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Michigan tests indicate the place of membrane curing in the pavement construction scheme.

Curing Concrete Pavements With Membranes*

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SYNOPSIS

To provide data to assess the advisability of continuing membrane curing of concrete pavements as an alternate method, laboratory and field tests were made to compare the effect of storage conditions on the physical properties of concrete, warping, temperature control, and strength and abrasion resistance of concrete cured with membranes and with wet burlap. A survey of pavements cured with clear membranes in spring and summer showed that cracking, when it occurred at all, was found predominantly in pavements laid in the morning hours. Comparing white-pigmented membranes with the usual wet-curing conditions in the field it was found to be efficient, practicable and about half as expensive as wet curing under the same conditions.

Despite the obvious advantages of membrane curing, many engineers have considered it only a wartime substitute for wet curing to be abandoned as soon as conditions permitted. Thus a thorough evaluation of the membrane method was desirable to determine whether it should be continued as an alternate method of curing concrete pavements.

Too little attention has been devoted in the past to an important function of curing—that of stress control by regulating early temperature and moisture changes in the concrete slab. Throughout this investigation, therefore, this regulatory function received fully as much emphasis as the hydration needs of the cement. Discussion of the fundamental factors in curing is contained in the basic report[1] of which this paper is a condensation.

The results indicate that membrane curing is an acceptable method provided the concrete is protected from the radiant heat of the sun during hot, clear weather to reduce premature cracking to a minimum. When employing membranes, probably the use of white pigments in the curing compound is the most practicable means of temperature control since it involves only a single field operation and is immediately active in retarding temperature rise.

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TABLE 1—SUMMARY OF CABINET

Curing conditions			8 hours			16 hours				24 hours			
Temp. ° F	Rel. hum., percent	Seal, sq ft per gal.	Moist. loss, per-cent	Dyn. mod., 10⁶psi	Flex. str., psi	Moist. loss, per-cent	Length change, percent	Dyn. mod., 10⁶psi	Flex. str., psi	Moist. loss, per-cent	Length change, percent	Dyn. mod., 10⁶psi	Flex. str., psi
75	30	0	12.1	.27	7	28.6	−.007	1.58	59	49.7	−.009	3.42	146
		200	10.0	.35	12	14.3	+.002	2.39	117	19.7	−.002	4.28	257
		100	11.5	.29	14	14.7	+.006	2.59	114	17.2	+.004	4.34	275
	50	0	10.1	.56	21	30.3	+.002	1.91	104	43.3	+.001	3.15	153
		200	6.6	.42	25	14.8	+.005	2.36	154	21.2	+.005	4.09	252
		100	6.8	.42	29	12.8	+.005	2.47	170	14.9	+.005	4.32	309
	95	0	8.7	.35	22	13.6	.000	2.43	116	17.9	+.001	4.58	276
		200	8.2	.35	22	12.6	+.004	2.58	120	14.5	+.003	5.32	331
		100	7.5	.38	21	11.8	+.003	2.62	150	12.8	+.002	5.26	346
	in water*	0	11.3	.47	16	11.3	+.008	2.47	127	11.0	+.015	4.09	250
100	14	0	18.5	.96	60	50.0	+.001	2.71	150	58.5	−.006	3.01	156
		200	8.3	1.30	74	24.0	+.002	3.62	250	35.8	−.002	4.32	275
		100	8.3	.87	63	17.3	+.006	4.22	266	27.8	+.002	4.50	330
	50	0	13.4	1.47	76	36.6	−.003	2.93	220	45.4	−.005	3.71	302
		200	9.7	1.85	88	20.1	−.001	3.48	321	26.3	−.005	4.48	429
		100	9.6	1.75	95	16.3	+.003	4.06	274	19.8	+.001	4.57	399
	95	0	9.9	1.88	66	16.8	+.007	4.53	269	21.0	+.001	5.34	344
		200	6.8	1.75	94	11.7	+.005	4.53	321	13.6	+.003	5.37	421
		100	7.3	1.84	80	11.9	+.003	4.35	293	13.1	+.003	5.34	403
	in water*	0	7.2	.50	20	6.9	+.009	3.46	177	5.9	+.009	4.63	294
120	10	0	22.0	1.59	90	52.1	−.002	3.14	163	62.3	−.007	3.44	176
		200	8.9	1.90	102	28.4	−.001	3.85	205	40.4	−.006	4.74	292
		100	8.4	1.58	100	23.4	+.006	3.88	260	32.1	+.004	4.98	316
	50	0	17.1	2.37	136	40.6	−.004	3.99	227	47.4	−.008	4.18	247
		200	8.5	2.77	156	22.9	−.006	4.51	315	30.3	−.010	4.96	347
		100	8.0	3.05	130	18.1	−.004	4.38	335	23.7	−.007	5.03	400
	95	0	10.3	2.68	138	18.4	−.001	4.60	246	23.9	−.003	5.28	310
		200	7.1	2.50	150	14.1	+.001	4.63	269	17.9	+.001	5.33	332
		100	6.6	2.53	131	12.5	+.003	4.62	283	15.1	+.002	5.43	347
	in water*	0	9.8	0.34	24	9.2	−.001	4.93	209	9.1	+.005	5.99	362

