CURING OF CONCRETE PAVEMENTS

Thesis for the Degree of M. S.
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This is to certify that the

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John Richard Evans

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Major professor

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CURING OF CONCRETE PAVEMENTS

By

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TABLE OF CONTENTS

CURING OF CONCRETE PAVEMENTS

The purpose of this study is twofold; (1) to establish the basic principles involved in the curing of Portland cement concrete, with particular reference to concrete pavement construction, and (2) to compare membrane curing with other methods on the basis of efficiency, practicability, and cost.

In order to establish a criterion by which to judge the comparative efficiency of the curing methods under investigation it will be necessary first to determine just what constitutes ideal curing. To do this, four questions must be answered: (1) What is the optimum moisture content for maximum desirable qualities of the concrete? (2) Is there enough water in the original mix to provide this optimum, or is additional water necessary? (3) What effect does the curing process have on the distribution of moisture within the concrete; i.e., to what depth does its zone of influence extend below the surface? (4) What effect does the curing process have on the development of those stresses in concrete during the early hardening period which may be caused by differential volume changes resulting from temperature and moisture gradients within the structure?

In addition to evaluating the relative efficiencies of the curing methods under investigation, practicability must also be considered. Here the problem is essentially that of finding to just what extent the actual field operation may be expected to accomplish its intended purpose. In other words, what factors may operate in practice to vitiate the beneficial effects of individual materials and methods?

Finally, all materials satisfactorily meeting essential requirements as to efficiency and practicability must be compared on a cost basis.

With the rapid development in recent years of concrete pavement construction practice and equipment, the old, conventional methods of curing have become cumbersome and difficult, if not impossible to apply. Cover materials are sometimes scarce or impossible to obtain. Even a seven day curing period at present day rates of construction may require keeping almost two miles of pavement wet behind the mixer. Often the supply of curing water is inadequate, and the problem of supervision and proper inspection is magnified.

As the result of this situation, a new industry has been built up to produce a curing material embodying a concept of the mechanism of curing differing somewhat from that which motivates the use of older methods. These materials depend for their curing action on sealing the mixing water within the concrete and do not require further watering or other attention after application. If results as good as those secured by wet curing can be obtained, the advantages are obvious.

A great deal of confusion and confliction of opinion still exists concerning the purpose and function of the curing operation in concrete construction. Each of the curing methods under consideration has its peculiar advantages and disadvantages. There is certainly an urgent need for a critical examination of the whole subject of curing on the basis of fundamental facts and for an unbiased evaluation of existing methods in the light of those facts.

DEFINITIONS AND DELIMITATIONS

Definition and Function of Curing

Curing and results of lack of curing are summarized in a concise manner in the 1929 report of A. S. T. M. Committee C-9, Sub-Committee XIII on Curing, as follows:

"For the purpose of clarifying the situation the sub-committee offers the following as to its understanding of what is meant by the term 'Curing' of Concrete and the results that may be expected from lack of 'Curing.'

"By good 'Curing' of concrete is meant the setting up of favorable conditions for chemical action during the setting and early hardening period.

"The general opinion at the present time is that the most favorable conditions exist when the concrete is warm and moist throughout. Temperatures that are regarded as favorable in practice, range from 70° F. to somewhat above 100° F.

"Our present knowledge of the behavior of portland cement and concrete while setting and hardening indicate that if these conditions of temperature and moisture are met:

" (a) A maximum amount of cement will be hydrated; and

" (b) The concrete will be subjected to a minimum amount of volume change during the period of low strength.

"There is also evidence that when improper or inadequate curing conditions prevail, the insufficient hydration of the cement will be revealed through low strength of the concrete and lack of durability with the passage of time, and that excessive cracking will result from the volume changes due to variations in temperature and in moisture content."

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 process, thus making water available for further absorption by the concrete subsequent to placing; (2) those which are designed to retain the original mixing water within the concrete by sealing the surface and which do not supply additional external moisture; and (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.

The first group includes ponding and wetted coverings of all kinds, such as burlap, cotton mats, earth, straw and calcium chloride when used as a surface application. Besides supplying moisture, this group also has a thermal insulating effect which prevents the development of high temperatures in the concrete. The second group comprises waterproof paper and liquid curing materials of all types - bituminous, sodium silicate, and the resinous and waxy solutions which dry to form a moisture-retaining membrane at the surface of the concrete. Calcium chloride integrally mixed with the concrete is the single outstanding member of the third group.

Because of the difficulty of controlling other variables in actual concrete construction which may affect the result, particularly weather and the time of day at which the concrete is placed, studies of efficiency will be limited to laboratory experiments and tests under closely controlled conditions. These studies will be supplemented by additional observations of experimental pavement sections in the field. In the present work an attempt will be made primarily to evaluate the principles underlying the use of three classes of materials mentioned above rather than to examine in detail all of the individual members of each group.

REVIEW OF RELATED STUDIES

Much work has been done by previous investigators on the subject of curing. Evidence from independent investigations of Lang (8,9,14)*, Gonnerman (6), Morris (13), Jackson and Kellerman (24), and others indicates a close relationship between the attainment of strength in concrete and the amount of water either retained in the concrete or supplied to it during the curing period. Large water losses during the early stages or great deficiencies of water throughout the curing period are found to be accompanied by low strength. Small losses and small deficiencies are found to be associated with high strength. These higher strengths apparently may be assured by either preventing moisture losses during the early curing period, or by replacing such deficiencies as they occur throughout the curing period. Most writers concede that there is enough water in the original mix to completely satisfy the hydration requirements of the cement.

On the basis of this evidence it may be inferred that any curing that will prevent excessive moisture losses from the concrete pavement will provide for the attainment of satisfactory strengths. It has been found that differences in effects produced by different methods of curing concrete pavements decrease with time and eventually disappear (14,26). It is common practice at present to discontinue curing and open the pavement for use at

* Numbers in parentheses refer to literature cited at the end of this paper.

seven days provided the minimum required strengths have been attained. From this time on nature does the curing, except for some extension of the process beyond the prescribed period in the case of membrane type curing compounds. Lang has shown that intermittent curing of the type that may be expected from natural weather conditions produces concrete of better quality than continuous water curing (14).

From these facts it appears that the development of strength at ages later than about seven days should not be a matter of primary concern except in arid regions. 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.

There has been an increasing tendency in the more recent investigations to emphasize the role that curing plays in the control of volume changes during the early hardening period. During this critical time 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, strength is developing at different rates at the top and bottom of the slab due to the temperature gradient. Sufficient quantitative data upon which to base a prediction of the effect of various curing methods on these processes are at present lacking. A considerable portion of the present work will be devoted to the study of this phase of the curing process.

CABINET STUDIES

Procedure

Due to the large number of specimens involved, 3" x 3" x 15" beams and 3" x 6" cylinders were used throughout the series. The specimens were cured in air at three different temperatures and three humidities. Six ages: 8, 16, 24, and 48 hours, and 3 and 7 days were selected; and three specimens were tested in flexure and three specimens in compression at each age. Length change, moisture loss and dynamic modulus of elasticity were determined for all remaining specimens at each age so that the eight hour values for moisture loss, length change and dynamic modulus are averages of 18 observations, the 16 hour values are averages of 15 observations, and so on. Fifty-four specimens were molded for each temperature and humidity, eighteen beams and eighteen cylinders being molded each day for three consecutive days. From each day's mix, one specimen was selected for each age and the other two specimens selected from the succeeding day's mixes. The eighteen specimens were divided into three groups for different methods of curing. Six beams and six cylinders were air-cured, six beams and six cylinders were sprayed with clear membrane compound at a coverage of 100 square feet per gallon and the remaining specimens sprayed with clear membrane compound at a coverage of 200 square feet per gallon. The curing period was not extended beyond seven days because this is the limit of curing operations in the field and because the effect of the cessation of curing has been demonstrated by Blanks, Meissner and Tuthill (28). The flexure and compressive specimens were tested in the condition that existed at that age. No effort was made to place all specimens in identical conditions with regard to moisture content, by such methods as saturating before testing, as it was desired to determine the exact characteristics of the concrete at that time and at that condition.

The mix for these specimens was designed by the Michigan State Highway Department's Mortar Voids Theory. The proportions are listed below.

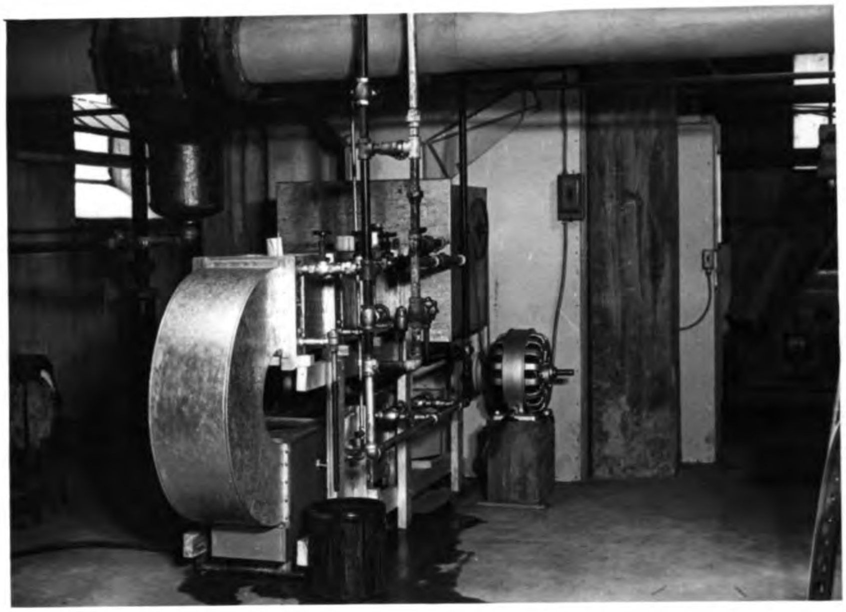
Material	Source	Quantity	Slump 3-4 in.
Cement	Peninsular Reg.	94#	
Fine Aggregate	Boichot - 2NS	215#	
Coarse Aggregate	Green Oak - 10A	344#	Note: Aggregate weights are bone dry
Water		53.5#	
NVX (.01% by weight of cement)		4.26 gms.	

To insure uniformity, the coarse aggregate was graded as follows; (1) passing 1 inch and retained on 3/4 inch. (2) passing 3/4 inch and retained on 1/2 inch. (3) passing 1/2 inch and retained on No. 8. The coarse aggregate was combined by the ratio of 1, 7, 12 by weight before mixing. The temperature of the mixing water was adjusted so the concrete temperature would be 75° plus or minus 2° F. just prior to molding. A two and one half cubic foot Smith Barrel mixer was used and a six minute mixing time was found necessary to entrain the proper amount of air. This seemingly long mixing time was essential because of the design of the mixing blades which were fixed to the sides of the drum and did not agitate with the desired efficiency.

