisture within the specimens, and to possible differences in the temperature of individual beams at the time of measurement, especially at early ages. It was obviously impracticable to measure the temperature of each beam individually, and variable rates of hydration and moisture evaporation exert heating and cooling effects which tend to unbalance temperature equilibria from moment to moment. The data in Table 1 do show quite generally, however, that shrinkage from the 8-hour length did not occur at any age or tem-



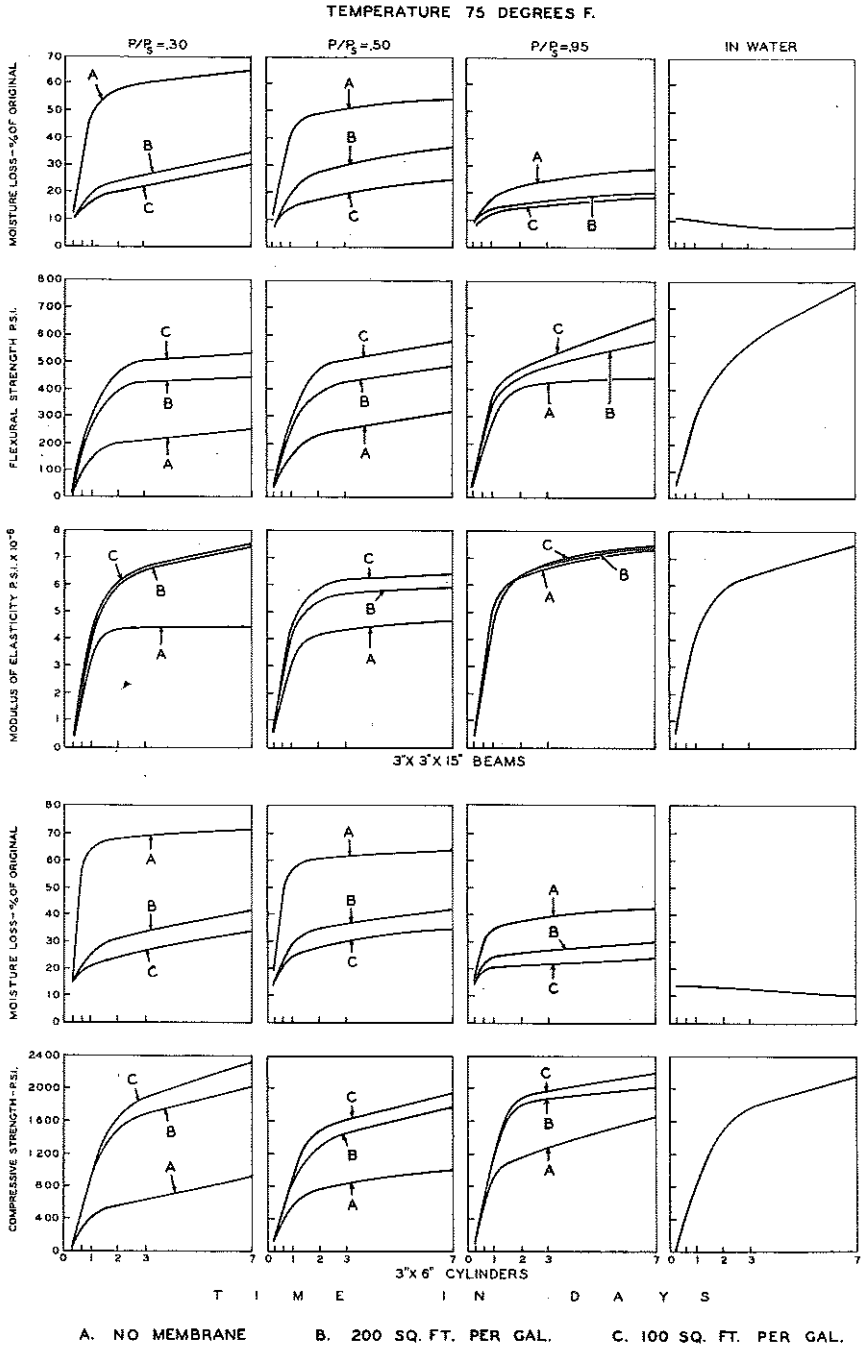


Fig. 4. Moisture loss and physical properties of concrete at 75° F.

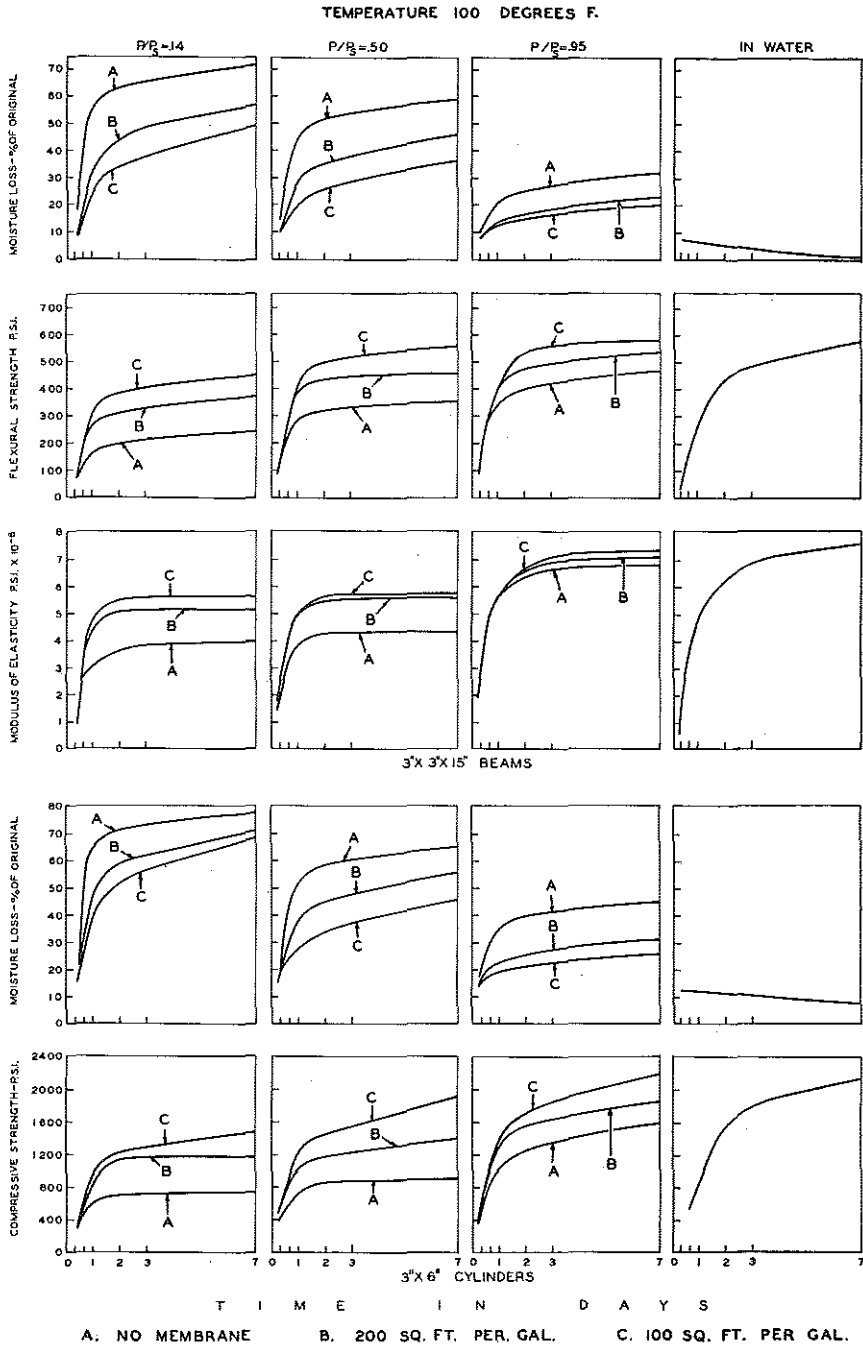


Fig. 5. Moisture loss and physical properties of concrete at 100° F.

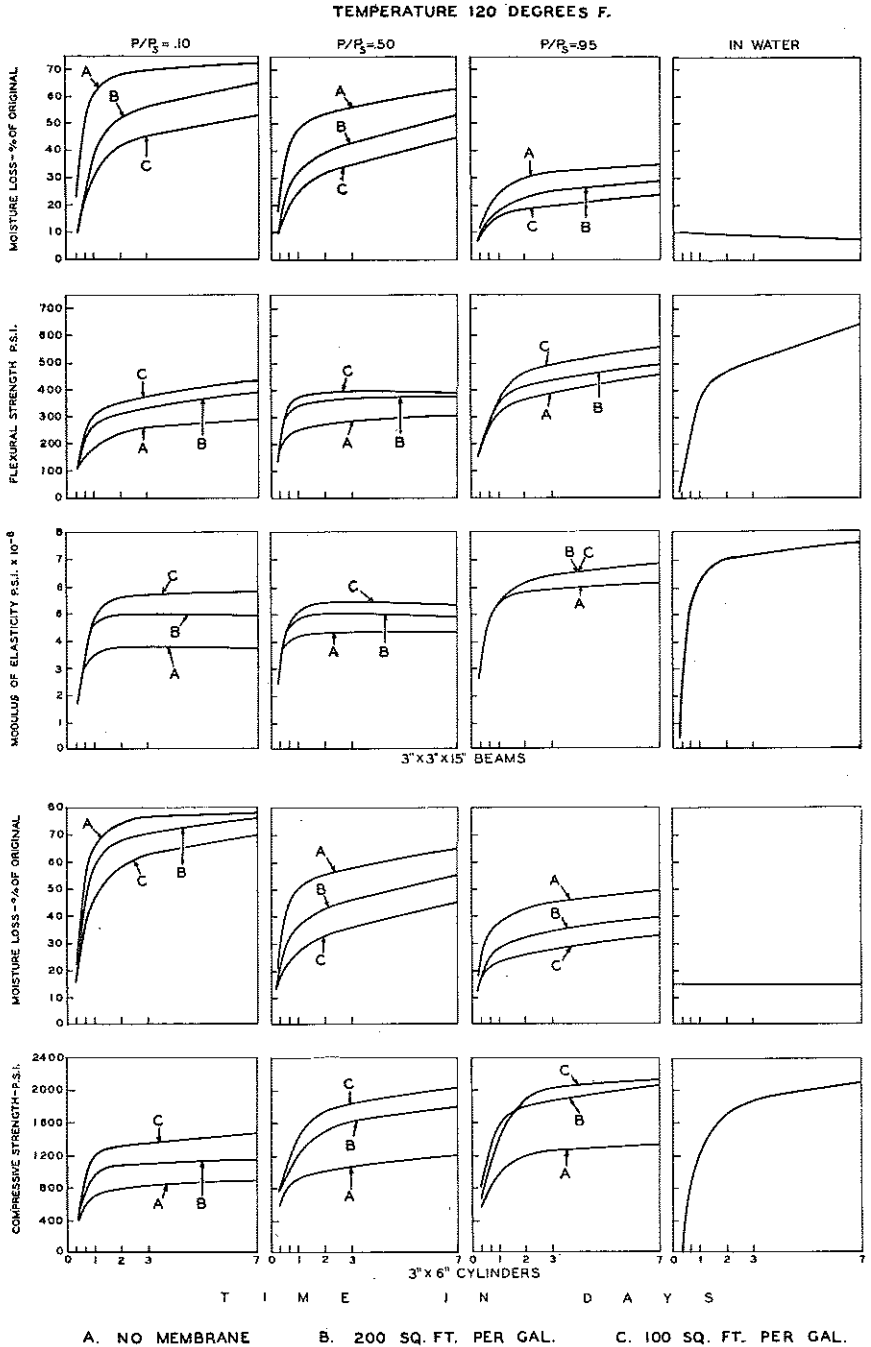


Fig. 6. Moisture loss and physical properties of concrete at 120° F.

perature of the test when moisture losses remained below about 20 percent; conversely, moisture losses in excess of 20 percent usually, but not always, resulted in a net contraction.

The curves for moisture loss, flexural and compressive strength, and modulus of elasticity present a similarity of form. The rise is very rapid during the first day, especially the first 16 hours, and is accelerated by higher temperatures. At the lower humidities maximum flexural strength and dynamic modulus are attained quickly at a low level due to rapid drying but very little increase takes place after 3 days; at the higher temperatures there is little gain after 36 hours. Rapid drying is sharply reflected in the prematurely stunted development of strength and elasticity, indicating virtual cessation of hydration at an early age.