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

LABORATORY STUDIES

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

Effect of storage conditions on physical properties of concrete

Scope of the 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 used to study 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

STORAGE DATA—3 x 3 x 15-in. BEAMS

2 days				3 days				7 days			
Moist. loss, percent	Length change, percent	Dyn. mod., 10^6psi	Flex. str., psi	Moist. loss, percent	Length change, percent	Dyn. mod., 10^6psi	Flex. str., psi	Moist. loss, percent	Length change, percent	Dyn. mod., 10^6psi	Flex. str., psi
58.0	−.013	4.28	191	60.5	−.014	4.42	185	65.2	−.024	4.25	248
24.7	−.004	5.50	393	27.1	−.005	6.51	421	34.5	−.010	7.33	430
20.3	+.006	6.04	423	22.7	+.008	6.44	569	27.9	−.001	7.47	512
49.1	−.003	4.15	239	51.2	−.006	4.26	224	55.0	−.013	4.63	299
27.4	+.003	5.38	337	29.9	+.002	5.62	418	37.0	−.006	5.84	557
17.5	+.003	5.43	465	19.6	−.001	6.13	503	24.7	−.003	6.32	568
22.3	+.001	6.03	407	24.2	.000	6.82	395	28.9	.000	7.40	420
16.1	+.004	6.20	442	17.2	+.005	6.80	456	20.2	+.004	7.33	552
14.1	+.003	6.10	406	14.8	+.005	6.77	495	18.3	+.002	7.18	638
9.3	+.011	5.81	427	8.5	+.013	6.24	532	6.7	+.014	7.52	757
63.8	−.014	3.65	187	66.5	−.015	3.81	218	71.6	−.023	3.92	243
43.5	−.007	5.15	323	49.0	−.011	5.13	320	57.0	−.023	5.12	373
34.8	−.002	5.58	419	38.7	−.005	5.48	401	49.3	−.018	5.60	412
51.6	−.009	4.28	310	54.1	−.006	4.24	310	58.5	−.016	4.27	351
35.0	−.008	5.41	459	37.8	−.010	5.58	433	45.9	−.018	5.47	456
25.8	.000	5.35	536	28.2	−.001	5.73	478	36.2	−.009	5.65	551
24.4	+.001	6.28	377	26.6	−.001	6.62	429	31.5	−.005	6.77	467
16.4	+.003	6.49	475	18.3	+.001	6.82	486	22.9	−.002	7.08	579
14.6	+.002	6.43	526	16.0	+.002	7.14	557	19.5	−.005	7.26	572
5.1	+.012	6.08	467	3.6	+.010	6.81	462	0.0	+.007	7.53	581
69.0	−.012	3.83	230	68.3	−.017	3.68	259	71.7	−.023	3.67	280
49.6	−.012	4.98	293	56.4	−.019	4.94	328	63.7	−.025	4.83	438
41.0	−.001	5.62	332	46.5	−.008	5.66	360	52.8	−.013	5.79	430
54.0	−.012	4.23	267	56.7	−.015	4.24	277	62.7	−.022	4.30	302
39.1	−.014	5.07	349	43.3	−.017	5.01	352	53.2	−.021	4.85	390
31.0	−.011	5.37	360	34.9	−.014	5.34	378	44.7	−.021	5.24	381
29.3	−.004	5.75	381	32.1	−.005	5.90	355	34.4	−.010	6.12	459
21.8	−.002	6.24	386	24.6	−.006	6.43	444	28.7	−.013	6.82	493
18.2	−.002	6.09	461	19.7	−.001	6.40	487	23.1	−.006	6.78	551
8.9	+.005	6.99	439	8.5	+.003	7.07	509	7.0	+.006	7.53	633