The beams were molded in plywood molds (Figure 1) lined with asphalt-backed paper liners to prevent the loss of mixing water. The beams were rodded 50 times in two layers and finished. These molds proved very effective and were ideal for the production required as well as considerably reducing costs, since twenty-one molds were required for any one day's molding. Three extra specimens were molded each day with the hot junction of a thermocouple in the center to be used for determining the specimen temperature prior to length change measurements. The paper liners were discarded after each molding; having been weighed to determine the amount of moisture absorbed. This amount rarely exceeded 30 grams.

The cylinders were molded in waterproof cardboard molds, rodded 25 times in two layers, and finished. These molds were weighed upon stripping to determine the moisture retained. The moisture loss to these molds was approximately 10 grams. One extra cylinder was molded from each mix for the purpose of determining the specific gravity of the concrete. Immediately after finishing, all specimens were weighed and placed in the cabinet (Figure 2) where the air was tempered to a specific temperature and humidity. The three curing temperatures were 75, 100, and 120 degrees F. For each temperature there were three humidities; 10%, 50%, and 95%. The relative humidity was maintained to the above figures to a tolerance of plus or minus 5% except for the 75 degree temperature, where the lowest humidity was 30%. The temperature was held to plus or minus 2° F. When the surface moisture had disappeared the specimens were weighed, brushed, and weighed again. The specimens that were to be air-cured were returned immediately to the cabinet and those requiring a membrane film were sprayed.

1. Mold Assembly; waterproof paper liner is shown on the right.



2. Walk-in cabinet. Heating coils, cooling coils, and water spray appear in the center of the photograph.

One third of the specimens were sprayed at a coverage of 200 square feet per gallon. The membrane was applied with a De Vilbis atomizer with the air pressure adjusted to give a rapid drying time. This was necessary because the specimens had to be handled eight hours after molding.

Eight hours after molding, the mold and specimen were weighed, the molds stripped and the following data tabulated: length, dynamic modulus of elasticity and weight of specimen. Prior to each length measurement the air temperature, specimen temperature, and length of the reference bar were recorded for use in computing the length change. The vertical comparator (Figure 4) for determining specimen length is similar to the instrument used in the autoclave test except that it has been extended to accomodate the fifteen inch specimen.

The specimens were broken in flexure using a twelve inch span and third point loading. The load from the hydraulic jack was transmitted to the beam through a calibrated dynamometer ring. A ten thousandths dial measured the deflection of the dynamometer ring and this deflection was converted into pounds and a table used to compute the modulus of rupture.

The compression specimens were loaded in a manner similar to the flexural specimens except that a heavier dynamometer ring was used. The early age of test eliminated the standard procedure of capping the cylinders with neat cement or plaster of paris. To provide a cap, a piece of 1/8 inch rubber gasket material was placed on the top and bottom surfaces. A test was conducted on this material to compare results with cylinders capped in the conventional manner. The capped cylinders show higher strengths for all ages. The following represent the amount that the strength of the capped

3. Sonic apparatus for determining dynamic modulus of elasticity.

4. View of vertical comparator.

cylinders exceeds the strength of cylinders capped with the gasket material: 2% at 1 day, 8% at 3 days, 25% at 10 days. One advantageous feature of testing with caps of this material is a closer concordance of results than was obtained with the plaster of paris capped cylinders.

Discussion

These tests were designed to determine the moisture content, called optimum moisture content, which would produce the maximum desirable qualities in a given concrete. The large moisture losses prevent a definite conclusion regarding this question. Tables I and II show that moisture losses of 10% for flexural specimens and 15% for compressive specimens in the first eight hours resulted in 7 day moisture losses above 20%. It was hoped that the range of moisture losses would be evenly distributed between 0% and 50% and that by comparing moisture loss and strength, a value of moisture loss could be found that would give maximum strength - compressive and flexural. The majority of the moisture losses ran above 35%. The meager results do indicate that there possibly does exist an optimum moisture content at approximately 85%.

The large moisture losses are due to a large extent to the surface mass relationship of the small specimens used for these tests. This factor is about 1 square foot per 8.5 pounds, while in actual paving construction it is 1 square foot per 100 pounds.

In order to determine the effect of moisture content at time of test upon flexural strength a group of specimens were immersed in water for 20 minutes and broken in flexure. Prior to wetting dynamic modulus, length and weight were recorded. This same data was observed after wetting and the

TABLE I

SUMMARY OF CABINET STORAGE DATA
3" x 3" x 15" Beams

URING CONDITIONS			8 HOURS				16 HOURS					24 HOURS				
p. F.	Rel. Hum. %	Seal sq. ft. per gal.	Age Hr.-Min.	Dyn. Mod. 10^6 psi	Flex. Str. psi	Moist. Loss %	Age Hr.-Min.	Dyn. Mod. 10^6 psi	Flex. Str. psi	Length Change in.x10^{-4}	Moist. Loss %	Age Hr.-Min.	Dyn. Mod. 10^6 psi	Flex. Str. psi	Length Change in.x10^{-4}	Moist. Loss %
5	30	0	7-50	.27	7	12.1	14-55	1.58	59	-11.0	28.6	27-40	3.42	146	-14.0	49.7
		200	7-48	.35	12	10.0	14-46	2.39	117	+ 2.5	14.5	27-08	4.28	257	- 5.0	19.7
		100	7-58	.29	14	11.5	15-04	2.59	114	+ 8.7	14.7	27-42	4.34	275	+ 5.8	17.2
	50	0	7-49	.56	21	10.1	15-25	1.81	104	+ 2.9	30.3	26-28	3.15	155	+ 2.2	45.2
		200	7-58	.42	25	6.6	15-21	2.88	184	+ 8.0	14.8	26-36	4.09	252	+ 8.0	21.2
		100	8-08	.42	29	6.8	15-27	2.47	170	+ 7.8	12.8	26-48	4.82	309	+ 7.7	14.9
	95	0	7-52	.35	22	8.7	15-35	2.43	116	+ 0.4	13.6	26-32	4.58	276	+ 1.0	17.9
		200	7-23	.35	22	8.2	15-38	2.58	120	+ 5.3	12.6	26-34	5.32	331	+ 4.0	14.5
		100	7-46	.38	21	7.5	15-50	2.62	150	+ 3.8	11.8	26-51	5.26	346	+ 3.5	12.8
	In water*	0	8-22	.47	18	11.3	15-52	2.47	127	+12.0	11.3	25-57	4.09	260	+23.0	11.0
0	14	0	7-37	.98	60	18.5	14-58	2.71	150	+ 2.0	50.0	27-05	3.01	156	-10.3	58.5
		200	7-47	1.30	74	8.3	15-01	3.62	250	+ 3.2	24.0	26-53	4.32	275	- 2.6	35.8
		100	7-16	.87	63	8.3	15-07	4.22	266	+ 9.0	17.3	26-48	4.50	330	+ 2.8	27.8
	50	0	8-46	1.47	78	13.4	15-18	2.96	220	- 4.8	36.6	24-54	3.71	302	- 7.2	45.4
		200	9-23	1.86	88	9.7	15-46	3.48	321	- 0.8	20.1	25-21	4.48	429	- 7.4	26.5
		100	9-30	1.75	86	9.6	15-44	4.06	274	+ 4.6	16.3	25-14	4.57	399	+ 1.1	19.8
	95	0	8-46	1.88	86	9.9	15-25	4.55	289	+10.3	16.8	26-34	5.34	344	+ 1.0	21.0
		200	8-27	1.75	94	6.8	15-43	4.53	321	+ 7.9	11.7	25-52	5.57	421	+ 5.1	15.6
		100	8-57	1.84	80	7.3	15-39	4.36	295	+ 4.5	11.9	26-22	5.34	405	+ 5.0	13.1
	In water*	0	8-15	.50	20	7.2	15-19	3.46	177	+13.8	6.9	27-12	4.65	294	+13.1	5.9
5	10	0	7-12	1.59	90	22.0	15-05	3.14	163	- 2.9	52.1	26-47	3.44	178	-10.7	62.5
		200	7-41	1.90	102	8.9	15-12	3.85	206	- 0.9	28.4	27-02	4.74	292	- 9.7	40.4
		100	7-06	1.58	100	8.4	15-19	3.86	260	+ 8.7	23.4	27-01	4.98	316	+ 5.4	32.1
	50	0	7-32	2.37	158	17.1	15-14	3.90	227	- 6.3	40.6	26-14	4.18	247	-11.4	47.4
		200	7-44	2.77	156	8.5	15-28	4.51	315	- 9.6	22.9	25-55	4.98	347	-14.7	30.5
		100	7-54	3.06	180	8.0	15-31	4.58	385	- 6.0	18.1	25-30	5.05	400	-10.5	25.7
	95	0	7-56	2.08	138	10.3	15-31	4.80	246	- 0.2	18.4	26-12	5.28	310	- 5.0	25.9
		200	7-44	2.50	150	7.1	15-28	4.63	269	+ 1.9	14.1	26-04	5.55	352	+ 1.9	17.9
		100	7-37	2.53	181	6.6	15-32	4.62	288	+ 4.4	12.5	26-04	5.45	347	+ 3.7	15.1
	In water*	0	7-20	3.84	24	9.8	15-12	4.98	209	- 1.7	9.2	25-38	5.99	362	+ 5.5	9.1