Specimens stored in water and at 0.95  $p/p_s$  exhibited a more regular gain and better concordance, and reached higher 7-day strengths than the others, better concordance probably being due to a more uniform distribution of moisture within the specimens at all ages. At 120° F. more moisture was lost at the same relative humidities than at 75° F. and, in general, early strengths were higher and 7-day strengths were lower.

It is quite apparent from the foregoing that unrestricted evaporation can result in rapid and excessive moisture losses with attendant shrinkage and serious retardation of strength development during the first 7 days. This fact again emphasizes the importance of early application of the curing material in order to minimize shrinkage and assure adequate early strength, even though the effect of the curing operation diminishes and disappears at later ages.

### Incidental Drying Tests

In order to gain some idea as to the depth of layer furnishing evaporable moisture, a few exploratory drying tests were run on mortar specimens, using a procedure similar to the ASTM water retention test for curing materials, except that no curing material was applied and specimens of three different thicknesses were used. Thicknesses of  $\frac{1}{2}$  inch, 1 inch and  $1\frac{1}{2}$  inches were obtained by first filling the standard 2 $\frac{1}{8}$ - by 6- by 12-inch pans to the required height with dummy mortar which was allowed to dry out in the laboratory air, after which the entire surface was sealed with asphalt cement and the pans filled to within  $\frac{1}{8}$  inch of the top with natural sand mortar having a flow

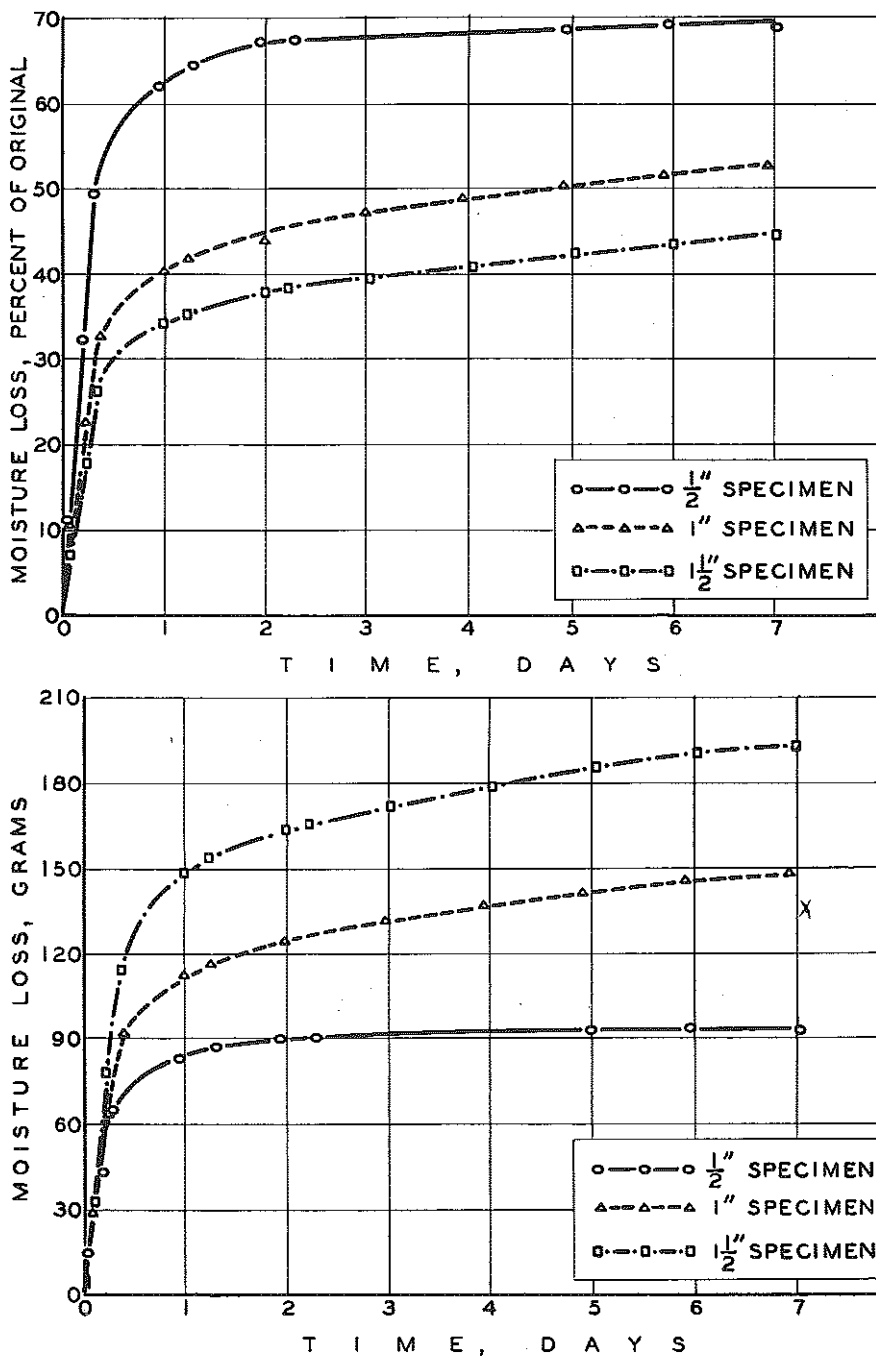


Fig. 7. Effect of specimen thickness on evaporation of moisture from air-cured mortar at 100° F. and 33-percent relative humidity

of 50 percent and  $w/c$  of 0.40 by weight. Specimens were molded in triplicate and placed in a cabinet with air at 100° F. and 33-percent relative humidity circulating horizontally across the surface of the mortar.

Drying curves for the three groups of specimens are shown in Fig. 7, in which moisture losses are represented both in grams and as percentages of original mixing water. Although the data are extremely limited, some general conclusions of interest may be drawn from them. First, the order of the curves is reversed in the two sets of graphs. The thinnest specimens lost the least total amount of water, but this total represented nearly 70 percent of the original amount present and was dissipated almost entirely at 36 hours. Second, water was drawn from depths in excess of 1 inch by evaporation during the first 24 hours but from about 36 hours to 7 days the rates of evaporation were nearly constant and equal for the two thicker specimens. This indicates that the rate of evaporation had become approximately equal to the rate of upward diffusion of moisture within the mortar (constant evaporation rate), and that the plane of evaporation had receded to about the same depth below the surface for both the 1-inch and the 1½-inch specimens (equal evaporation rate).

The above conclusions were apparently confirmed by an examination of the specimens at the end of the test. The mortar blocks were removed from the pans, broken transversely, and the freshly-exposed surfaces sprayed immediately with a solution of phenolphthalein in absolute alcohol. The ½-inch specimens gave only a faintly discernible indication of color throughout their depth, showing lack of sufficient active moisture to carry the hydroxyl ion, while both the 1-inch and 1½-inch specimens showed a colorless, dehydrated band at the surface varying in thickness from about 1/8 to 3/16 inch, with the characteristic deep basic color of the indicator underneath this band extending to the bottom.

These experiments demonstrate two facts of practical importance. The first is that when curing is either inefficient or absent, nearly all of the water lost from a concrete pavement by evaporation on a summer day probably comes from a depth of not more than 2 inches and the wearing surface is almost completely desiccated at the existing temperature. The second has to do with laboratory tests for water retention of curing materials, and is that the thicknesses of specimens used in such tests should be at least 1½ inches when the moisture loss is computed on the basis of surface area only. The effect of

specimen thickness on moisture loss is less the more efficient the curing and the shorter the test period. It is obvious from the curves of Fig. 7 that the use of thinner specimens in the water retention test imposes severer restrictions on curing materials when the maximum permissible moisture loss is specified on a percentage basis rather than unit area of evaporating surface.

## WARPING TESTS

### Description of Tests

The principal object of this series of experiments was to measure the warping of 8- by 12- by 84-inch concrete beams cured by clear membrane, white membrane, and wet burlap when exposed to radiant heat on the top surface only. Four series of three beams each were cast: Series 1, 2, and 3, to compare the three curing materials mentioned above on waterproofed, dry sand, and saturated sand subbases respectively; and Series 4 on a saturated sand subbase, to compare clear membrane, no curing, and dry burlap over clear membrane, dry burlap being added in the latter case for the sole purpose of heat insulation.

For Series 1 the waterproofed subgrade was obtained by lining the wooden forms completely with a box made of asphalt-backed paper coated on the inside with a mixture of asphalt cement and slow-curing road oil so that when the forms were loosened the paper and seal would adhere to all surfaces of the concrete except the top, thus reducing moisture losses through these surfaces to a minimum.

Forms for Series 2, 3 and 4 had similar liners except that the bottoms in each case were left open to the subgrade. The subgrade consisted of a natural sand conforming to specifications for fine aggregate for concrete and was contained in wooden forms also having a waterproof lining of heavy paper and soft asphalt. The sand was air-dry for the first two series, and kept saturated by maintaining a water table within the range of capillary rise for the last two.

Thermocouples and corresponding Bouyoucos moisture cells were installed at the top, middle and bottom of the midsections of the beam. End studs for measuring length changes at the top and bottom of each beam were flat and provided with V-blocks to locate the measuring bar.

Warping measurements were made with a 40-inch clinometer fitted with transverse and longitudinal spirit levels, and a micrometer screw

graduated in hundredths of a millimeter at one end which permitted readings to 0.0004 inch. Differences in elevation of the center and ends of the beam were determined by placing the points of the clinometer on metal inserts located along the longitudinal centerline of the top surface. The two end inserts were sections of brass rod, plane on the ends, with small holes drilled at the center to locate the cone-shaped points of the clinometer, and the center insert had a milled slot across its upper face, lengthwise of the beam, to allow for slight changes in gage length.

An attempt was made to measure length changes at the top and bottom of each beam by means of a caliper arrangement without the use of external references, but proved unsuccessful. End posts equipped with contacts and V-blocks were then installed about 2 feet from the ends of the beams from which to measure differences in length, but the results obtained with this method were also somewhat inconsistent.

A light bank of incandescent bulbs with reflectors was hung from pulleys on a framework so that the height was readily adjustable to obtain an intensity of radiant heat sufficient to produce a maximum temperature of 120° to 130° F. in the top surfaces of beams cured

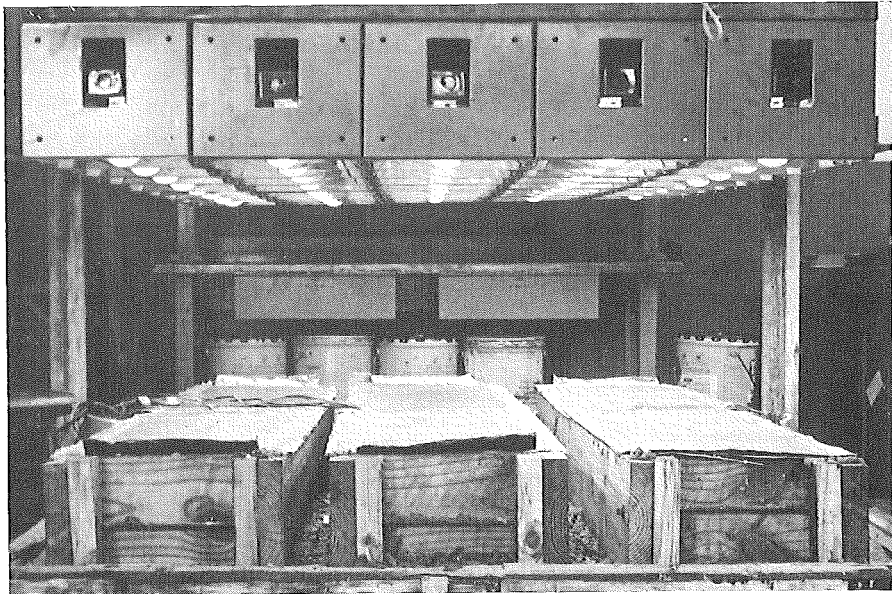


Fig. 8. View of beams used for warping tests on waterproofed subgrade showing arrangement of lights to produce daytime heating effects.



TABLE 3—*Properties of concrete used in warping tests*

Series No.	Slump, inches	Entrained air, percent	Seven-day Comp. strength, psi
1.....	5 $\frac{1}{4}$	5.7	3165
2.....	6 $\frac{3}{4}$	6.1	3040
3.....	5 $\frac{3}{4}$	7.0	3140
4.....	4 $\frac{3}{4}$	4.5	3320

with clear membrane. A complete installation with lights on is shown in Fig. 8.