humidities of 10, 50 and 100 percent. The only significant deviation was at 75 F where the minimum humidity attainable was 30 percent.

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 sq ft per gal. respectively. Details of materials, mix proportions and the procedure followed in making, storing and testing the specimens have been described elsewhere.[1]

Discussion—Quantitative data on the behavior of air-entraining concrete under a variety of environmental conditions make possible an approximate evaluation of different curing methods on the basis of the particular set of conditions produced by each. Also the several groups of specimens can be considered to represent elements of a concrete slab at different depths below the surface on a summer day and data from these tests will be used later for stress calculations.

The cabinet storage data are presented in Tables 1 and 2. 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 to 7 days was not sufficient to restore all of the moisture lost during setting and hardening prior to immersion.

TABLE 2—SUMMARY OF CABINET DATA—3 x 6-in. CYLINDERS

Curing conditions			8 hours		16 hours		24 hours		2 days		3 days		7 days	
Temp., ° F	Rel. hum., percent	Seal, sq ft per gal.	Comp. str., psi	Moist. loss, percent	Comp. str., psi	Moist. loss, percent	Comp. str., psi	Moist. loss, percent	Comp. str., psi	Moist. loss, percent	Comp. str., psi	Moist. loss, percent	Comp. str., psi	Moist. loss, percent
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	1169	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	1585	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.

Even at the relatively large moisture losses observed, the strength and modulus of elasticity of the concrete were not adversely affected to any considerable extent until moisture losses of 20 to 25 percent were exceeded.

The data in Table 1 also show generally that there was no shrinkage from the 8-hour length at any test age or temperature 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. Strength and dynamic modulus increased rapidly during the first day, especially the first 16 hours, and were accelerated by higher temperatures. At the lower humidities maximum flexural strength and dynamic modulus were attained quickly at a low level due to rapid drying but little increase took place after 3 days; at the higher temperatures there was 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 in air at 95 percent relative humidity 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.

Warping tests

Scope—The principal object of these experiments was to measure the warping of 8 x 12 x 84-in. 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 solely for heat insulation.

A bank of incandescent bulbs provided sufficient radiant heat to produce a maximum temperature of 120 to 130 F in the top surfaces of beams cured with clear membrane. Details of materials and procedures used in these tests may also be found in the publication already referred to.[1]

After curing, 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-in. span. Immediately after the flexural tests, the fractured surface was sprayed with phenolphthalein in absolute alcohol to determine the depth of desiccation. Data for these tests are given in Table 3 and photographs of the beams of Series 1 are shown in Fig. 1, in which the desiccated 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 which indicates less surface desiccation 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. 2. A load of 18 lb was applied to the wearing tool by suspending a 1-lb weight from the end of the drill press arm. Data are given in Table 4, each value representing the average of 18 tests.

Warping—The time-warping curves of Fig. 3 through 6 show that the beams kept continuously moist with wet burlap varied least in temperature and warped least of any in the four series of tests. Beams cured with clear membrane are at the opposite extreme, while those with white membrane coatings show a substantial reduction of both temperature and warping from these upper extremes. It should be pointed out 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 to the concrete, an important factor in the problem.