URING CONDITIONS			2 DAYS					8 DAYS					7 DAYS				
p. F.	Rel. Hum. %	Seal sq. ft. per gal.	Age Hr.-Min.	Dyn. Mod. 10^6 psi	Flex. Str. psi	Length Change in.x10^{-4}	Moist. Loss %	Age Hr.-Min.	Dyn. Mod. 10^6 psi	Flex. Str. psi	Length Change in.x10^{-4}	Moist. Loss %	Age Hr.-Min.	Dyn. Mod. 10^6 psi	Flex. Str. psi	Length Change in.x10^{-4}	Moist. Loss %
5	30	0	51-15	4.28	191	-19.0	38.0	74-20	4.42	185	-21.0	60.5	7-0-22	4.25	249	-36.0	65.2
		200	50-50	5.50	395	- 6.0	24.7	75-20	6.51	421	- 7.0	27.1	7-0-20	7.38	480	-15.0	34.5
		100	51-20	6.04	425	+ 8.3	20.5	73-52	6.44	560	+11.5	22.7	7-0-22	7.47	512	- 1.0	27.9
	50	0	49-35	4.15	289	- 4.7	49.1	74-12	4.26	224	- 8.3	51.2	7-1-58	4.63	299	-19.0	56.0
		200	49-32	5.30	357	+ 5.2	27.4	75-36	5.62	418	+ 2.3	29.9	7-1-55	5.84	557	- 8.7	37.0
		100	49-41	5.43	465	+ 5.1	17.5	75-41	6.15	608	- 1.0	19.6	7-2-45	6.82	568	- 4.0	24.7
	95	0	49-13	6.08	407	+ 2.0	22.3	73-51	6.82	396	- 0.4	24.2	7-1-28	7.40	420	- 0.5	26.9
		200	49-22	6.20	442	+ 6.4	16.1	74-14	6.80	456	+ 7.0	17.2	7-1-45	7.35	552	+ 6.0	20.2
		100	49-19	6.10	406	+ 5.1	14.1	73-57	6.77	495	+ 7.5	14.8	7-1-48	7.18	638	+ 3.7	18.3
	In water*	0	49-56	5.81	427	+17.0	9.8	74-12	6.24	552	+20.0	8.5	7-2-08	7.52	787	+21.0	6.7
0	14	0	50-30	3.65	187	-21.0	65.8	74-42	3.81	218	-28.0	66.5	7-3-47	3.92	245	-34.0	71.6
		200	50-50	5.15	325	-11.0	45.5	74-57	5.13	340	-18.0	49.0	7-3-57	5.12	375	-34.0	57.0
		100	50-45	5.58	419	- 2.8	34.8	74-59	5.46	401	- 8.1	38.7	7-4-08	5.60	412	-27.0	49.3
	50	0	49-52	4.28	310	-12.9	51.6	72-45	4.24	310	- 9.5	54.1	7-0-25	4.27	351	-24.0	56.5
		200	49-40	5.41	459	-12.3	35.0	75-37	5.56	453	-14.6	37.8	7-0-52	5.47	456	-27.0	45.9
		100	49-46	5.35	536	- 0.2	25.6	73-42	5.75	478	- 2.0	28.2	7-0-62	5.65	581	-18.0	36.2
	95	0	49-53	6.29	377	+ 1.2	24.4	74-22	6.62	429	- 1.5	26.6	7-0-50	6.77	457	- 7.0	31.5
		200	50-00	6.49	478	+ 3.9	16.4	74-52	6.82	486	+ 1.3	18.3	7-0-48	7.08	579	- 5.3	22.9
		100	49-50	6.43	526	+ 3.2	14.5	74-10	7.14	557	+ 5.0	15.0	7-1-15	7.28	572	- 7.7	19.5
	In water*	0	52-52	6.08	467	+18.1	5.1	75-54	6.81	462	+14.8	3.6	7-5-50	7.53	541	+10.5	0.0
5	10	0	50-43	3.88	280	-18.6	69.0	74-45	3.68	259	-27.1	66.5	7-1-22	3.67	280	-54.7	71.7
		200	51-26	4.98	295	-17.4	49.6	75-00	4.94	328	-29.0	56.4	7-1-30	4.83	458	-37.0	65.7
		100	51-09	5.62	352	- 1.0	41.0	74-20	5.66	360	-12.2	46.5	7-1-00	5.79	430	-20.0	52.8
	50	0	49-52	4.23	267	-17.5	54.0	74-29	4.24	277	-22.0	56.7	7-2-10	4.30	302	-33.7	62.7
		200	50-05	5.07	349	-20.7	39.1	74-05	5.01	352	-24.8	45.5	7-2-12	4.65	390	-32.0	55.2
		100	50-17	5.37	360	-16.7	31.0	74-10	5.34	378	-21.5	34.9	7-2-13	5.24	381	-31.0	44.7
	95	0	50-15	5.75	381	-6.3	29.3	74-32	5.90	355	- 6.8	32.1	7-2-20	6.12	459	-15.0	34.4
		200	50-29	6.24	386	-2.6	21.8	74-12	6.45	444	- 8.8	24.6	7-2-20	6.82	495	-19.3	28.7
		100	50-45	6.09	461	-2.5	18.2	74-20	6.40	487	- 0.8	19.7	7-2-45	6.78	551	- 9.7	23.1
	In water*	0	49-45	6.99	459	+8.0	8.9	74-50	7.07	509	+ 4.8	8.5	7-2-0	7.58	638	+ 2.0	7.0

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

SUMMARY OF [illegible]

6" x 6" Cylinders

Curing Conditions: Temp. °F.	Rel. Hum. %	Seal Sq. ft. per gal.	8 Hours: Age Hr.-Min.	Comp. Str. psi	Moist. Loss %	16 Hours: Age Hr.-Min.	Comp. Str. psi	Moist. Loss %	24 Hours: Age Hr.-Min.	Comp. Str. psi	Moist. Loss %	2 Days: Age Hr.-Min.	Comp. Str. psi	Moist. Loss %	3 Days: Age Hr.-Min.	Comp. Str. psi	Moist. Loss %	7 Days: Age Hr.-Min.	Comp. Str. psi	Moist. Loss %
75	30	0	8-27	30	15.8	15-20	174	52.5	25-40	438	65.2	49-52	548	66.8	73-30	628	68.6	7-1-0	905	71.7
		200	8-27	34	14.1	15-20	326	19.8	25-40	1170	24.8	49-52	1529	31.4	73-30	1805	35.5	7-1-0	2005	41.4
		100	8-27	37	14.7	15-20	428	17.5	25-40	965	20.5	49-52	1715	23.6	73-30	1885	26.0	7-1-0	2045	35.1
	50	0	8-10	78	18.7	15-40	326	48.8	25-55	580	57.0	49-55	740	60.6	73-20	805	61.1	7-2-25	904	65.6
		200	8-10	110	13.6	15-40	470	22.5	25-55	867	29.2	49-55	1206	34.4	73-20	1347	38.2	7-2-25	1778	41.1
		100	8-10	110	13.2	15-40	481	20.5	25-55	941	23.4	49-55	1486	27.2	73-20	1601	29.9	7-2-25	1820	34.5
	95	0	8-05	82	16.1	15-55	448	28.5	26-40	915	34.7	48-55	1119	37.2	73-45	1257	39.1	7-1-30	1636	42.5
		200	8-05	97	14.4	15-55	501	21.7	26-40	1092	24.2	48-55	1802	25.5	73-45	1845	26.7	7-1-30	2006	30.0
		100	8-05	90	14.2	15-55	507	18.7	26-40	1112	20.2	48-55	1552	20.5	73-45	2000	21.1	7-1-30	2175	23.7
	In water*	0	7-50	21	13.5	16-05	567	14.5	27-00	892	14.3	49-55	1530	15.6	74-20	1767	15.5	7-2-45	2130	10.9
100	14	0	8-00	261	21.4	15-20	467	60.7	25-20	651	65.9	50-20	641	72.5	75-20	705	73.4	7-4-30	726	77.1
		200	8-00	264	15.1	15-20	530	37.5	25-20	900	50.5	50-20	1145	57.8	75-20	1116	62.5	7-4-30	1154	70.8
		100	8-00	248	14.1	15-20	720	17.4	25-20	974	45.6	50-20	1287	51.2	75-20	1197	57.7	7-4-30	1463	68.5
	50	0	8-00	376	18.8	15-54	596	45.2	24-00	686	51.5	49-50	868	57.6	72-25	888	60.5	7-0-50	895	64.7
		200	8-00	561	15.1	15-54	725	27.7	24-00	904	35.5	49-50	1178	44.5	72-25	1170	47.1	7-0-50	1362	55.5
		100	8-00	467	15.1	15-54	855	25.5	24-00	1186	28.9	49-50	1189	32.8	72-25	1518	37.0	7-0-50	1375	45.5
	95	0	8-20	291	17.0	16-05	752	28.6	26-00	995	34.8	49-35	1165	38.0	73-45	1515	40.9	7-1-15	1555	44.7
		200	8-20	338	12.8	16-05	1040	20.7	26-00	1158	22.5	49-35	1554	25.3	73-45	1598	27.0	7-1-15	1827	30.6
		100	8-20	329	12.4	16-05	870	18.1	26-00	1545	19.2	49-35	1698	20.7	73-45	1823	21.7	7-1-15	2150	25.6
	In water*	0	8-00	29	12.1	15-00	517	11.9	26-05	865	11.4	53-15	1575	10.7	75-05	1797	9.9	7-3-0	2114	6.6
120	10	0	8-10	391	20.8	15-50	615	57.2	26-05	702	64.3	50-15	810	71.1	74-30	858	75.6	7-1-10	897	77.0
		200	8-10	494	13.4	15-50	728	47.3	26-05	1055	56.4	50-15	1057	64.5	74-30	1114	70.7	7-1-10	1154	75.6
		100	8-10	506	14.2	15-50	1006	38.9	26-05	1227	45.4	50-15	1302	50.8	74-30	1336	62.8	7-1-10	1460	70.6
	50	0	8-05	597	19.9	15-45	869	43.2	25-10	859	48.9	50-05	977	54.8	74-15	1053	57.3	7-2-35	1183	63.8
		200	8-05	850	12.4	15-45	973	28.6	25-10	1259	36.0	50-05	1508	41.5	74-15	1635	45.7	7-2-35	1798	54.8
		100	8-05	789	12.7	15-45	1128	20.8	25-10	1428	26.6	50-05	1760	31.8	74-15	1947	35.8	7-2-35	1913	44.5
	95	0	8-30	544	17.4	15-55	808	35.1	25-45	980	37.2	49-25	1174	41.4	73-35	1240	44.6	7-2-35	1306	49.2
		200	8-30	793	11.5	15-55	1055	25.3	25-45	1585	27.1	49-25	1760	32.1	73-35	1860	34.1	7-2-35	2105	39.5
		100	8-30	657	11.6	15-55	1104	21.6	25-45	1550	22.9	49-25	1750	25.4	73-35	2070	28.0	7-2-35	2100	32.8
	In water*	0	8-00	31	14.8	15-50	852	15.7	24-35	1200	14.7	50-15	1467	14.8	75-0	2011	14.7	7-2-0	1915	14.9

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

dynamic modulus decreased an average of .750 x 10^{-6}, the length increased 0.0013 inches and the modulus of rupture increased 35%. In most cases the moisture penetrated to the core of the 3" x 3" section so that the stresses established by a wet shell and a dry core were practically eliminated. There is no doubt that a moisture gradient was present and that the outer fibers were in some degree of compression, but this is believed to be slight. The increase in modulus of rupture can be attributed partly to the relief of shrinkage stresses and the effect of the modulus of elasticity of water. The moisture that has penetrated the beam is thinly distributed over the particle surfaces and thereby offers resistance to separation. These two factors are believed responsible for the greater strengths indicated by the water storage flexural specimens.

The data for modulus of elasticity development, modulus of rupture, and moisture loss present a similarity of form. For lower humidities and temperatures there is little gain in modulus of elasticity or modulus of rupture after three days. At 120 degrees the development of E and modulus of rupture ceases to change appreciably after 36 hours. Compressive strength does not act in the same manner. For most temperatures and humidities, compressive strength continues to gain for the entire seven day period. Approximately 85% of the total compressive strength is developed in the first three days.

To more accurately determine moisture gradients and the depth of the layer furnishing evaporable moisture, a series of beams were molded of varying thicknesses. These beams were molded in standard A. S. T. M. pans in thicknesses of 1/2 inch, 1 inch, and 2 inches. The 1/2 inch specimen was dryed to a constant weight (seven days) at 100° F. and 30% relative humidity. The fractured surface was sprayed with phenolphthalein and showed the entire surface to be dehydrated. The one inch and two inch specimens reveal the layer of dehydration to extend only 5/32 of an inch. This concurs with the layer of dehydration found in the air-cured beam of the warping studies. For the eight inch depth of beam, (subjected to more severe drying conditions than the small specimens mentioned above), the layer of dehydration was 3/16 of an inch.