Concrete for the beams was transit-mixed and proportioned in the ratio 1:2.3:4.0 by weight using air-entraining cement, natural sand, and gravel of 1½-inch maximum size. The nominal cement content was 5.5 bags per cubic yard of concrete and the water-cement ratio 0.45 by weight or 5.12 gallons per bag. Table 3 gives the properties of the concrete for the four series.

After finishing, normally about 8:00 a.m., the light bank was turned on, its height properly adjusted, and temperature and moisture cell readings taken immediately. When the surface moisture had disappeared, the two outside beams of Series 1, 2 and 3 were sprayed with white and clear membranes respectively at the rate of 200 square feet per gallon and the central beam covered with saturated burlap.

Five hours after finishing, the ends of the forms were loosened and initial measurements taken. The lights were left on from 8:00 a.m. to 6:00 p.m. and temperature readings taken at 2-hour intervals throughout the first 24 hours; moisture, length and warping measurements were made at 4-hour intervals. The first day's data indicated, however, that relatively little change occurred from 1:00 a.m. to 8:00 a.m., so readings for this period were discontinued for the rest of the tests. Lights were on daily from 8:00 a.m. to 6:00 p.m., and a set of readings was always taken just before switching on or off.

At the end of 7 days the burlap was removed from the central beam in Series 1 and 2 and observations continued for 3 more days to determine the effect of similar practice in the field operation. Time did not permit a further extension of the study of post-curing effects, but additional data along these lines should prove interesting.

Upon completion of the curing period the beams were broken in the center, removed from the subgrade and the two halves tested in flexure using a centerpoint loading on a 30-inch span. Immediately after the

TABLE 4—*Flexural strength and surface dehydration of beams used in warping tests*

Series	Subgrade	Duration of curing, days	Curing treatment	Flexural strength, psi	Thickness of dehydrated layer, inches
1. . . . .	Waterproofed. . . . .	10	Clear membrane. . . . .	511	1/8
			White membrane. . . . .	528	1/16
			Wet burlap*. . . . .	690	1/16
2. . . . .	Dry sand. . . . .	10	Clear membrane. . . . .	578	1/8
			White membrane. . . . .	596	1/16
			Wet burlap*. . . . .	687	1/16
3. . . . .	Saturated sand. . . . .	7	Clear membrane. . . . .	563	1/16
			White membrane. . . . .	655	Slight
			Wet burlap. . . . .	725	Slight
4. . . . .	Saturated sand. . . . .	7	Clear membrane. . . . .	634	3/32
			Dry burlap on clear. . . . .	588	1/16
			No curing. . . . .	536	5/32

\*Wet burlap removed at the end of 7 days.

flexural tests, the surface of fracture was sprayed with phenolphthalein in absolute alcohol to determine the depth of dehydration.<sup>4</sup> Data for these tests are given in Table 4 and photographs of the beams of Series 1 are shown in Fig. 9, in which the dehydrated layer appears as a thin white line across the top of the section. This line is not nearly as well-defined in the beam cured with white membrane (Fig. 9) which indicates less surface dehydration in this beam than in the other two of the same series.

Each beam end was subjected to a wear test using the apparatus illustrated in Fig. 10. Penetration of the tool into the surface was measured by a thousandths dial mounted on the shaft of the drill press and was taken as the average of four readings at the quarter-points of the circular path. A load of 18 pounds was applied to the wearing tool by suspending a 1-pound weight from the end of the drill press arm. Data are given in Table 5, each value representing the average of 18 tests.

## Discussion

**Warping**—It is immediately evident from the time-warping curves of Figs. 11 through 14 that the beams kept continuously moist with wet burlap exhibited the smallest variation in temperature and least warping of any in the four series of tests. Beams cured with clear membrane are at the opposite extreme, while those with white mem-

<sup>4</sup>By "dehydration" is meant here the loss of evaporable water only.

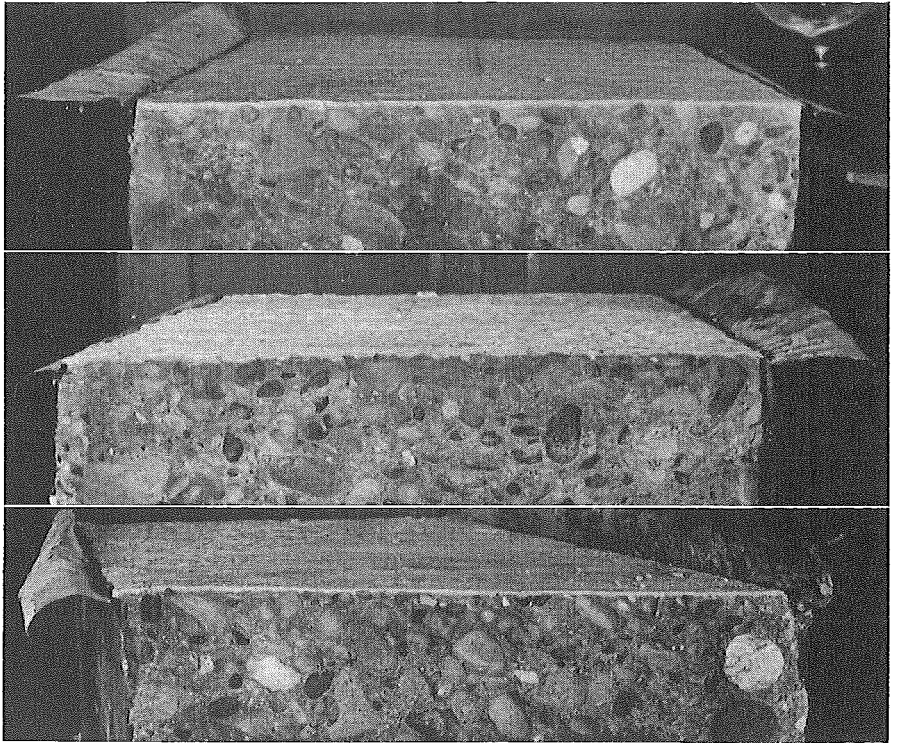


Fig. 9. Surface desiccation of beams on waterproofed subgrade. Desiccated layer appears as a thin white line across the top of the fracture.

Upper—Clear membrane, 10 days.

Middle—White membrane, 10 days.

Lower—Wet burlap 7 days, air 3 days.

brane coatings show a substantial reduction of both temperature and warping from these upper extremes. It should be pointed out here that the intention in these experiments was to compare the two types of membrane curing with an ideal method rather than with burlap curing as such. Wet curing of concrete pavements for 7 days is extremely unusual in modern practice, 3 days being the ordinary limit, and a more realistic comparison would further take into account the continuity of water supply, a very important factor in the problem.

All beams without exception exhibited a permanent upward curl almost from the moment of final set. At no time after the first 10 hours, except for a few periods of maximum surface temperature in the burlap-cured beam, of Series 1, was any beam warped concave

TABLE 5—Summary of wear tests

Curing method	Penetration, inches			
	1 min.	3 min.	5 min.	10 min.
Clear membrane.....	.032	.067	.092	.138
White membrane.....	.026	.060	.075	.123
Wet burlap.....	.025	.048	.071	.117

downward. This phenomenon can be attributed to the influence of three factors: 1) temperature gradients at the time when the concrete is passing from the plastic to the elastic state; 2) moisture gradients; and 3) differential autogenous volume change.

Temperature gradients of 15 degrees or more are established in the

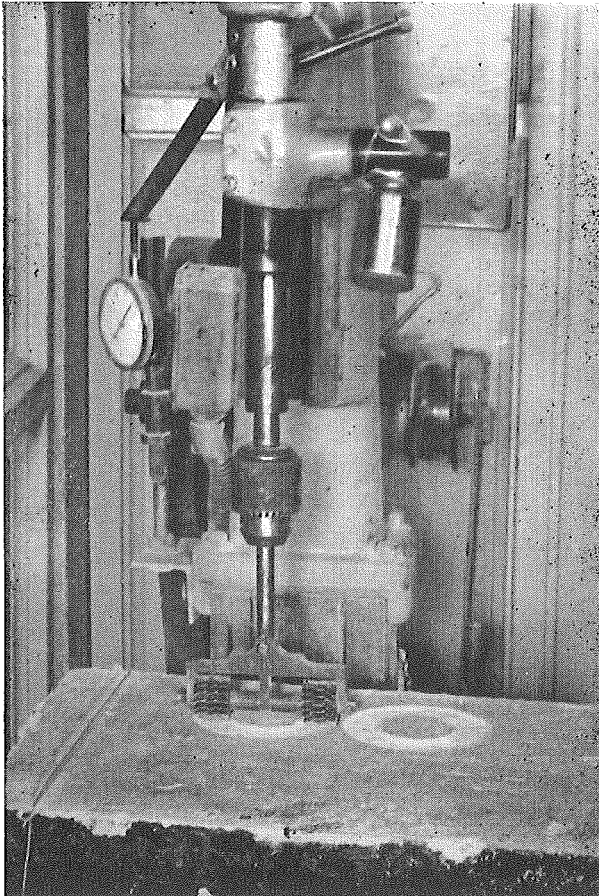


Fig. 10. Beam end being subjected to wear test.

WATERPROOFED SUBGRADE

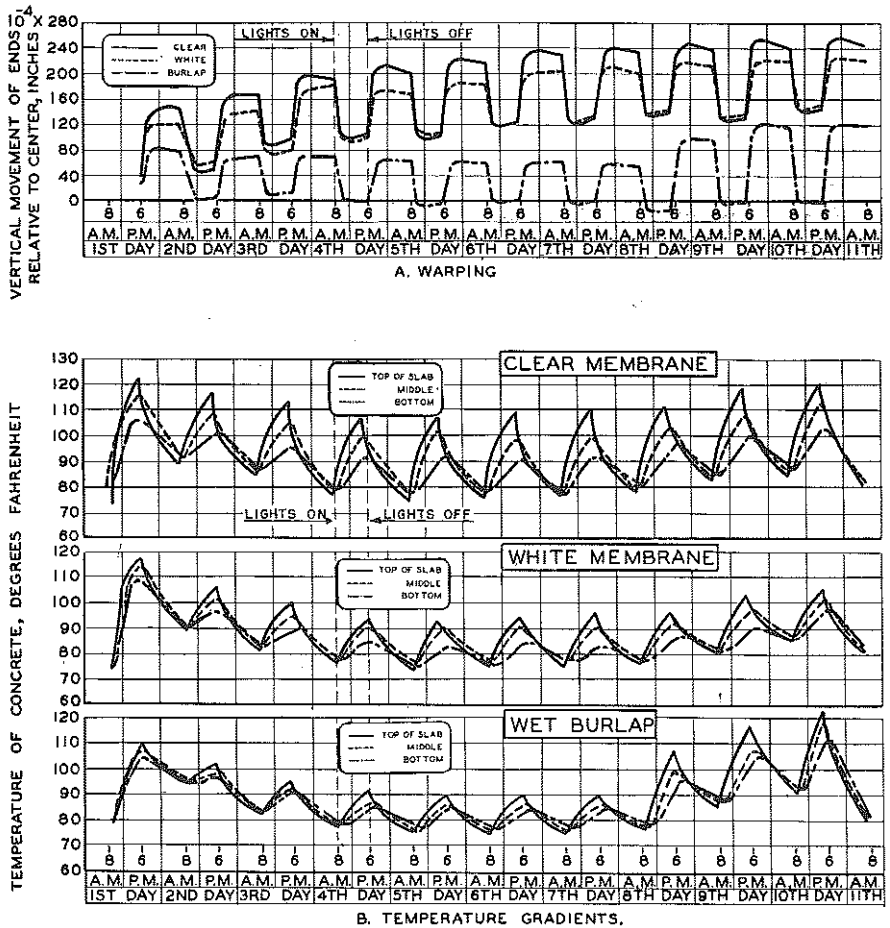


Fig. 11. Temperature gradients and warping in beams of series I.

8-inch slabs before final set takes place and produce a differential thermal volume change which occurs initially without appreciable stress because of the plasticity of the concrete in this interval. From the cabinet study data in Table 1, it may be seen that concrete at 100° F. had already attained approximately one-fourth of its 7-day modulus of elasticity at 8 hours and at 120° F. the ratio is still greater. Thus an elastic structure is being established at a time when a considerable temperature difference exists between the top and bottom of the slab, and the concrete is becoming rigid with the top layer in

an expanded condition. Any reduction of the temperature gradient from this time onward tends to produce uplifting of the beam ends.