Data from this series was also used to correlate observations from the warping studies. The rate of development of dynamic modulus of elasticity and modulus of rupture was applied to the data collected for the beams under simulated daylight conditions to determine causes and effects. The values which will be quoted in the discussion of warping studies were derived from graphs for the cabinet studies. The average temperature during any period was used as the temperature from which to determine various moduli.

The ultimate strength of concrete that has been air or membrane cured does not vary appreciably for the range of temperatures used in these experiments. The rate of development is higher for higher temperatures, but the rate decreases more rapidly than at lower temperatures. Moisture losses at 120° F. are higher than the moisture losses at 75° F. at the same relative humidity.

WARPING STUDIES

Procedure

These experiments were conducted on 8" x 12" x 84" beams molded on various subgrades: waterproof, dry, and wet sand. The concrete was transit mixed with Peninsular Air Entraining Cement and designed by the Michigan State Highway's Mortar Voids Theory. The proportions and pertinent data are listed below.

Material	Source	M.S.H.D. Spec.	Quant.	Spec. Grav.	Absorp.
Cement	Peninsular A. E.		94#	3.18	
Fine Aggregate	Boichot Agg. Co.	2NS	215#	2.64	0.88
Coarse Aggregate	American Agg. Corp. Green Oak	6A	377#	2.64	1.58
Water			50.5#		

Cement Factor - 5.5 sacks per cubic yard

b/b_o - 0.78

Theoretical air-free weight - 155.04 lbs. per cubic foot

To check the condition of the concrete at delivery, unit weight and slump were determined for each of the four batches. In addition to the above, two standard compression cylinders were made and a sample of the mix was placed in a drying oven at a temperature of 220° F. to determine the approximate moisture content. The following table indicates the properties of the concrete that was delivered.

Series	Approx. Moist. Per Cent	Slump	Entrained Air Per Cent	Seven Day Compr. Strength
I	6.71	5 1/2	5.7	3165
II	6.88	6 1/4	6.1	3040
III	6.77	5 3/4	7.0	3140
IV	6.28	4 3/4	4.5	3320

For the first series on waterproof subgrade the wooden forms were lined completely with a box made of asphalt backed paper which was coated with a mixture of 67% penetration asphalt and 33% slow-curing road oil so that when the forms were loosened the paper and seal would adhere to the concrete on all surfaces except the top, and thereby reduce to a minimum the moisture loss from those sides. The II, III, and IV series had a similar liner of asphalt backed paper, the difference being that only the sides and ends were covered and coated; the bottom surface of the beam was left open to the subgrade.

The installations in each of the three beams of the four series were identical and included three thermocouples, three Bouyoucos moisture cells, two measuring studs in each end of the beam, and three studs in the top surface of the beam. The end studs for measuring length change were flat and provided with Vee-blocks to locate the reference bar in the same position for each measurement. A complete installation, prior to molding, is shown in Figure 5. The studs in the top surface were located 40 inches apart on the longitudinal center line of the beam. The center stud of the three was milled across the diameter, with a 3/16 inch cutter, to a depth that would

5. Photograph showing beam molds, thermocouple and moisture cells, measuring studs and reference monuments for length change measurements on dry sand subgrade.

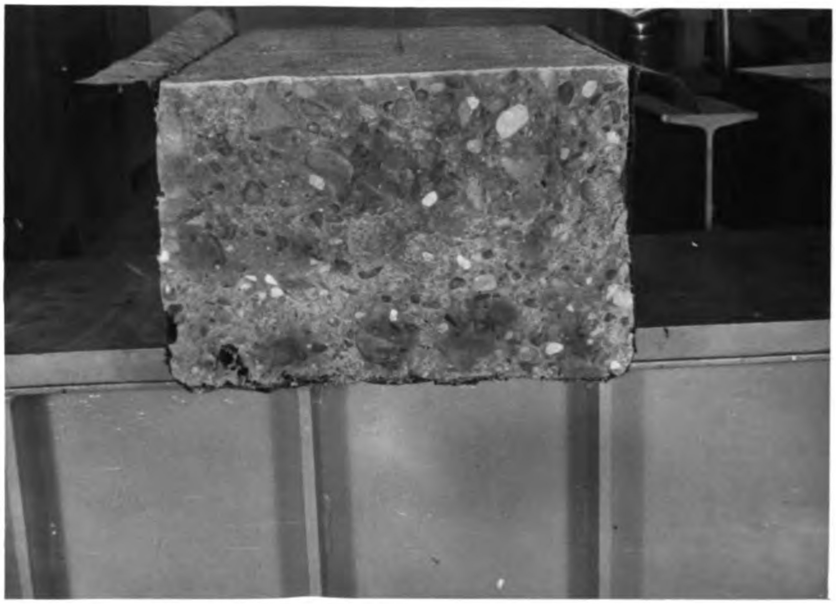
6. The clinometer for warping measurements is shown at right center. The length change reference rod is shown at left center.

accommodate the clinometer points (Figure 6). The end plugs for warping measurements were drilled so the clinometer points would bear on the top surface of the plug. The moisture cells and thermocouples were placed opposite each other at three locations in the midpoint of the beam; (1) slightly below the top surface of the beam, (2) in the center, (3) slightly above the bottom surface.

It was desired to accomplish length change and warping measurements without the aid of outside references, however, the length change proved to be of such a character that this was impossible and it became necessary to construct end posts (Figure 7) from which to refer all length change measurements. For warping measurements, a clinometer (Figure 6) was designed which permitted readings accurate to 0.0004 inches. For all warping measurements the transverse bubble was levelled first and the longitudinal bubble centered by means of the calibrated screw. The dial which was attached to the screw was graduated in one hundredths of a millimeter. The reference bar (Figure 6) was used to measure the distance from the end post to the stud in the end of the beam. Prior to each reading the reference bar was "zeroed" in a standardizing gage and the temperature of the gage recorded for future calculations.

After finishing, normally about 8:00 a.m., the light bank was turned on and its height adjusted to initiate a temperature at the slab surface of approximately 125° F. Temperature and moisture cell readings were taken immediately. When the surface moisture had disappeared, the membrane compounds, both clear and white, were applied at a coverage of 200 square feet

7. End posts used as reference for length change are located in center foreground. Plugs for warping measurements are faintly visible on beam surfaces.



8. Section of beam cured with clear membrane on waterproof subgrade. Surface of fracture sprayed with phenolphthalein to indicate dehydrated layer at top of beam. Layer is well defined and about 1/8" deep.

per gallon. The wet burlap was also applied at this time although it is realized that in actual field operation this would not occur for several more hours.

Five hours after finishing, the ends of the forms were removed and the initial readings taken from the end posts to the top and bottom end plugs. The initial clinometer readings were taken at this time. The lights were left on from 8:00 a.m. to 6:00 p.m. to simulate actual daylight conditions. The following schedule was adopted for the observations: (1) before lights were turned on, (2) before lights were turned off and periodically until midnight. The temperature readings were taken at two hour intervals; the moisture cells, length change, and warping measurements at four hour intervals. An examination of the data revealed that relatively little change occurred from 1:00 a.m. to 8:00 a.m., so readings for this period were discontinued after the first twenty-four hours.

After seven days the burlap was removed from the beams of Series I and II and observations continued for three days to determine the conditions that would follow a similar practice in field operation. The membrane coated specimens were left in the same condition that existed for the first seven days. It is unfortunate that time did not permit a more extensive period of observations.

Upon completion of the controlled curing period the beams were removed from the subgrade and one half of each beam was tested in flexure with the finished surface in tension and the other half of the beam was tested with the finished side in compression. The loading was centerpoint of a 30 inch span. Immediately after the flexural tests, the surface of fracture was sprayed with phenolphthalein to indicate the depth of the layer of dehydration. Data for these tests are given in Table III and photographs of the fractures are shown in Figures 8 to 15.

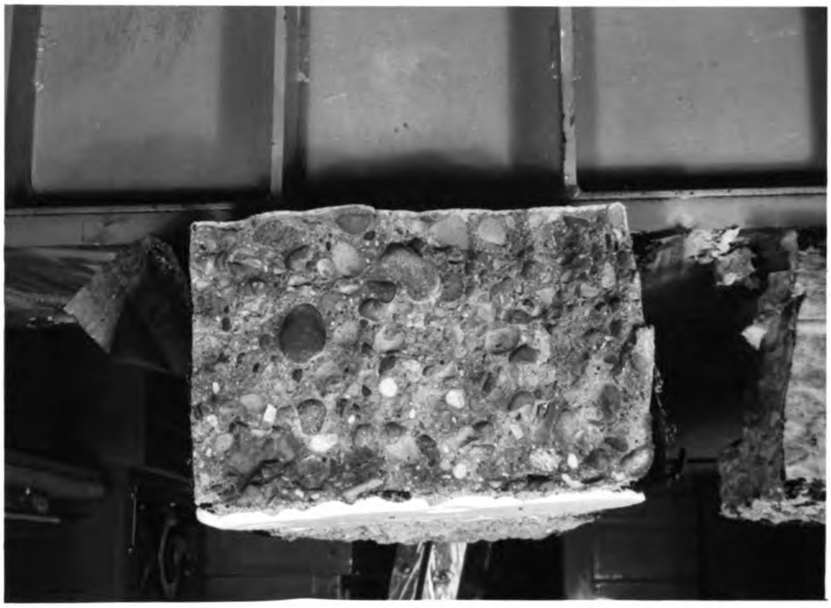
Each beam end was subjected to a wear test (Figure 16) similar to the test suggested by Master Builders to determine the resistance to penetration. Six tests were made on each specimen; the penetration was measured by a thousandths dial mounted on the shaft of the drill press. Dial readings were taken at four points around the circumference of the wear tool at periods of 0, 1, 3, 5, and 10 minutes. The average difference of these readings was taken as the depth of penetration. To maintain a constant pressure on the wearing tool, a one pound weight was suspended from the drill press arm. This weight caused a pressure of approximately eighteen pounds on the beam surface. In some cases the wearing tool bounced considerably, especially when a particularly large, hard piece of aggregate was encountered. This caused a deeper penetration than ordinarily would have occurred and was considered in the final average. To compensate for uneven wear of the tool, the outside cutter on each side was removed and new cutters placed on the inside edge at the completion of each test. The new cutter moved the width of one cutter toward the outside of the tool after each test and was in a position to be removed entirely after nine tests. Data are given in Table IV.

9. Section of beam cured seven days with wet burlap followed by three days of no curing on waterproof subgrade. Dehydrated layer is thin, well defined and about 1/16" thick.

10. Section of beam cured with white membrane on waterproof subgrade. Surface of fracture sprayed with phenolphthalein to indicate dehydrated layer at top of beam. This layer is not well defined in the photograph and is only about 1/16" deep.

11. Section of beam cured with clear membrane, on dry sand subgrade. Dehydration line is sharply defined and about 1/8" thick.