Moisture gradients effective in producing warping are not established until after the constant-rate period of evaporation is over, which corresponds roughly to the final setting time of the cement. When the plane of evaporation falls below the surface, however, a differential drying shrinkage takes place which tends to counteract temperature effects during daylight hours, but which adds to the forces causing upward movement of the ends of the slab after the heat source is removed. The time at which these various phenomena occur is

DRY SAND SUBGRADE

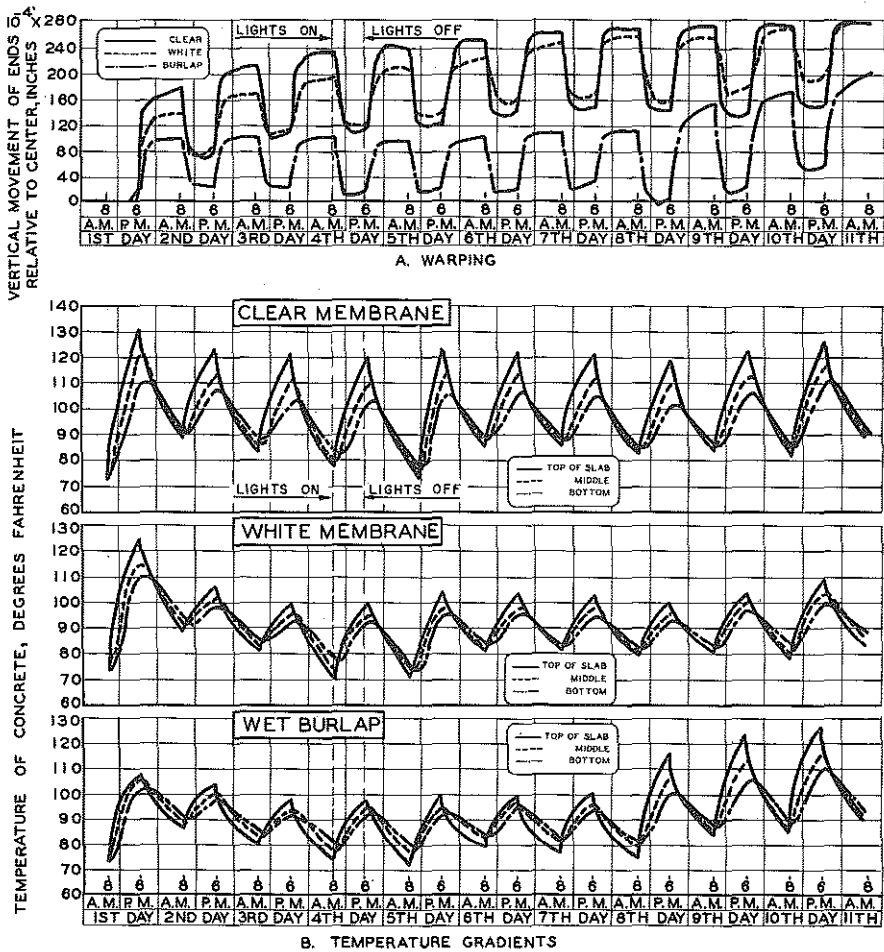


Fig. 12. Temperature gradients and warping in beams of series 2.

SATURATED SAND SUBGRADE

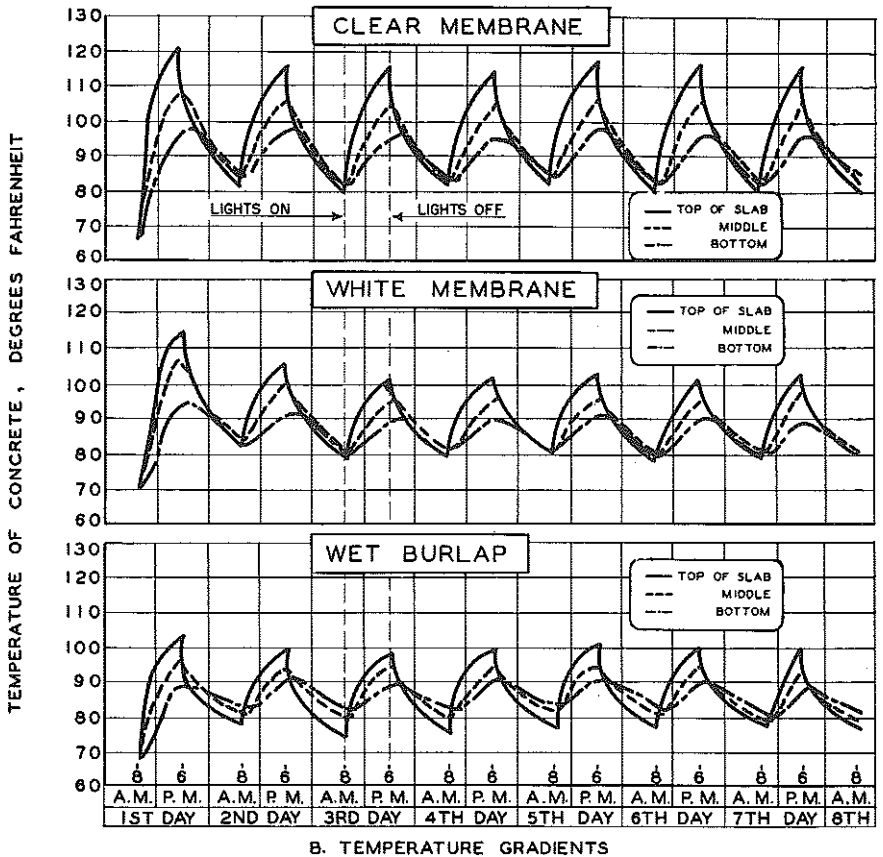
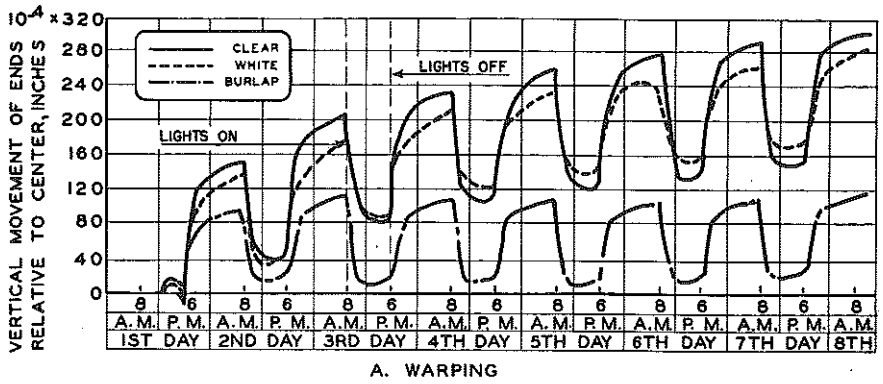


Fig. 13. Temperature gradients and warping in beams of series 3.

SATURATED SAND SUBGRADE

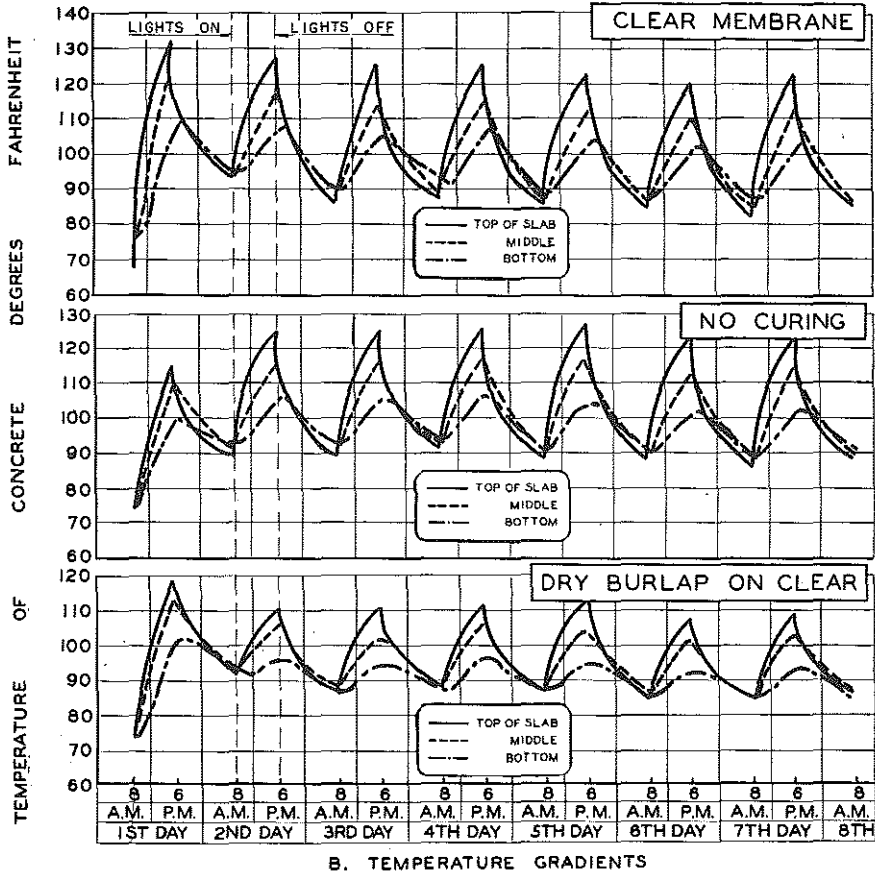
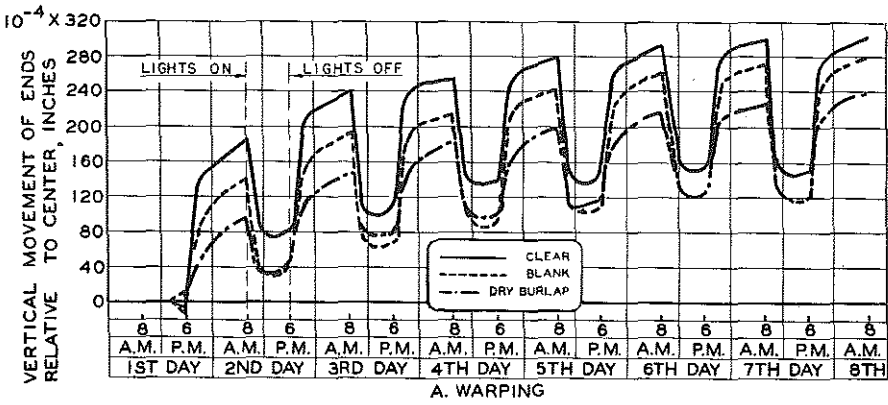


Fig. 14. Temperature gradients and warping in beams of series 4.



important, and it should be remembered that *while, in general, no significant moisture gradient exists up to the time when final set takes place, a temperature gradient very near the maximum has been built up in the interim.* Little real compensation for temperature gradients, therefore, is brought about by moisture gradients during the first day, since the concrete has already set in a heat-distorted structure before moisture effects come into play.

Evaporation of moisture does exert a direct compensatory influence on the warping of the slab, however, through its cooling effect on the surface. This is well illustrated by the warping curves of Fig. 14, which show considerably lower temperatures during the first day for the air-cured beam than for the membrane-cured one. The same graphs further serve to demonstrate that the warping pattern is pretty well established during the first few hours of exposure to radiant heat when it is observed that the end deflections of the air-cured beam remained below those of the membrane-cured one during the entire 7 days in spite of the fact that both maximum temperatures and temperature gradients attained in the former equalled after the first day and subsequently exceeded those in the latter.

The third factor to be taken into account in the interpretation of the warping data is differential autogenous shrinkage. Autogenous shrinkage is the contraction in absolute volume of the cement-water system which accompanies the hydration reactions, and has been discussed previously. Differential autogenous shrinkage may arise from two causes, 1) heterogeneity of the concrete, and 2) different rates of hydration reactions through the depth of the slab induced by temperature and moisture gradients. The effect of the latter is probably more or less transitory, although it may be significant in the early behavior of the pavement, but that of the former is permanent. Although the use of the air-entraining concrete has resulted in much better control of segregation and bleeding, the fact still remains that the surface layer of finished concrete in place is very likely to differ in important respects from the bottom, especially in cement content, porosity, and volume response to changes in temperature and moisture. It has been observed by some investigators that a residual upward curl remains in concrete slabs dried from both surfaces, even when no temperature gradient exists (5, 11). Apparently this differential volume change does not progress very far in concrete kept continuously moist from the time of finishing. Once allowed to dry,

however, the slab cannot be restored to its initial flat condition by addition of water to the top surface.

The total warping at any instant is the resultant of the effects produced by temperature gradients, moisture gradient and differential autogenous volume change. When the heat source is removed, all three factors contribute to upward movement of the slab ends.

The curves of Figs. 11 through 14 also emphasize the significance of the time of taking initial or base measurements when making observations of this kind. It is obvious that widely varying results may be obtained depending upon the particular time chosen for reference measurements. In these experiments the first readings were taken 5 to 6 hours after finishing and it is possible that curling had already begun. From the data shown it seems probable that pavement slabs poured during the morning on bright summer days could never be actually warped concave downward and would exhibit only a relative downward movement of the ends except under the most extreme conditions.

The effect of the removal of the wet burlap is shown in the curves for Series 1 and 2. As soon as the covering was removed, the temperature gradients and warping amplitudes increased greatly. The burlap-cured beam of Series 2 rapidly assumed a progressively increasing residual set but this effect was much subdued in the corresponding beam of Series 1. The type of subgrade and consistency of the concrete may have influenced the result but the data are much too limited to draw any certain conclusions in the matter.

**Temperature Control**—The importance of temperature control in regulating the forces causing warping has been amply demonstrated. The use of white-pigmented membrane in these tests brought about a significant reduction in maximum temperatures attained, amounting to about 15 degrees when compared with the temperatures of beams cured with the clear compounds. The reduction in temperature gradient is reflected in correspondingly lower deflections of the slab ends. It should be kept in mind also that lower temperatures reduce moisture losses by lowering the vapor pressure of the evaporable water in the concrete, and lower moisture losses are partially responsible for the decrease in warping.

To reduce temperatures during the curing period a dry burlap covering was applied as soon as possible to the surface of a beam (Series 4) that had been previously sprayed with clear membrane

curing compound. A temperature reduction of 15 degrees followed this practice and resulted in a 26-percent decrease in warping when compared with beams cured with clear compound only. Comparable results were obtained by the use of white-pigmented compound.

**Strength and Abrasion Resistance**—The data of Table 4 indicate that satisfactory flexural strengths exceeding current specification requirements of the Michigan State Highway Department were obtained in all cases except the two membrane-cured beams of Series I. There is no apparent explanation for the anomaly that lower strengths were developed in beams cast on a water-proofed subgrade than in those cast on a dry subgrade and cured by identical procedures. As was to be expected, the strength of wet-cured beams were consistently higher than the others, and the beneficial effect of the saturated subgrade on strength is also noticeable.

Results of the wear test presented in Table 5 show that resistance to surface abrasion was affected somewhat by the curing methods employed. The average depth of penetration of the wearing tool into the burlap-cured concrete was 17.5 percent less than in concrete cured with clear membrane and 5 percent less than in white membrane-cured beams. For concrete roads, resistance to wear is a secondary consideration, since the pavement will ordinarily succumb to the more destructive forces of traffic loads and weather long before it is worn out.

## EARLY TEMPERATURE AND WARPING STRESSES

No attempt will be made here to develop a detailed analysis of stresses in concrete pavements, but it does seem worthwhile to indicate briefly the nature and magnitude of the forces acting on the slab during the critical early period, and its ability to resist such forces. Knowledge of this phase of the problem will provide the basis for an estimation of the degree of temperature and moisture control necessary to prevent premature cracking. The only stresses considered in the following discussion will be direct tensile stresses induced by restraint of overall length change of the slab due to change in uniform temperature, and bending stresses resulting from warping.

### SUBGRADE FRICTION STRESSES

When a concrete pavement contracts, owing to one or more of the causes already mentioned, tensile stress is induced by resistance offered by the subgrade to movement of the slab. Similarly, expan-

sion of the pavement produces compressive stress. The type and condition of the subgrade exert a very great influence indeed on the magnitude of these stresses. In general, heavy soils offer greater resistance to slab movement than light or granular soils, and damp, firm subgrades resist movement more than either very dry or very wet ones (7, 10, 30). Moreover, subgrade resistance is not uniform but increases from nearly zero for extremely small movements to twice the weight of the slab when large movement takes place, so that the intensity of frictional resistance is greatest at the end portions and least at the center of the slab. Still another pertinent fact which has been noted by Teller and Sutherland (31) is that frictional resistance may be considerably greater during the initial movement than it is later after several reversals of direction have taken place.

Theoretically, the forces of frictional restraint exerted when the pavement is cooling cause maximum tensile stress at the midsection of the slab. The amount of tension thus created at the center may be calculated roughly by equating the frictional force developed for unit width over half the slab length to the tension existing in the concrete as follows:

$$\frac{Wh}{12} \times \frac{L}{2} \times f = 12h \times S_f$$

or

$$S_f = \frac{WLf}{288} \dots\dots\dots(6)$$

- where  $S_f$  = tensile stress in psi,
- $W$  = unit weight of concrete, lb. per cu. ft.,
- $L$  = length of the slab in feet,
- $f$  = coefficient of subgrade resistance, and
- $h$  = thickness of the slab in inches.

It may be noticed that, according to the above equation, friction stress depends neither on the thermal coefficient of expansion nor the amount of temperature change, although it may be induced entirely by a change in temperature.

When the slab is fully restrained, so that change in length due to temperature is prevented, the maximum stress in the concrete is given by the equation

$$S_t = Eet \dots\dots\dots(7)$$

in which  $S_t$  is the unit stress due to temperature,  $E$  and  $e$  are the modulus of elasticity and thermal coefficient of expansion of the concrete respectively, and  $t$  the change in uniform or overall temperature of the slab (4).

### WARPING STRESSES

In an earlier part of this discussion it was stated that three factors combine to produce upward warping of the ends of concrete slabs poured in the morning of a bright summer day. In the present calculation of warping stresses only one of these factors, that of vertical temperature gradient, will be considered. Data with which to evaluate quantitatively the individual effects of differential moisture and autogenous volume changes are exceedingly difficult to obtain and practically none exist. Without going into such refinements as the effects of subgrade reaction and transverse warping stress on longitudinal warping stress, a reasonable approximation of the maximum warping stress due to temperature gradient in a slab of sufficient weight to prevent it from warping away from the subgrade except near the ends may be found by means of the relation

$$S_w = \frac{Eet}{2} \dots\dots\dots(8)$$

where  $S_w$  is the maximum warping stress,  $E$  and  $e$  are the modulus of elasticity and thermal coefficient of expansion of the concrete respectively, and  $t$  is equal to the difference in temperature between the top and bottom surfaces of the slab (8).

### AN ILLUSTRATIVE EXAMPLE

It will be interesting to apply the foregoing stress analysis and data from Table 1 to the behavior of a concrete pavement cured with a clear membrane on a bright summer day in Michigan. On September 9, 1947, temperature measurements were made throughout the day and part of the night on five pavement slabs poured at intervals between the hours of 7:30 a.m. and 3:30 p.m. inclusive. This two-lane pavement was 22 feet wide, 9 inches thick and constructed according to current Michigan State Highway Department design, which provided in the present instance for 100-foot contraction joints with load transfer dowels, no expansion joints, and 86 pounds of steel reinforcement per 100 square feet.

The original purpose of the study was to find the maximum temperature attained in the surface of concrete poured at different periods of the day, and for that reason thermocouples were installed only in the top of all slabs except the one poured at 7:30 a.m. in which an additional thermocouple was inserted to measure temperature at the bottom of the slab also. The weather was clear except for a slight haze and some cloudiness around 2 p.m. with a fresh breeze in the morning, and the maximum air temperature of 89° F. was reached at about 3 p.m. Surface temperatures at all five stations are charted in Fig. 15, and both top and bottom temperatures at the first station appear in Fig. 16. The short vertical lines drawn through the curves indicate the time of application of the membrane.

Considering first the graph of top and bottom temperatures at the single station, Fig. 16, the following facts may be noted:

1. Between 12 noon and 1 p.m. a vertical temperature gradient of about 20° F. had already been established, and this gradient was maintained until the top surface began to cool at 3 p.m.

2. Final set of the cement probably occurred somewhere between 12 and 1 o'clock, which represents a period of from 4½ to 5½ hours from the time of mixing, the setting reactions being accelerated somewhat by the increase in temperature.

3. The temperature gradient decreased rapidly after the maximum temperature in the top surface was reached at 3 p.m., then vanished at about 6 p.m., after which a reversal occurred and the gradient increased in the opposite direction very gradually to 7° F. at 2 a.m.

4. At 12 midnight the temperature in the bottom of the slab was approximately the same as at the time of final set and was slowly decreasing.

Bearing the foregoing facts in mind, an attempt may now be made to determine the conditions existing in the first slab of the day's pour at midnight of the same day.

First, it must be remembered that in this particular pavement the concrete was fully restrained until the 100-foot, weakened-plane contraction joints opened by cracking. Therefore, the tensile stress existing in the slab before the ends were freed is given by equation (7). The thermal coefficient of expansion of concrete containing natural aggregates is very close to  $5 \times 10^{-6}$ , and the dynamic modulus and flexural strength may be taken from Table 1 as  $4.5 \times 10^6$  and 300

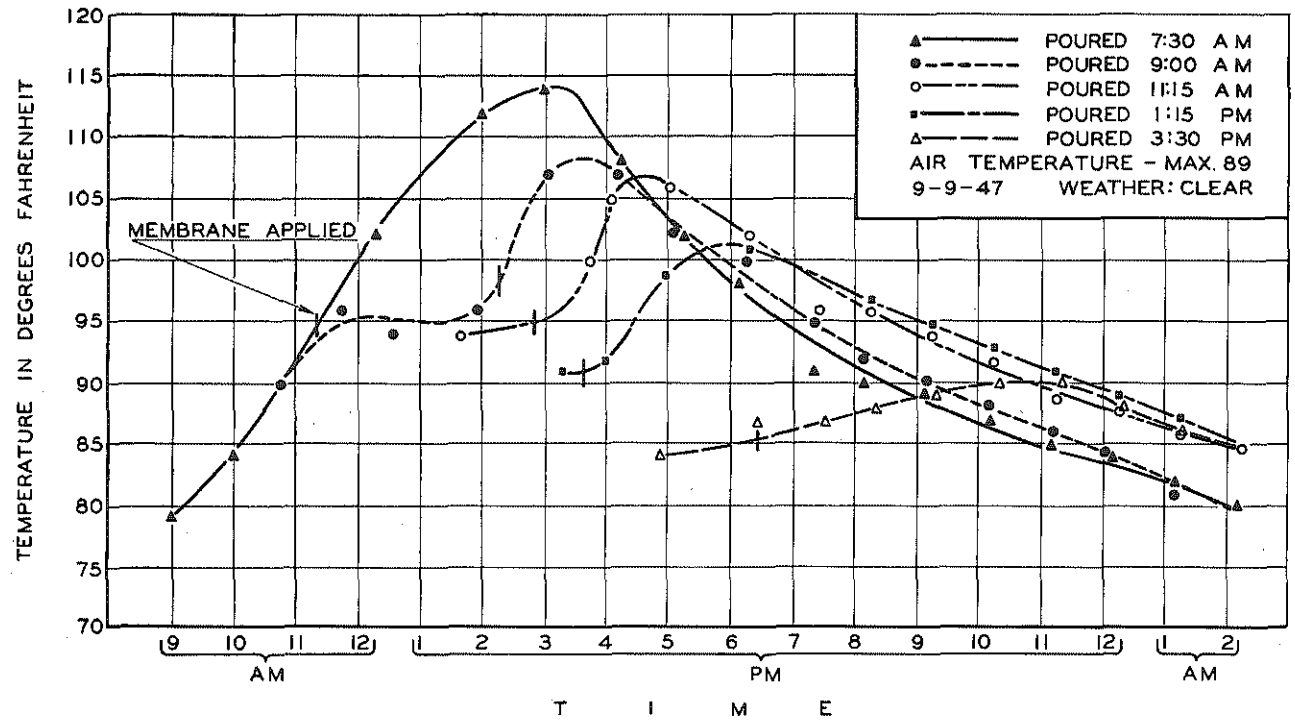


Fig. 15. Surface temperatures of pavement slabs poured at different times of the day.

psi. respectively. Now the resistance of the concrete to direct tensile forces is not more than half its flexural strength, or about 150 psi. at this stage. The use of equation (7) brings out the fact that a drop of only 7 degrees in the average temperature of the slab would be sufficient to crack the joints. From the temperature curves of Fig. 16 it seems quite certain that the joints should have cracked by midnight.

Next, the temperature gradient effective in producing warping at any instant must be calculated under the condition that no warping stress due to temperature exists when the temperature gradient prevailing in the concrete at the time of final set is present. Mathematically the effective temperature differential may be expressed thus:

$$t_w = T_T - T_B - (T_{HT} - T_{HB}) \dots\dots\dots(9)$$

where  $t_w$  = temperature differential effective in causing warping,

$T_T, T_B$  = temperatures in the top and bottom surfaces respectively at the given time, and

$T_{HT}, T_{HB}$  = temperatures in the top and bottom surfaces respectively at the time hardening takes place.