12. Section of beam cured seven days with wet burlap followed by three days of no curing on dry sand subgrade. Dehydration line is sharply defined and about 1/16" deep.



13. Section of beam cured with white membrane on dry sand subgrade. Dehydration line is sharply defined and about 1/16" thick.

14. Section of beam with no curing on wet sand subgrade. Dehydration line is sharply defined and about 3/16" thick.

15. Section of beam cured with clear membrane covered with dry burlap-wet sand subgrade. Dehydration line is thin, irregular and not clearly defined.

16. Beam end subjected to wear test. Dial for measuring penetration is visible at left center.

TABLE III

Series	Specimen	Average Modulus of Rupture, psi	Thickness of Dehydrated Layer	Curing Treatment and Duration
I	Clear	511	1/8"	10 Days - Clear membrane compound
I	Burlap	690	1/16"	7 Days - Wet burlap and 3 day air cure
I	White	528	1/16"	10 Days - White membrane compound
II	Clear	578	1/8"	10 Days - Clear membrane compound
II	Burlap	687	1/16"	7 Days - Wet burlap and 3 day air cure
II	White	596	1/16"	10 Days - White membrane compound
III	Clear	563	1/16"	7 Days - Clear membrane compound
III	Burlap	725	slight	7 Days - Wet burlap
III	White	655	slight	7 Days - White membrane compound
IV	Clear	654	3/32"	7 Days - Clear membrane compound
IV	Air-Cured	536	5/32"	7 Days - Air cured
IV	Dry Burlap on Clear	588	1/16"	7 Days - Dry burlap on clear membrane

TABLE IV

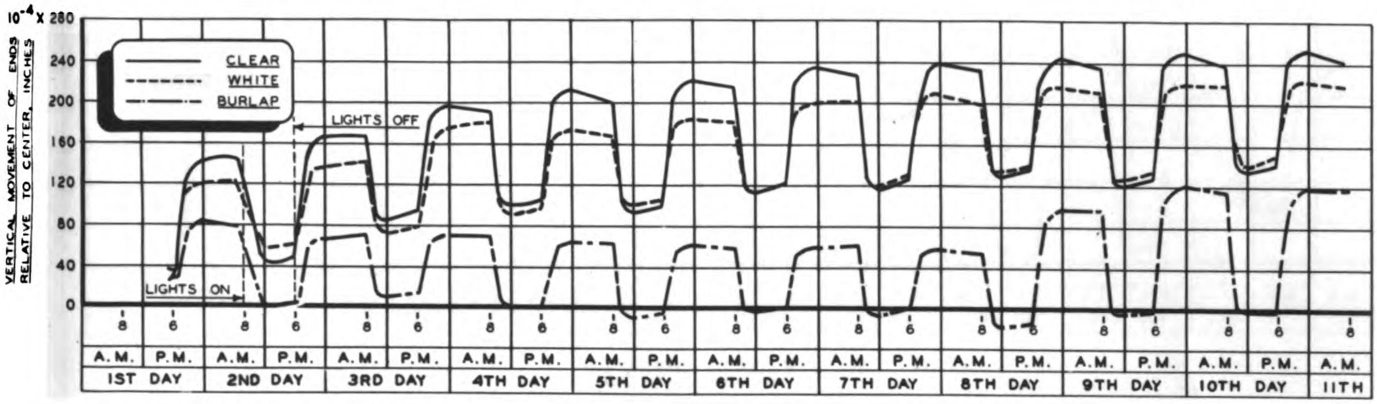
AVERAGE DEPTH OF WEAR PENETRATION
Average of 18 Tests

Type of Curing	TIME 1 min.	3 min.	5 min.	10 min.
Clear Membrane	.0320"	.0670"	.0915"	.1375"
Wet Burlap	.0245"	.043"	.071"	.117"
White Membrane	.0263"	.060"	.075"	.123"

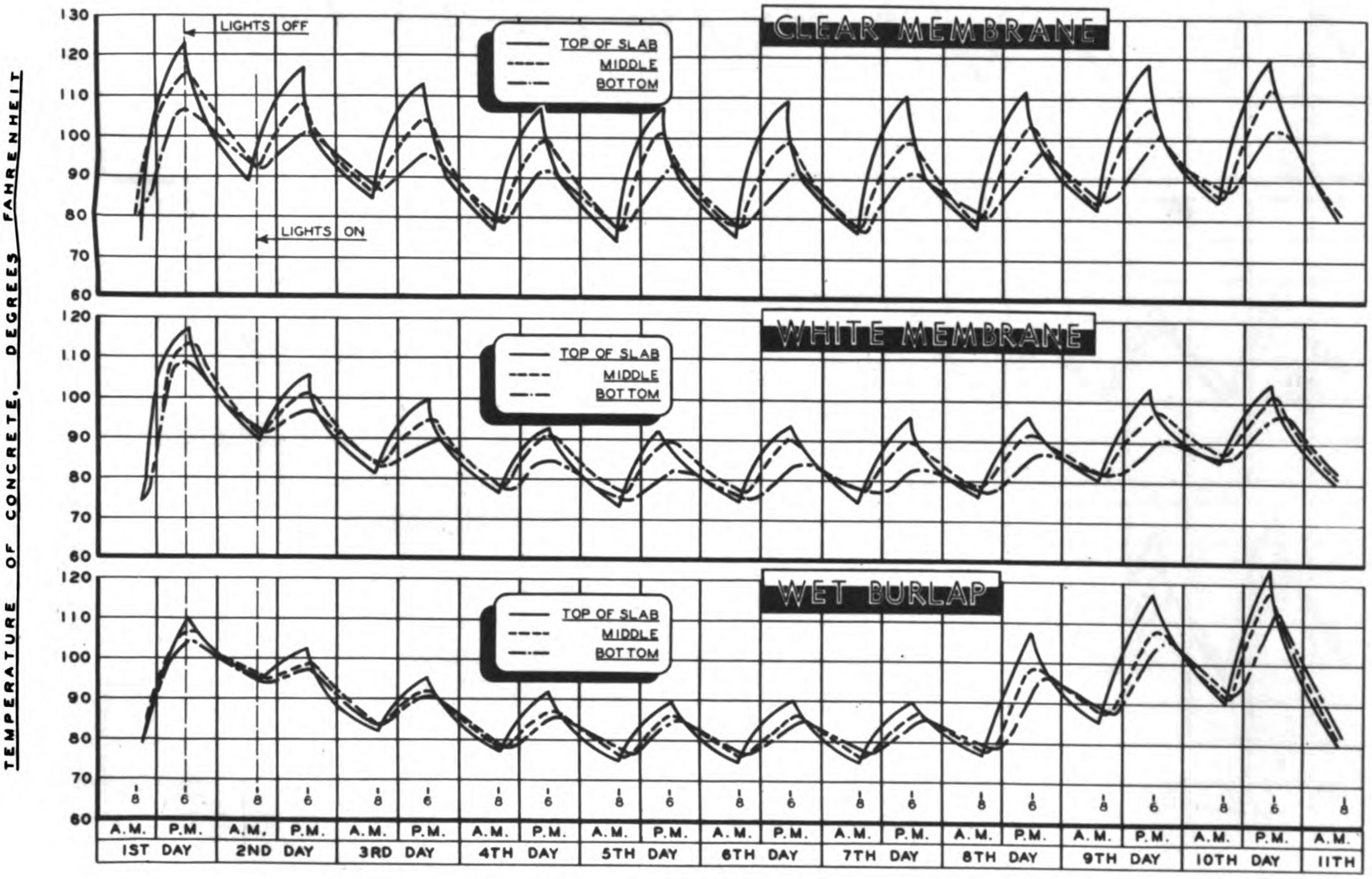
Discussion

The warping curves in Figures 17 to 20 incl. show that there is only relative downward warping and that a progressive permanent set exists in membrane cured beams that increases for approximately six days. Three factors influential in producing warping (movement of ends relative to center) are: (1) temperature gradients, (2) moisture gradients, (3) differential autogenous volume change.

During summer paving, temperature gradients of twenty degrees may be established in the concrete four hours after finishing. This results in differential thermal volume change which occurs without stress due to plastic flow, as the concrete has not yet assumed its elastic properties. The beams exhibit elastic properties at an age of eight hours when the dynamic modulus of elasticity is about 2.5×10^6 (35% of total E). This elastic structure is established at a time when a temperature difference of twenty degrees F. exists between the top and bottom fibers. When the temperature gradient is reduced or top and bottom fibers are at the same temperature, the beams warp upward.



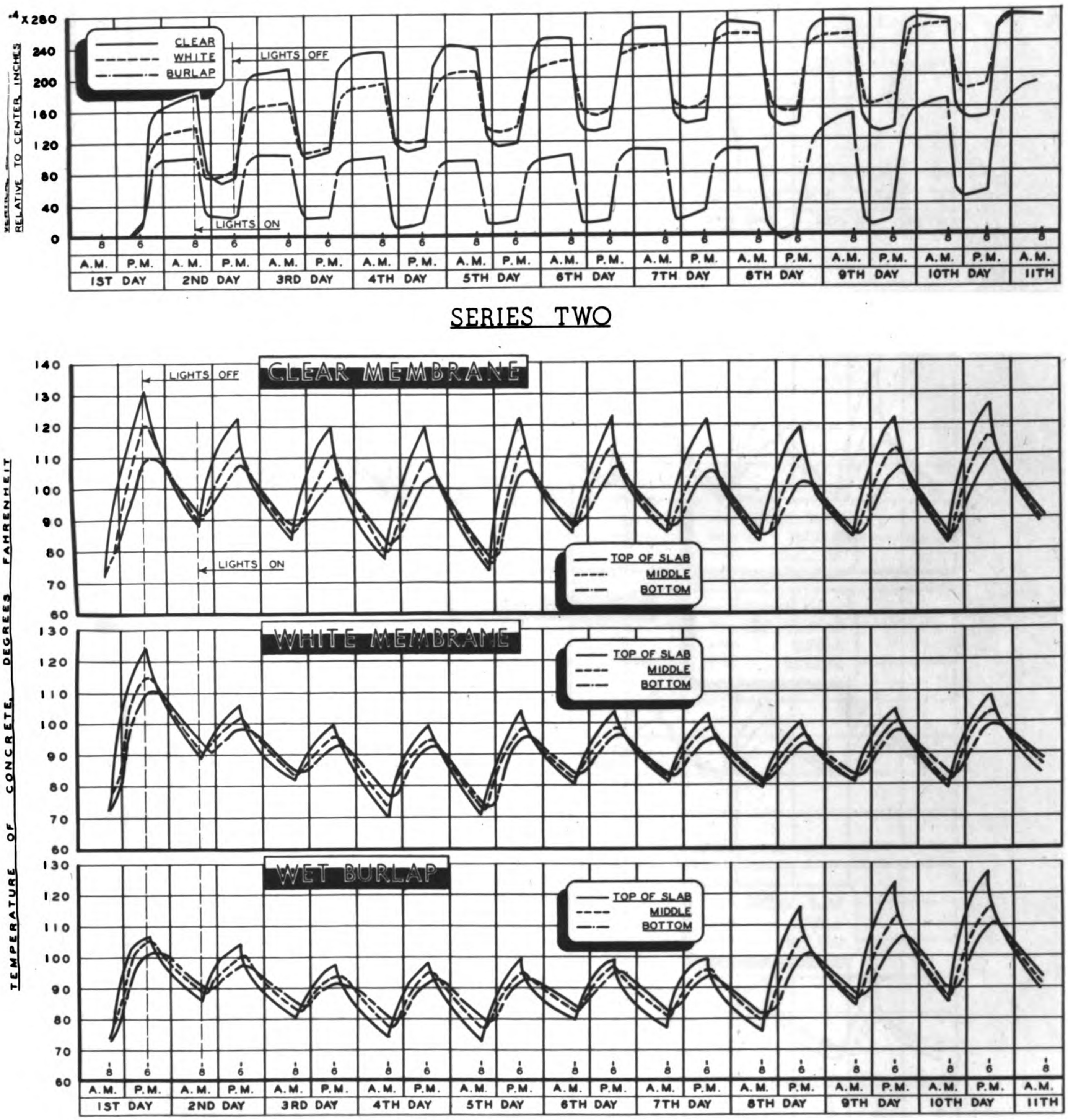
SERIES ONE



WATERPROOFED SUBGRADE

TEMPERATURE GRADIENTS AND WARPING
IN RELATION TO CURING AND SUBGRADE CONDITIONS

FIGURE 17



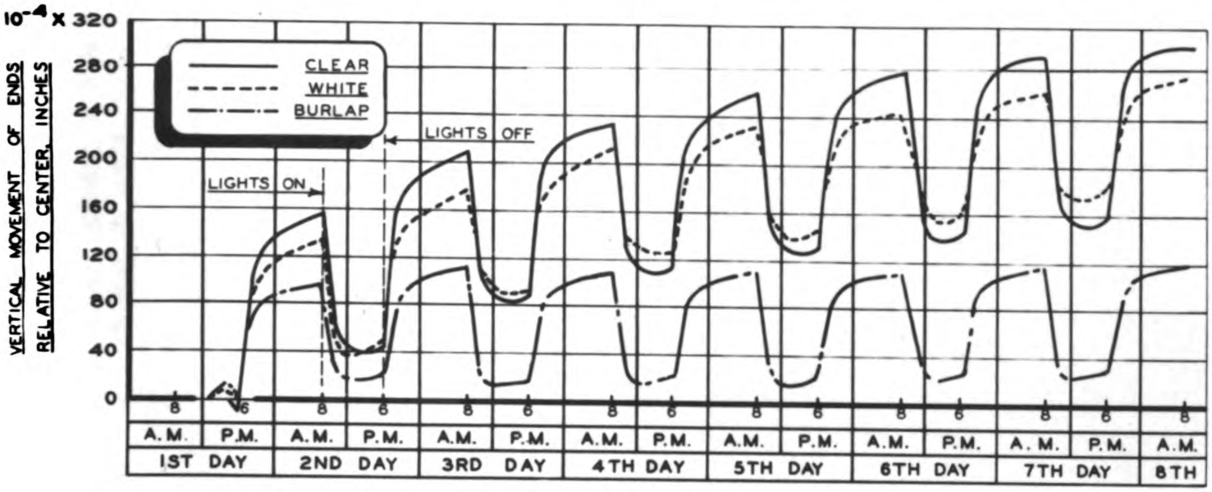
DRY SAND SUBGRADE

TEMPERATURE GRADIENTS AND WARPING
IN RELATION TO CURING AND SUBGRADE CONDITIONS

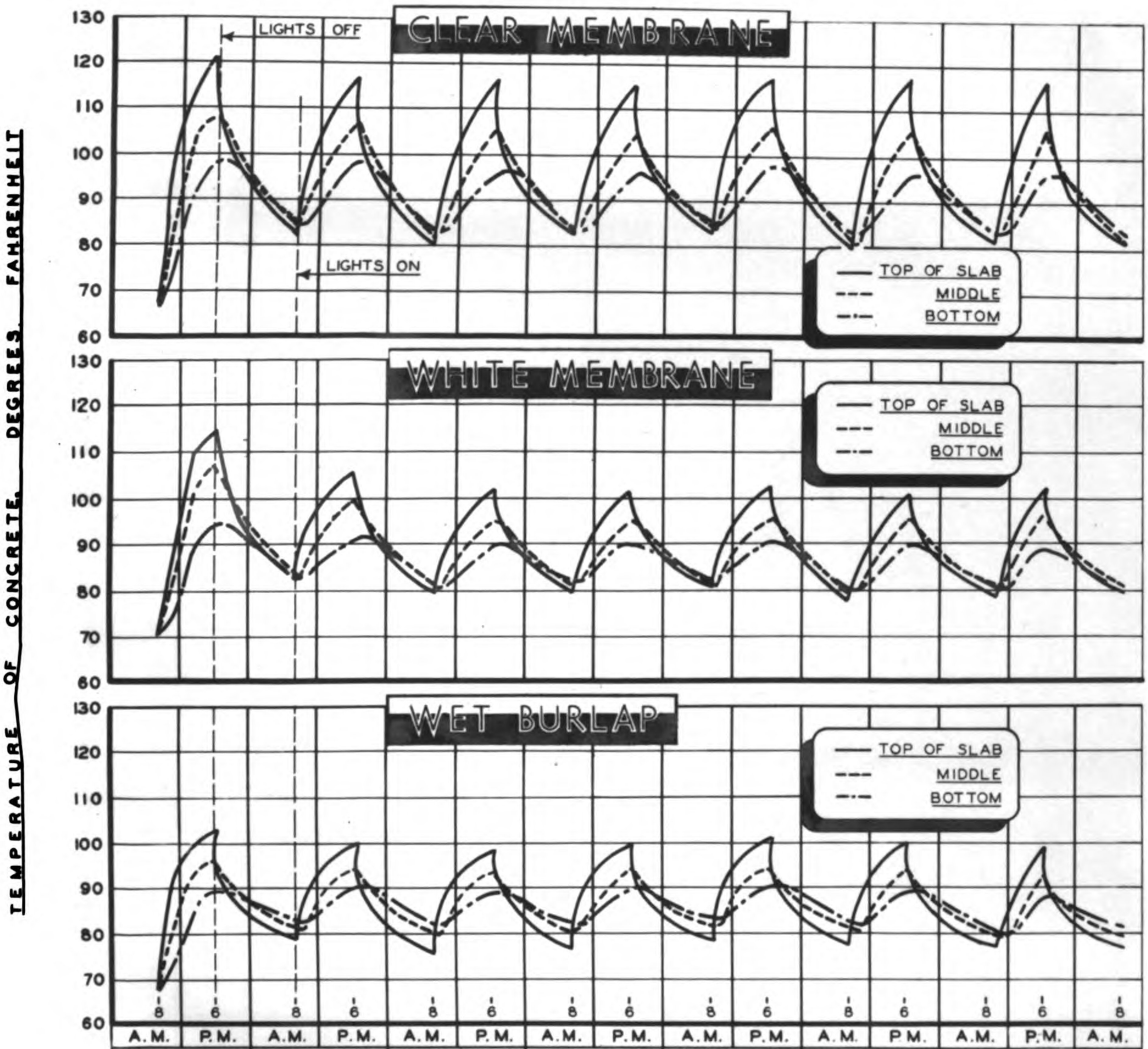
FIGURE 18

TEMPERATURE OF CONCRETE, DEGREES FAHRENHEIT

VERTICAL MOVEMENT OF ENDS RELATIVE TO CENTER, INCHES



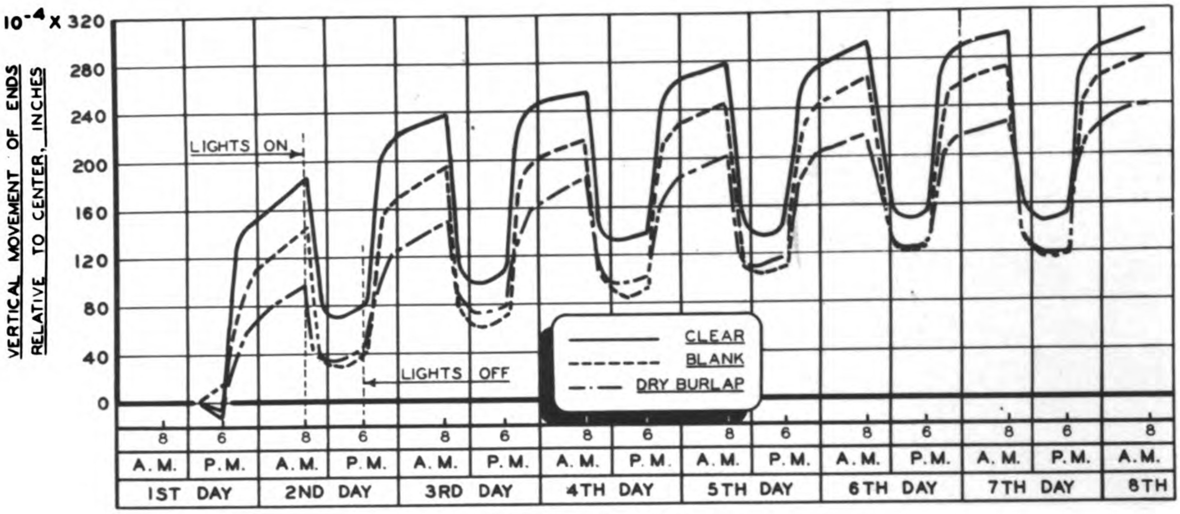
SERIES THREE



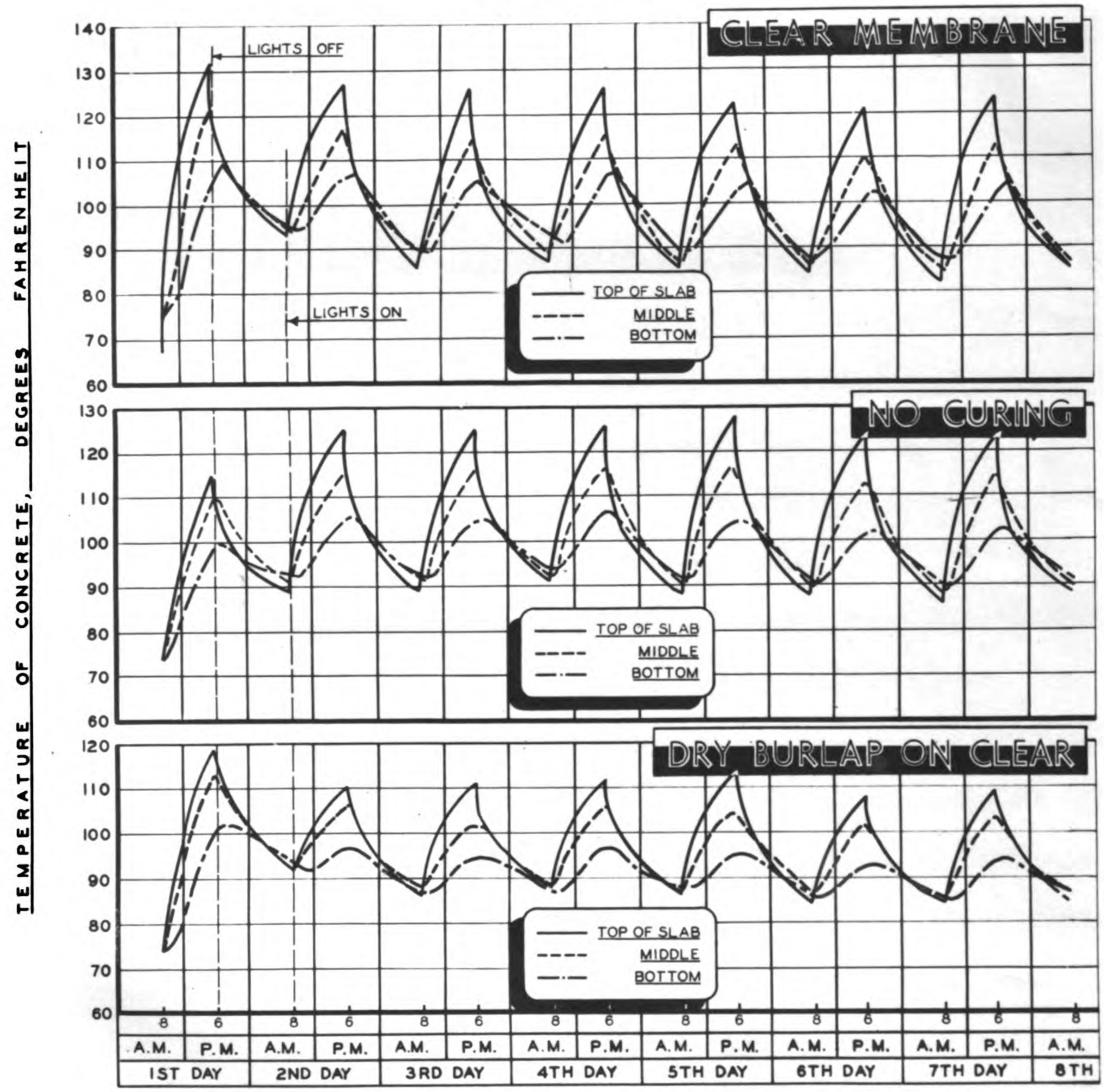
SATURATED SAND SUBGRADE

TEMPERATURE GRADIENTS AND WARPING
IN RELATION TO CURING AND SUBGRADE CONDITIONS

FIGURE 19



SERIES FOUR



SATURATED SAND SUBGRADE

TEMPERATURE GRADIENTS AND WARPING

IN RELATION TO CURING AND SUBGRADE CONDITIONS

FIGURE 20

Moisture gradients effective in producing warping are not established until after surface moisture has disappeared; usually about two hours after finishing. As evaporation occurs from the top surface, the upper fibers shorten and cause upward warping. Slight delays in the application of curing material generally will not affect warping from this cause to any extent as plastic flow will relieve stresses up to an age of five hours. However, it is not advisable to delay application as hair cracking and crazing are apt to occur due to rapid drying.

Due to temperature variations at different levels in the beam, the concrete is proceeding through its chemical reaction at a varying rate. That is, the concrete in the surface layer has set and is developing strength at a more rapid rate than the concrete in the bottom layer. This causes differential autogenous volume change which is always shrinkage (25). Autogenous volume change is caused by the difference in volume of the hydrated cement particles and the unhydrated cement particles plus water. The unhydrated cement particles plus water have a lower specific gravity than the solid products of hydration plus the remaining water.

The total warping is the algebraic sum of warping caused by temperature and moisture gradients and differential autogenous volume change. When the heat source is removed, all three factors are effective in producing upward warping. After ten hours at a high (125°) temperature, the concrete has developed 40% of its total dynamic modulus and, therefore, has sufficient strength to warp when the temperature gradient is reduced. The ordinate of the time-warping curve, when there is a negligible temperature gradient, is referred to as permanent set and is a combination of the three effects stated above. When heat is applied to the top surface of membrane cured beams the amount of upward warping is decreased but never entirely eliminated. When maximum temperature gradients are established the ordinate of the warping curve indicates warping from effects other than temperature, as the temperature gradient at this time is similar to the gradients that existed when the concrete assumed its final structure. It is doubtful that conditions would be established in the field that could result in other than relative downward warping.

The effect of removal of the wet burlap is well shown in Series II. The wet burlap was removed after seven days and the permanent set increased 75% in three days. Had time permitted sufficient observations, it is likely that the permanent set of the wet burlap cured beams would equal the set of the membrane cured beams which had reached a constant value at six days. The burlap was continuously moist for the seven day period, a condition that is difficult, if not impossible, to duplicate in the field.

The slight difference in the warping curves of Series I and II, and III and IV for the first four hours can be attributed to a one hour difference in the time of initial readings. The initial readings of Series I and II were taken one hour later than the initial readings of Series III and IV. A twenty-four hour delay in the time of initial reading can influence the trend of the curves greatly. Results of observations begun at this time would show both upward and downward warping occurring with various temperature gradients. From data for this series of tests, in which the concrete assumes its final structure with temperature gradients present, as in summer paving, it is reasonable to conclude that the pavement will never be actually warped downward, but will only vary in degree of upward warping.

The beams in these tests show that measurable warping occurs at an age of about six hours at which time the modulus of rupture of the concrete is approximately 120 psi. The maximum stress due to the weight of the beam as it is lifted is 52 psi and is not sufficient to cause cracking.

The behavior of the air-cured beam of Series IV is interesting because it shows less warping than the clear membrane cured beams. This can be explained by the cooling effect of the white color of the concrete surface and rapid evaporation from the top surface, both of which result in lower temperatures and less difference in temperature between the top and bottom fibers. The rapid moisture loss from the surface also causes a differential volume change between top and bottom fibers that is relieved by plastic flow at early ages, but is influential in producing a slight upward warping at an age of six hours. From the age of twenty-four hours until seven days the daily changes are of the same magnitude as the changes for the clear membrane cured beam, but the maximum warping is only 88% of the maximum total warping of the clear membrane cured beam, which emphasizes the importance of temperature control during early curing periods.