At midnight, then,  $t_w = -5 - 20 = -25^\circ$  F.,  $E$  and  $e$  are taken as  $4.5 \times 10^6$  psi. and  $5 \times 10^{-6}$  respectively and the warping stress due to temperature only is found from equation (8) to be 281 psi. It might be pertinent here to call attention to the fact that the warping stress is directly proportional to the difference in temperature between the top and bottom of the slab, and, in the present case, a reduction of 12 degrees in the difference would decrease the warping stress approximately 50 percent.

Finally, the amount of subgrade resistance to slab movement after the ends are freed by cracking at the joints remains to be calculated. Assuming a friction coefficient,  $f$  of 1.0, and the unit weight of concrete to be 150 pounds per cubic foot, the maximum frictional stress at the midsection is found from equation (6) to be 52 psi. The determination of this value presupposes that there exists a sufficient drop in temperature at the bottom of the slab to cause appreciable contraction at the subgrade surface and that dowel friction at the joints can be neglected. It has already been noted that the temperature of the bottom surface of the slab at midnight was about the same as at the time of final set. In spite of this fact it is probable that



appreciable contraction did take place owing to the fact that the modulus of elasticity was still low at noon and some plastic deformation would occur throughout the depth of the slab when the concrete was compressed during the temperature rise from the time of final set to the time when maximum temperatures were attained. In any event, a further drop in temperature of the entire slab amounting to 10° F. or more could be expected from midnight to sunrise, which would tend to develop tensile stress in the concrete.

When the slab is curled concave upward the upper fibers are in tension and the lower in compression. Contraction of the slab as a whole creates a tensile stress at the bottom surface and this tensile stress acts to relieve the compressive stress induced by warping. Relief of compressive stress at the bottom of the slab results in a corresponding reduction of tension at the top. Assuming the maximum tension from subgrade resistance of 52 psi., the net warping stress owing to temperature amounts to 281 minus 52, or 229 psi. This figure does not take into account the two other factors contributing to warping in the same direction, i.e. moisture gradients and differential autogenous volume changes. Since the flexural strength of the concrete at the age considered in the analysis is about 300 psi., it is plainly evident that the induced stresses are dangerously near the rupturing point in the example given.

The conditions cited in the present instance are by no means the most severe that could be encountered in hot weather concreting. The sun was far past the summer solstice when the measurements were made, and substantially higher temperatures and temperature gradients could be expected earlier in the season, especially in late spring when the ground is still relatively cool and the sun is hot. The foregoing illustration has been presented with the idea of pointing out the magnitude of the stresses that may be expected in summer concreting under a definite set of conditions and to show the need of adequate temperature and moisture control in order to minimize early cracking, or incipient cracking, of the pavement.

The temperature curves of the five slabs poured at different times of the same day (Fig. 15) require little comment and their meaning is obvious. It may be observed, however, that the application of the membrane was unduly delayed in the case of the slab poured at 9 a.m. with the result that the temperature did not rise above 96° F. until after 2 p.m. and then reached a maximum of about 108° F. between 3 and 4 p.m. Nevertheless, this slab may have fared worse

than the first one because of excessive surface drying. It is quite evident that the two slabs poured in the afternoon were in a much better position to come through the first 24 hours in a structurally sound condition than the three which were placed during the morning, other things being equal.

### FIELD STUDIES

Studies of curing on construction projects performed in connection with the investigation were of two types differing in purpose and method of approach. The first was concerned with the practicability of the use of white-pigmented curing compounds on pavements, and the second consisted in the acquisition and interpretation of data on the condition of recently constructed concrete pavements which were cured with clear membrane compounds. The study of white membranes was made on the Grand Ledge Experimental Project as a part of an investigation of wider scope planned primarily to evaluate the new standards of pavement design adopted by the Michigan State Highway Department for postwar construction.

#### The Grand Ledge Curing Experiment

At the time this experiment was carried out it was realized that white curing compounds were superior to the clear type from the viewpoint of thermal effects produced in the concrete under radiant heat, and that they had been used with excellent results on structures of certain types, such as canal linings, where color was not an objectionable feature. For use on pavements, however, the possible effects of the white color on operator vision and the change in general appearance due to weathering and traffic are important considerations, and the principal object of the study was to learn something of these effects.

**Scope**—In order to obtain a practical demonstration of the performance of white-pigmented membrane, two consecutive 100-foot slabs in the south lane of the 22-foot, 8-inch pavement between stations 576+00 and 578+00 were cured with a white compound and the corresponding slabs in the north lane with the clear compound furnished on the job. The white material was sprayed on the pavement at the rate of 200 square feet per gallon with an ordinary hand-operated orchard sprayer, while the clear compound was applied at the

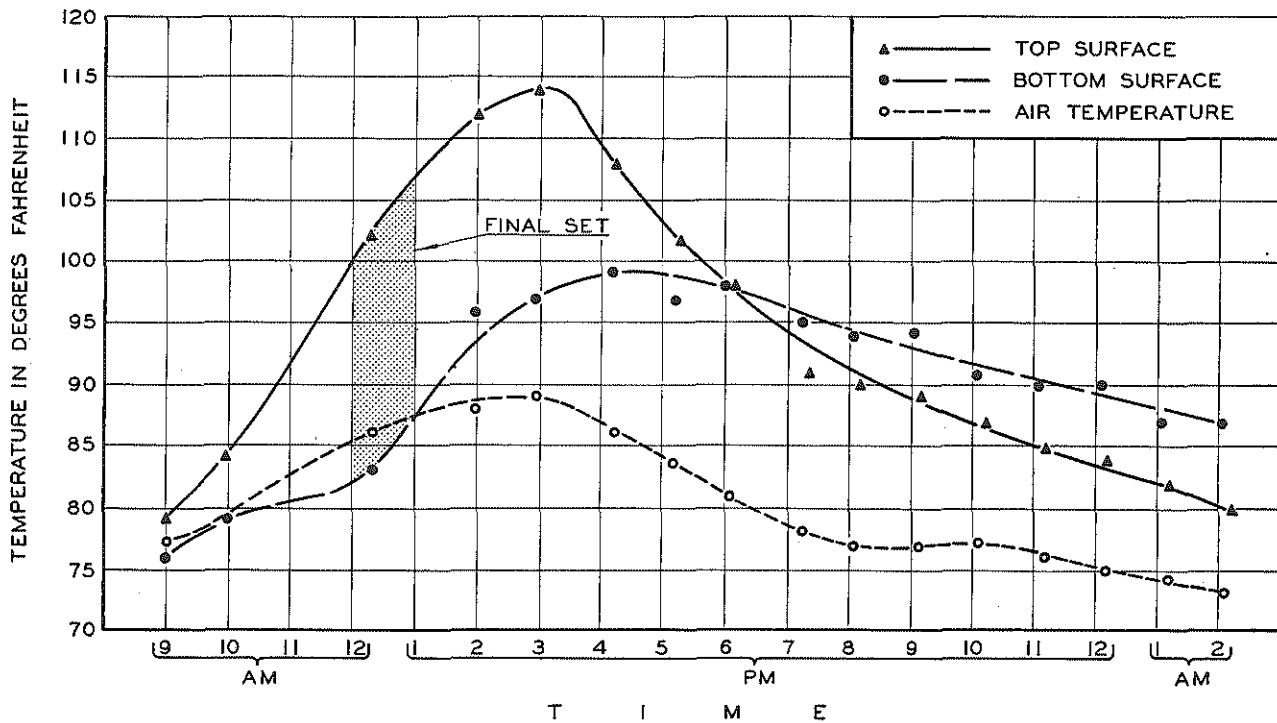


Fig. 16. Temperatures of pavement slab poured at 7:30 a.m.

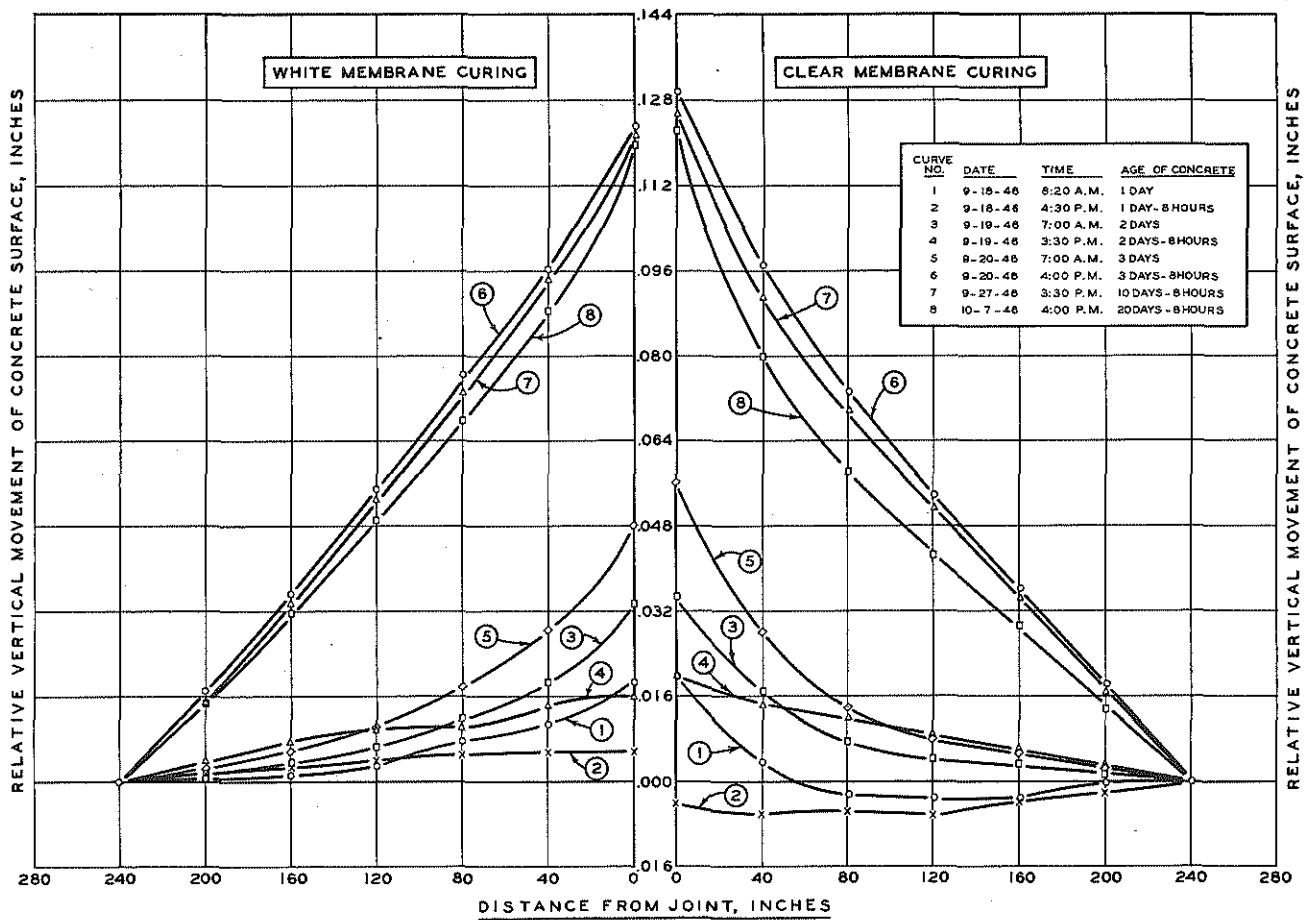


Fig. 17. Early warping of 100-foot pavement slabs at a contraction joint.

same rate of coverage by the traveling distributor used by the contractor on the entire project.

Thermocouples and moisture cells were placed in the concrete at the top, middle and bottom of the slab in each lane to measure differences in thermal and moisture effects produced by the two types of curing compound. Seven inserts 40 inches apart for clinometer warping measurements were set along the outside edge of both lanes of the pavement for a distance of 20 feet on each side of the common contraction joint. Initial readings were taken approximately 6 hours after the finishing operation, and at various intervals over a period of 3 weeks thereafter. The pavement was also inspected several times to note the general appearance and weathering of the white membrane.