The white membrane compound accomplishes its intended purpose and reduces the temperature of the concrete during curing. There is a reduction in temperature of fifteen degrees from those temperatures experienced during the seven day curing period in concrete cured with clear membrane compound. The temperature gradient present when the concrete assumes elastic properties is responsible for about 95% of the permanent set existing at an age of twenty-four hours, and, therefore, temperature control at early ages is important.

To reduce temperatures during curing, a dry burlap covering was applied to the surface of a beam that had been sprayed with clear membrane compound. It was found that a temperature reduction of fifteen degrees followed this practice and resulted in a 26% decrease in warping when compared with beams cured with only clear membrane compound. Comparable results were obtained by use of white membrane compound.

The data computed from the resistance of moisture cells is of little value except to indicate trends. The moisture that is in chemical combination with the cement and is therefore still present in the concrete does not affect the cells, which indicate only the unbound water in the concrete. Whether this moisture is lost by evaporation or is in chemical combination can not be determined from these observations. The moisture cells indicated a change of approximately 28% in the unbound water in seven days, part of which was lost by evaporation. The flexural strength showed satisfactory development at this age and tends to substantiate the fact that the original mixing water is more than sufficient to hydrate the cement.

Table IV shows the relative hardness of the finished surface or resistance to penetration. This data indicates that the surface hardness is only slightly affected by the curing methods used. The average depth of wear penetration of wet burlap cured concrete is 17.5% less than the depth of wear penetration of clear membrane cured concrete and 5% less than that of white membrane cured concrete. The time-depth of penetration curve is approximately linear after a depth of 1/32 inch has been penetrated.

FIELD STUDIES

To determine the problems existing in practice regarding application, rate of coverage, and maintenance of films after application, two one hundred foot sections of a paving project were cured with white membrane compound. The rest of the project was cured with clear membrane compound. Three thermocouples and three Bouyoucos moisture cells were imbedded in the concrete at different levels to determine temperature and moisture gradients. For measurements of warping, seven clinometer plugs forty inches apart were placed in the top surface of the slab parallel to and eighteen inches in from the edge. Measurements some years ago on another pavement had indicated that warping of one hundred foot slabs was confined to the end sixteen feet. The clinometer plugs extended twenty feet from each side of the joint. It was revealed in a short time that this twenty foot length was insufficient as the warping, or curling, extended much farther back than this.

The flexural specimens made from the paving mix were cured with clear membrane compound. The finished surface was sprayed at 200 square feet per gallon when the surface moisture had disappeared. At twenty-four hours the forms were stripped and the remaining surfaces sprayed. The specimens were then placed on the pavement surface for six days. Results of tests at seven days show that flexural strengths need not be a matter of concern, as beams cured in this manner have moduli of rupture well above the minimum required by Michigan State Highway Specifications.

The white membrane compound presented slight difficulties during application. The pigment settled rapidly and formed soft solids which clogged the nozzle of the spraying apparatus and prevented rapid and efficient coverage.

Several photographs taken at the time of application and at an age of two months show the contrast between the two membrane films at 200 square feet per gallon. The white membrane compound left traces that were barely visible after two months, but at no time after the pavement was open to traffic was the glare objectionable. See Figures 21, 22 and 23.

Discussion

The curves in Figure 24 were plotted from clinometer readings as follows: (1) point seven (240 inches from the joint) was considered as fixed so no vertical movement occurred, (2) the ordinate of point six (200 inches from the joint) is the change in elevation of point six in relation to point seven, (3) the ordinate of point five is the sum of the ordinate of point six and the change in elevation between point five and point six. The ordinate of point one is then the change in elevation of point one with respect to point seven. Since point seven is not fixed as assumed, the ordinates of the other plotted points will vary according to the vertical movement of point seven. This movement is not significant up to an age of three days. The curves, although not presenting a complete picture, are valuable in showing the type of warping that does occur and are in agreement with the laboratory warping studies.

The pavement was poured in mid-September and the high temperatures normally experienced during summer construction were not encountered. The highest temperature in the clear membrane cured slabs was ninety-seven degrees F. and in the white membrane cured slabs was eighty-seven degrees F. The temperature difference between the top and bottom fibers was only ten degrees in both slabs.

21. Photo indicates initial difference in appearance of white and clear membrane applications (9-17-46). Current spraying equipment for applying clear membrane compounds is shown in background.

22. General view of pavement after application of membrane films. (9-17-46).

23. General view showing condition of pavement two months after application of white and clear membrane compounds. (11-13-46)

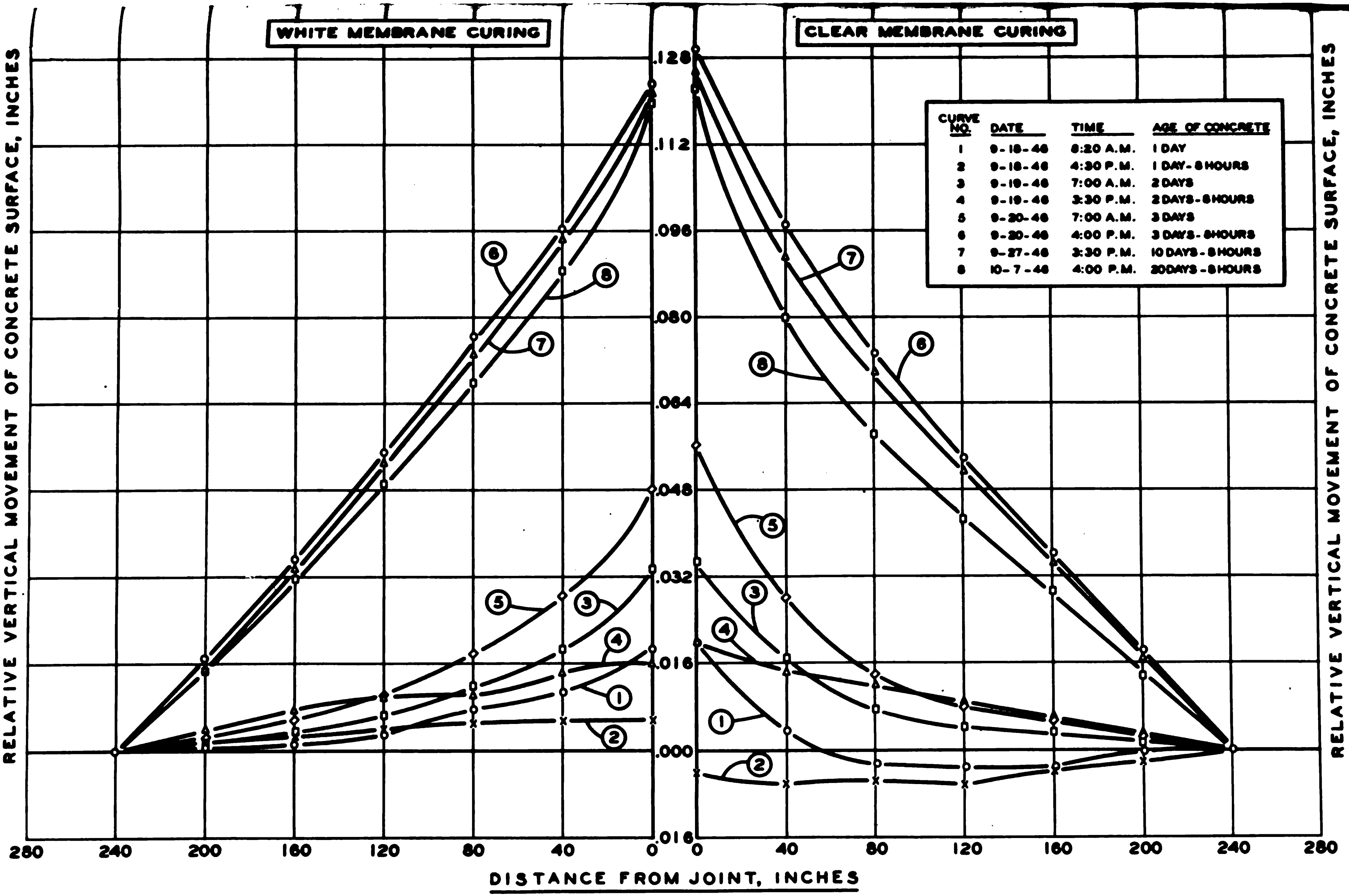


FIGURE 24

EARLY WARPING of 100 FOOT PAVEMENT SLABS at a CONTRACTION JOINT

After an age of thirty-two hours the minor irregularities disappeared and there was upward warping only. Different temperature gradients changed the magnitude but not the direction of the warping. At an age of three days the warping increased considerably as did the slope of the curve at point seven. This indicates that prior to this age the warping was confined to the end twenty feet of the slab and at subsequent ages the strength of the concrete was adequate to support a greater load and warping was occurring over a greater length, possibly one-half of the slab or fifty feet.

The curves show that warping was not affected appreciably by the type of membrane curing compound for this pavement which was poured under moderate summer conditions. The white membrane compound applied during hot summer days would reduce the temperature gradient and result in lower stresses as the pavement cools and warps. The temperatures and temperature gradients present when the concrete assumes elastic properties are the most influential factors in producing warping at an age of twenty-four hours. Thus, if temperature control is rigidly exercised during the early curing period the stresses which are developed when temperature gradients are reduced and the stresses resulting from slab movement on the subgrade due to thermal volume change will be minimized.

There has been only a small amount of highway paving in the past two years and, therefore, scant information is available regarding present day cost of burlap curing, ponding, and other curing methods except curing with membrane compounds. Recent investigations reveal that the cost of membrane curing will vary from $0.08 to $0.10-1/2 per square yard. Unit costs of membrane curing are easily determined because of the ease of application (requiring at most two men) and because the cost per gallon for membrane compounds is fairly well established. It is difficult to determine present day unit costs for burlap curing and ponding due to scarcity of labor and materials. Although there is some disagreement among local contractors, it is fairly well established that other curing methods will cost from two to three times as much as membrane curing. In addition to reducing costs, membrane curing eliminates application and inspection difficulties, which have been considerably magnified by the speed of modern paving practice. Experience indicates that keeping burlap continuously moist in the field is almost impossible, and that strength and durability may be reduced due to wetting and drying during the early curing period. It is felt that the slow moisture loss occurring through membrane films is more satisfactory than the rapid moisture changes occurring in intermittent burlap curing. The physical properties of membrane cured concrete at seven days are not equal to the physical properties of concrete cured with continuously moist burlap, but previous investigations (14,26) reveal that these initial differences disappear in time. These differences in properties are not great at seven days and it is estimated that at an age of fourteen days they will be eliminated (28). When comparing various physical properties it is assumed that when curing the burlap is kept moist, which in field operation is not the case. Alternate wetting and drying plus the effect of "thermal shock" when the burlap is removed can be expected to induce stresses and result in a reduction in strength and other physical properties.

In conclusion, membrane curing can be expected to produce concrete equal in quality at an age of fourteen days to the concrete produced by seven day initial wet burlap curing; to alleviate application, maintenance, and inspection problems and reduce costs.

CONCLUSIONS

1. Evidence indicates that the original mixing water is more than adequate to provide for the hydration requirements of the cement.
2. There is a strong possibility that an optimum moisture content of 85% of the original mixing water will provide a concrete with the maximum desirable qualities.
3. The resistance to wear penetration was not affected appreciably by method of curing.
4. Large temperature differentials in the slab when the concrete assumes elastic properties are primary causes of warping at early ages.
5. Pavements poured during summer months will undergo only upward warping.
6. Temperature control is the most important factor to be considered during the early hardening period.
7. Membrane curing can be expected to give results favorably comparable to wet burlap curing.
8. White membrane compounds are superior to the clear compounds for hot summer paving.

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BIBLIOGRAPHY

1. 1926, A. C. I., Vol. XXII, p. 395

2. 1926, Vol. XXV, Pp. 522-549

3. 1929, A. S. T. M. Proceedings, Vol. XXIX, Part I, p. 303, "Report of Sub-Committee on Curing of Concrete"

4. 1929, A. C. I., Vol. XXV, p. 210, "Volume Changes" by R. E. Davis

5. 1929, Highway Research Board, "Special Investigations of Curing of Concrete Pavement Slabs" by Lang and Burgraff

6. 1930, A. C. I., Vol. XXVI, p. 359, "Study of Methods of Curing Concrete" by H. F. Gonnerman

7. 1930, A. C. I., Vol. XXVI, p. 407, "Investigations of Volumetric Changes in Concrete from Causes Other Than Stress" by R. E. Davis

8. 1930, Highway Research Board, p. 370, "Special Investigations of Curing Concrete Pavement Slabs" by F. C. Lang

9. 1931, A. S. T. M. Proceedings, Vol. XXXI, Part I, p. 356, "Curing Digest" by F. C. Lang

10. 1931, A. S. T. M. Proceedings, Vol. XXXI, Part I, p. 331, "Report of Sub-Committee on Curing of Concrete"

11. 1931, Highway Research Board, Pp. 240-261, "Factors Affecting Volume Change in Concrete and Their Significance in Design" by C. H. Scholer

12. 1931, Highway Research Board, Part I, Pp. 262-270, "Volume Changes in Concrete Slabs in the Field" by Bert Meyers

13. 1932, Highway Research Board Proceedings, p. 339, "Use of Paper for Curing Concrete Pavements" by M. Morris

14. 1934, Highway Research Board, "Intermittent Curing of Concrete" by F. C. Lang

15. 1934, A. S. T. M. Proceedings, Vol. XXXIV, Part II, p. 38, "Effect of Duration of Moist Curing on the Principal Properties of Concrete" by Timms

16. 1935, A. C. I. Proceedings, Vol. XXXV, p. 368, "Methods of Test for Determining Volume Changes in Concrete" by R. E. Davis

17. 1935, A. S. T. M. Proceedings, Vol. XXXV, p. 380, "Chemistry and Physics of Concrete Shrinkage" by R. W. Carlson

18. 1935, A. S. T. M. Proceedings, Vol. XXXV, Part II, p. 383, "Shrinkage of Concrete" by Inge Lyse

19. 1938, A. C. I. Proceedings, Vol. IX, "Concrete Curing Compounds" by Meissner and Smith

20. 1938, A. C. I. Proceedings, p. 34, "Measurement of Moisture Content in Concrete" by R. W. Spencer

21. 1938, A. C. I. Proceedings, January-February, p. 371, "Impervious Membrane Cures"

22. 1939, Highway Research Board, p. 284, "Experiments in Curing Concrete Pavements" by Bert Meyers

23. 1940, A. C. I. Proceedings, April, p. 529, "Testing the Efficiency of Concrete Curing Methods" by H. D. Dewell

24. 1942, Highway Research Board, p. 352, "Volume Changes in Sand Gravel Concrete" by Jackson and Kellerman

25. 1942, A. C. I. Proceedings, April, p. 425, "Early Volume Changes and Their Control" by M. A. Swayze

26. 1943, A. S. T. M. Proceedings, Vol. XLIII, Pp. 1051-1065, "Effect of Curing Methods on Durability of Concrete as Measured by Changes in Dynamic Modulus" by B. G. Long and H. J. Kurtz

27. 1944, Highway Research Board, p. 207, "Influence of Various Curing Methods on Strength and Abrasive Wear Resistance of a Portland Cement Concrete" by H. C. Vollmer

28. 1946, A. C. I. Proceedings, April, p. 493, "Curing Concrete With Sealing Compounds" by Blanks, Meissner and Tuthill

29. 1946, A. C. I. Proceedings, January-February, "Shrinkage Stresses in Concrete" by G. Pickett