**Results and Discussion**—The curves in Fig. 17 were plotted from clinometer readings to represent the longitudinal profile of the end portions of the two slabs for both white and clear membranes with reference to the point (No. 7) farthest from the joint. This reference point did not remain fixed and, consequently, the ordinates of the other plotted points varied according to the vertical movement of point 7. After 32 hours the minor irregularities disappeared and there was only upward warping at the joint edge. Different temperature gradients changed the magnitude but not the direction of warping, which is in agreement with the laboratory studies. It is interesting to observe how the concrete was lifted at progressively greater distances from the ends as drying continued and its flexural strength increased until at 3 days the curvature extended more than 20 feet back from the joint, as indicated by the increased slope at point 7.

There was very little difference in the warping of the slabs cured with white and clear membranes in this test. It was late in the season and the highest temperatures measured in the tops of the slabs were only 97° F. for the clear and 87° F. for the white membrane, with a 10-degree differential in each case. Probably the dowels and tie-bars were equalizing influences also.

The photographs in Figs. 18 through 20, taken immediately after application of the two types of curing compound and at 1 and 2 months respectively, show that the white membrane weathered away rapidly and uniformly without exhibiting mottling or other unsightly weathering effects. Inspection of the pavement also revealed that at no time after opening of the pavement to traffic was there any objectionable glare from the white surface.

The results of the experiment strongly indicate that there should be no serious problems encountered in the use of white compounds, and there can be no doubt that their use would materially enhance the structural stability of concrete pavements cured with membranes. These conclusions should be still further verified by a full-scale trial of white-pigmented compounds for at least a mile on a concrete pavement construction project.

### Survey of Postwar Pavements

In connection with the appraisal of Michigan's new standards of pavement design mentioned previously, condition surveys have been made of a sizable group of concrete pavements built in the state during the past two years. All of these pavements were cured with clear membranes so there is, unfortunately, no opportunity to compare the effects of various curing methods on pavement performance. The surveys illustrate very pointedly, however, some of the remarks made earlier concerning the critical nature of the stresses which may be induced in pavements during the early hardening period.

The results of the surveys listed in Table 6 show that nearly all projects for which data are available had cracked to some extent



Fig. 18. White membrane immediately after application.



**Fig. 19.** White membrane one month after application.



**Fig. 20.** White membrane 2 months after application.

TABLE 6—Cracking of postwar pavements

Project No.	Length, miles	Construction dates		Survey date	Total slabs	Slab cracking					
		From	To			Cracked slabs		Morning pour		Afternoon pour	
						No.	Percent of total	No.	Percent cracked slabs	No.	Percent cracked slabs
1946 Construction											
F 3-47, C1	5.182	9-5-46	10-17-46	2-11-47	274	3	1.09	3	100	0	0
F 23-6, C4	6.590	9-5-46	10-26-46	11-12-47	336	11	3.27	11	100	0	0
F 25-30, C2	1.999	8-15-46	9-4-46	2-18-47	102	16	15.68	16	100	0	0
F 70-49, C3	4.300	8-2-46	9-20-46	2-13-47	219	29	13.24	27	93	2	7
F 71-19, C12	3.600	9-6-46	10-4-46	4-28-47	176	23	13.06	9	39	14	61
F 71-20, C7	4.563	7-22-46	9-6-46	4-28-47	237	40	16.87	32	80	8	20
F 79-30, C5	4.780	9-30-46	11-5-46	2-20-47	243	14	5.76	3	21	11	79
1947 Construction											
F 11-42, C3	1.758	9-27-47	10-17-47	12-15-47	84	3	3.57	0	0	3	100
F 14-33, C1	5.919	8-20-47	10-7-47	2-24-48	327	32	9.78	24	75	3	25
F 15-2, C7	5.859	6-5-47	7-21-47	9-18-47	307	39	12.70	31	79	3	25
F 19-41, C1	5.000	8-22-47	10-20-47	4-7-48	363	11	3.03	5	45	6	55
F 30-4, C3	4.870	9-4-47	10-30-47	3-1-48	252	23	9.12	15	65	3	35
S 32-52, C2	0.373	7-17-47	7-21-47	11-19-47	18	2	11.11	0	0	2	100
S 32-52, C3	5.005	6-4-47	7-16-47	11-19-47	253	37	14.62	33	89	4	11
F 34-15, C3	4.965	9-24-47	10-20-47	1-14-48	260	2	0.76	0	0	2	100
U 37-5, C3	1.769	7-2-47	8-22-47	10-13-47	246	32	13.00	27	84	3	16
F 44-33, C2	0.199	9-2-47	9-3-47	4-1-48	10	1	10.00	1	100	0	0
F 50-48, C2	2.081	8-18-47	9-2-47	4-1-48	102	37	36.27	22	59	15	41
F 56-27, C4	4.929	6-3-47	7-2-47	10-15-47	270	34	12.59	30	88	4	12
F 56-20, C1	7.195	7-21-47	9-19-47	10-16-47	367	12	3.26	12	100	0	0
F 59-36, C2	5.097	6-12-47	7-26-47	10-1-47	257	48	18.67	44	92	4	8
F 70-49, C4	3.566	5-26-47	6-26-47	11-20-47	188	48	25.53	38	79	10	21
F 72-7, C4	4.906	7-21-47	8-19-47	10-17-47	247	27	10.93	23	85	4	15
F 73-30, C3	4.838	9-3-47	9-30-47	4-6-48	264	13	4.92	5	38	6	62
F 73-30, C4	1.991	10-5-47	10-13-47	4-7-48	88	4	4.54	1	25	3	75
F 74-49, C1 & 2	4.900	8-11-47	9-18-47	4-15-48	271	23	8.48	14	61	9	39
S 74-49, C3	4.000	9-20-47	10-20-47	4-13-48	205	13	6.34	8	62	5	38
S 77-41, C2	1.522	8-21-47	9-25-47	4-12-48	193	24	12.43	13	54	11	46
M 79-38, C2	1.280	10-14-47	10-18-47	4-8-48	65	10	15.38	6	60	4	40
Totals					6197	611	9.85	453	74	158	26



within a few weeks of their completion dates. The exact time when the cracks appeared is unknown, but it was probably much earlier than the survey date indicates. Cracking was more extensive in some than in others, but in all of the pavements built during the summer months, cracking, when occurring at all, was found predominantly in slabs of the morning's pour. Pavements constructed later on in the fall do not in general exhibit this tendency.

There are a great many factors which may contribute to premature cracking, and the curing operation cannot be expected to compensate for all of them. The properties of the cement and aggregates as well as the proportioning, mixing, placing and finishing of the concrete not only determine its potential strength; they also exert a very considerable influence on contraction and warping stresses through their effect on the modulus of elasticity, coefficient of thermal expansion, homogeneity, and volume response to changes in moisture content of the slab in place. As we have seen before, the type and condition of the subgrade are also influential factors in cracking.

Proper curing can delay cracking, thus resulting in a saving in maintenance costs, but the ultimate crack pattern is probably established chiefly by the basic factors mentioned in the preceding paragraph. As far as curing is concerned, the significant lesson to be learned from the data in Table 6 is that, for projects representing a wide range of materials, weather conditions, location, and constructional details, there were approximately three times as many cracked slabs in the morning pours as in the afternoon pours. This means that, potentially at least, the total cracking at early ages could have been reduced about 50 percent in the above group of projects by effective temperature control.

An example of the effect of one of the above-mentioned factors, that of cement, is strikingly illustrated in Fig. 21, wherein the survey of an entire project is shown. The brand of cement was changed about midway in the project (Station 153+22), with the result that the widespread cracking previously in evidence is seen to suddenly cease. In this case some individual characteristic of the cement, unidentifiable in standard chemical and physical tests, tipped the balance; but the fact still remains that such cracking as did occur is found almost invariably in the morning pours.

## COMPARISON OF CURING METHODS

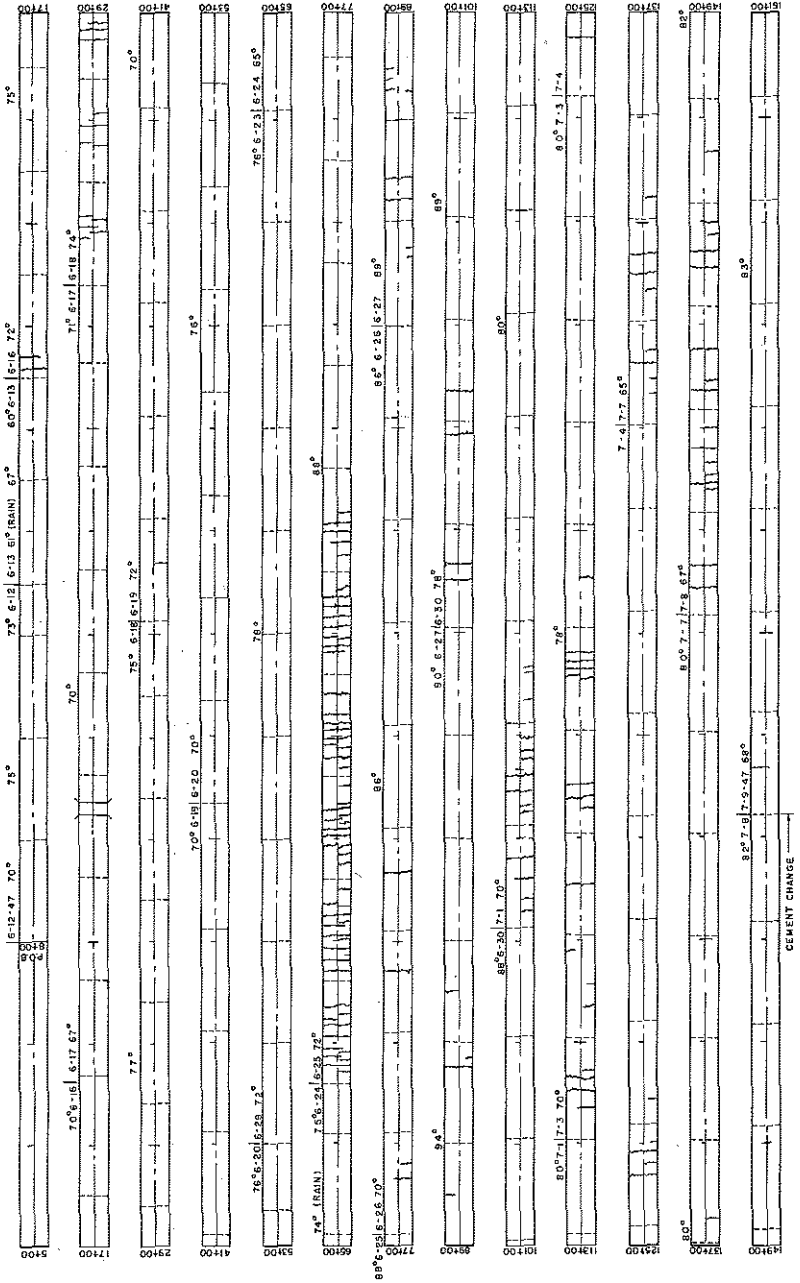
An excellent summary of the advantages and disadvantages of membrane curing based on considerable experience and research has been given by Blanks, Meissner and Tuthill (2), of the United States Bureau of Reclamation, in their paper referred to previously and will not be repeated here. The results of the present investigation, however, have made possible a more quantitative evaluation of some of the factors enumerated by them, particularly with respect to stresses induced by differential heating. Moreover, the above-mentioned authors were apparently loath to mention some of the practical aspects of the curing operation having to do with enforcement of specification requirements. In the following comparison of membrane and wet curing methods, the relative merits of the two will be judged on the basis of three general qualities, namely efficiency, practicability, and cost, each of which embraces several specific considerations.

### EFFICIENCY

The sense of the term *efficiency* as used herein is taken as the extent to which a particular curing method fulfills all of the requirements set forth in the definition and function of curing when conditions are controlled so as to secure optimum results from the method.

There can be no question of the superiority of wet curing over membrane curing for hot weather concreting in the quality thus defined. The temperature-regulating effect of water is very great indeed and, together with the continuous external supply of moisture to maintain a maximum rate of hydration and prevent undue shrinkage, will insure minimum induced stress and maximum strength gain during the early hardening period. From the viewpoint of moisture requirements, curing by membrane is entirely adequate but some means of early temperature control during hot, clear weather should be provided. Probably the most practical way of doing this is by the use of white-pigmented compounds. Other satisfactory methods are 24-hour initial moist curing, the use of heat-insulating coverings of various kinds, and shifting construction operations to a later period of the day. All practical means of reducing temperatures and temperature gradients should be employed in hot weather concreting, regardless of the curing method used (27).

For cold weather construction membrane curing has advantages



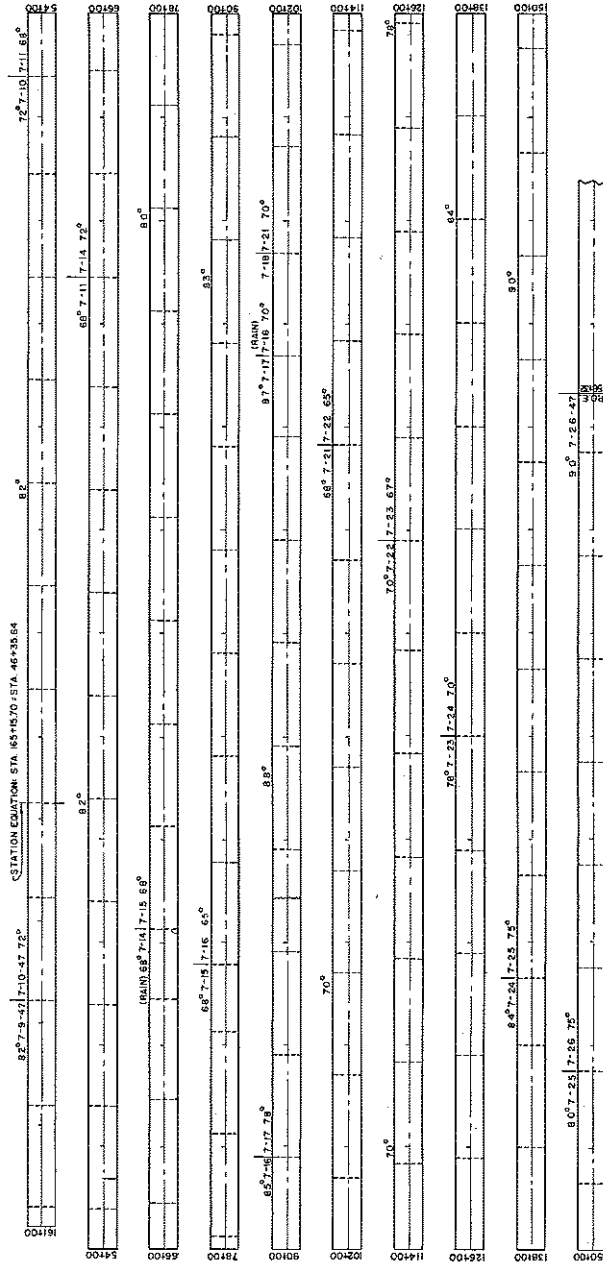


Fig. 21. Influence of cement on pavement cracking.

over wet methods. There is less freezable water in the cement paste and the concrete is therefore better able to withstand lower temperatures without frost damage. Furthermore, the restriction of evaporation provided by the membrane very appreciably preserves warmth in the slab and, in conjunction with some insulator like dry straw or earth, will provide considerable protection against freezing. At such times, additional water is neither necessary nor desirable.

### PRACTICABILITY

By practicability is meant not only feasibility but also what may be termed *control expectancy* in actual practice; in addition to its usual meaning it denotes the extent to which the field operation may be expected to provide the conditions necessary for optimum results from the method.

The preceding definition applied to wet curing raises a number of implications among which may be mentioned the following: 1) the difficulty of supplying curing water for a mile or more of pavement behind the mixer; 2) laxity in keeping the covering wet during the curing period; 3) difficulty in maintaining inspection sufficiently vigilant and forceful to see that the covering is kept wet; and 4) resistance shown by contractors, to whom wet curing is a troublesome and expensive operation. These problems are too familiar to most engineers to require detailed discussion, but it might be pointed out in this connection that in the laboratory warping tests described earlier, it was necessary to saturate the burlap at least once every hour to keep it moist during the day. Candor must compel the admission that such practice is seldom, if ever, found in general concrete pavement construction.

Membrane curing is not without practical problems also, but they present much less difficulty than those of wet curing. The major problem encountered in the early days of membrane curing was that of securing uniform distribution of the compound on the pavement surface. Traveling distributors with shielded spray nozzles have largely overcome this trouble and the equipment is being progressively improved. Rate of coverage must be watched also, and it is wise to check the amount of curing material used against the surface area covered. A third factor requiring close attention is the time of application of the material. Curing equipment should operate well up behind the finishers, and the compound should be sprayed on as soon

as the surface moisture has disappeared. Undue delay results in excessive surface drying which may combine with temperature effects to crack the pavement; it results also in discontinuous films caused by the compound penetrating the concrete surface rather than bridging the voids. When delay is unavoidable, the pavement surface should be resaturated with water before applying the membrane.

### COST

It is very difficult to obtain comparable data on costs of clear membrane and wet curing methods, principally because the two types have not been contemporaneous. Membrane curing with clear compounds did not come into wide use until the beginning of the war and its adoption as a temporary alternate was accompanied by an almost complete cessation of the use of other methods in Michigan. From such data as are available from contractors, however, it is safe to say that the cost of membrane curing is not more than one-half that of wet curing. At the present time the cost of wet curing is almost prohibitive when added to the already inflated costs of concrete pavement construction, and this situation is probably aggravated by the unwillingness of contractors to return to the more cumbersome methods formerly in general use.

### MEMBRANE VERSUS WET CURING

The comparison between membrane curing and wet curing may be summarized in a very few words. Wet curing is superior when properly carried out, but with modern construction rates bringing new problems of operation and control, it seems to be no longer practicable for concrete pavement construction. Membrane curing has given a creditable performance, but some provision should be made in the future for temperature regulation during hot weather concreting. It has some advantages in cold weather construction and considerable advantage in cost.

## SUMMARY

The more important points made as a result of the present investigation are broadly recapitulated as follows:

1. The original water content of a plastic concrete paving mix is approximately double the amount required for hydration of the cement compounds. Water in excess of minimum hydration requirements must be available, however, as a medium for the continued actions of hydrolysis and hydration during the curing period.

2. The results of this investigation strongly indicate that retention of about 80 percent of the original net mixing water at the end of a 7-day curing period is sufficient for continued hydration and development of adequate strengths during the period.

3. In most regions of this country the particular method of artificial curing initially employed does not significantly affect the ultimate strength or behavior of pavement concrete at advanced ages.

4. The method of curing does affect the physical properties and structural stability of pavement concrete at early ages, however, through its influence on temperature and moisture gradients within the slab. On hot summer days the effects of temperature during the early hardening period are critical, but the occurrence of temperature cracking in a pavement of given design depends not only on the rate and extent of temperature change but also on the character of the subgrade, the physical and chemical properties of cement and aggregates, and the proportioning, mixing, placing and finishing of the concrete.

5. There is considerable evidence to show that temperature cracking is apt to occur more frequently in sections of pavement poured in the morning than in the afternoon on hot summer days. When using membrane curing compounds such cracking can be appreciably reduced by: 1) the use of white-pigmented curing compounds; 2) initial 24-hour curing with wet burlap, followed by saturation with water and application of membrane; 3) the use of dry, protective coverings of other types in conjunction with membrane curing compounds, including shading; or 4) by shifting construction operations to a later period of the day.

6. Pavements poured in hot weather exhibit concave upward warping only, the degree of which is determined largely by the magni-

tude of the temperature gradient existing when the concrete sets and hardens, and the time of application of curing materials.

7. Although curing with wet coverings under ideal circumstances still provides the most favorable conditions within the concrete during the setting and early hardening period, it is definitely recognized that ideal conditions are extremely difficult to realize in practice and seldom obtain on a pavement construction project. For this reason, more uniformly satisfactory results are to be expected from the use of membrane curing compounds than from those methods which demand constant attention and supervision during the entire curing period.

8. For construction during the fall or early winter in temperate climates membrane curing has the advantages of preserving warmth in the slab through restriction of evaporation, and of creating a condition of minimum saturation at the threshold of the freezing season.

9. There was no significant difference in surface hardness or wear resistance of concrete beams cured with wet burlap and white membrane. Beams cured with clear membrane exhibited somewhat lower resistance than the others.

10. Available data show that the unit cost of membrane curing before the war was about half that of wet curing methods.



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## APPENDIX

DESCRIPTION OF MATERIALS AND PROCEDURE USED IN  
CABINET TESTS

## Materials

Cement: Local brand of Type 1, having the following chemical composition:

<i>Ultimate</i>		<i>Proximate</i>	
SiO <sub>2</sub>	22.07	C <sub>3</sub> S	43.11
CaO	63.21	C <sub>2</sub> S	30.84
Al <sub>2</sub> O <sub>3</sub>	5.42	C <sub>3</sub> A	10.01
Fe <sub>2</sub> O <sub>3</sub>	2.59	C <sub>4</sub> AF	7.87
SO <sub>3</sub>	2.21	CaSO <sub>4</sub>	3.76
MgO	3.46		
Loss on Ign.	1.01		
Insol. Res.	0.55		
Free CaO	1.46		
Na <sub>2</sub> O	0.37		
K <sub>2</sub> O	0.65		

Aggregates: Natural sand and gravel having the following characteristics:

	Bulk Sp. gravity	Absorption percent	Fineness modulus
Sand.....	2.63	0.88	2.62
Gravel.....	2.63	1.71	6.45

Coarse aggregate made up from separated sizes as follows:

Size.....	1— $\frac{3}{4}$ in.	$\frac{3}{4}$ — $\frac{1}{2}$ in.	$\frac{1}{2}$ in.—No. 4
Weight, percent.....	5	35	60

Fine aggregate grading:

Sieve.....	$\frac{3}{8}$ in.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Percent passing...	100	100	94	75	51	17	1	0

**Membrane Curing Compound**

Composition, percent by weight:

Non-volatile, 42.67  
 Volatile 57.33

Weight per gallon, pounds 7.28

Drying time (to touch), hour ¼

Color Brownish-red

Color permanence Fades to a yellow-brown on exposure.

Curing test, A.S.T.M. Designation C-156

Moisture loss, 7 days, percent by weight of water content at time of application of curing compound 5.7

**Proportioning**

Cement, sand and gravel were mixed in the ratio 1:2.3:3.7 by weight, with a nominal cement factor of 5.5 bags per cubic yard of concrete and water-cement ratio of 0.49 by weight. Neutralized Vinsol resin was added to the mixing water in the amount of 0.01 percent of the weight of the cement.

**Properties of Concrete**

Slump: 3 to 4 inches

Entrained Air: See Table 1-A

Specific Gravity of Hardened Concrete: See Table 1-A

**Procedure**

Mixing: Each batch was mixed 1 minute dry and 6 minutes wet in a Smith barrel mixer of 2½ cubic foot capacity. This length of time was found to be essential to obtain thorough mixing because of mixer design. Temperature of fresh concrete: 75 F. ±2.

TABLE 1-A—Properties of concrete used in cabinet tests

Series		Average Sp. Gr. (bulk)	Average air content percent
Temperature, °F.	Relative humidity		
75	30	2.41	5.5
	50	2.39	5.4
	95	2.41	5.3
	In water	2.47	4.9
100	14	2.43	5.3
	50	2.38	5.5
	95	2.41	5.4
	In water	2.40	5.9
120	10	2.40	5.6
	50	2.41	5.6
	95	2.42	4.4
	In water	2.38	5.6

**Molding**—Beams were cast in demountable plywood molds lined with waterproof paper boxes 3- by 3- by 15 inches, and metal plates placed inside these at the ends to carry stainless steel inserts for measuring length changes. Concrete was placed in two layers, each layer rodded 50 times with a  $\frac{3}{8}$ -inch bullet-nosed rod.

Cylinders were cast in waxed cardboard molds 3- by 6 inches, which had been dipped in paraffin to coat the bottom 1 inch for additional waterproofing. Concrete was placed in two layers, each layer rodded 25 times.

**Measurements**—Specimens were weighed immediately after finishing and all except those destined for water storage were placed directly in the storage cabinet at the prescribed temperature and humidity. Water storage specimens were covered with wet burlap at room temperature for the first 8 hours, then weighed, stripped, weighed again and length and sonic measurements taken after which they were placed in the constant-temperature water bath; 8-hour strength specimens were broken at this time. Length measurements at subsequent periods were corrected to specimen temperatures at 8 hours.

Cabinet storage specimens were weighed, brushed, reweighed and sealed with membrane at the required rate of coverage on the exposed side as soon as the surface moisture disappeared. At the end of 8 hours in the cabinet, beam specimens were stripped, and weight, sonic and length measurements made, after which the remaining surfaces were coated with curing compound and the beams returned to the cabinet. Cylinders were weighed, stripped, weighed again and the remaining surfaces sprayed with curing compound; 8-hour strength specimens, both beams and cylinders, were broken at this time. Carriers made of heavy wire were used to facilitate handling of the specimens at this stage.

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