All beams 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 downward. This can be attributed to the influence of (1) temperature gradients at the time the concrete is passing from the plastic to the elastic state, (2)

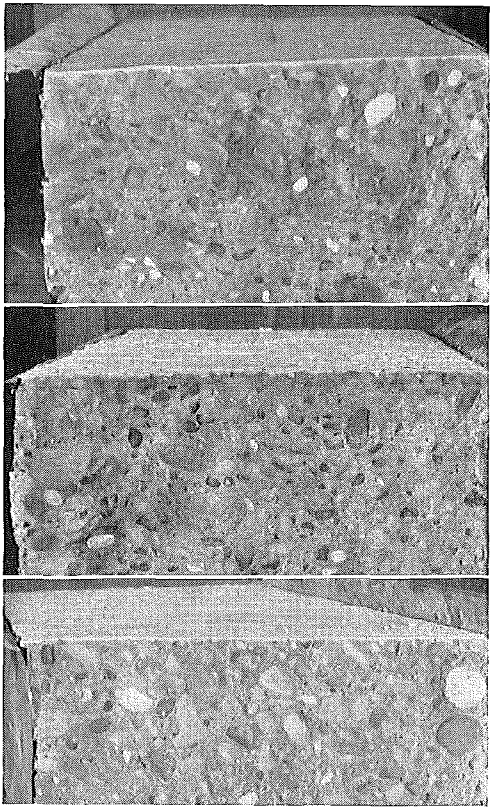


Fig. 1—Surface desiccation of beams on waterproofed subgrade. Desiccated layer shows as a thin white line across the top of the fracture. Upper—Clear membrane, 10 days. Middle—White membrane, 10 days. Lower—Wet burlap 7 days, air 3 days

TABLE 3—FLEXURAL STRENGTH AND SURFACE DESICCATION OF BEAMS USED IN WARPING TESTS

Series	Subgrade	Duration of curing, days	Curing treatment	Flexural strength, psi	Thickness of desiccated layer, in.
1	Waterproofed	10	Clear membrane	511	⅛
			White membrane	528	$\frac{1}{16}$
			Wet burlap*	690	$\frac{1}{16}$
2	Dry sand	10	Clear membrane	578	⅛
			White membrane	596	$\frac{1}{16}$
			Wet burlap*	687	$\frac{1}{16}$
3	Saturated sand	7	Clear membrane	563	$\frac{1}{16}$
			White membrane	655	Slight
			Wet burlap	725	Slight
4	Saturated sand	7	Clear membrane	634	$\frac{3}{32}$
			Dry burlap on clear	588	$\frac{1}{16}$
			No curing	536	$\frac{5}{32}$

*Wet burlap removed at the end of 7 days.

moisture gradients and (3) differential autogenous volume change.

Vertical temperature differences of 15 degrees or more were established in the 8-in. slabs before final set took place and produced a differential thermal volume change which occurred initially without appreciable stress because of the plasticity of the concrete in this interval. The data in Table 1 show 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 was still greater. Thus, an elastic structure is being established 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 later reduction of the temperature gradient tends to produce uplifting of the beam ends.

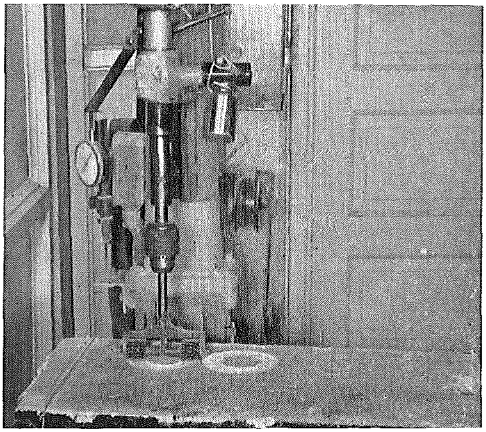


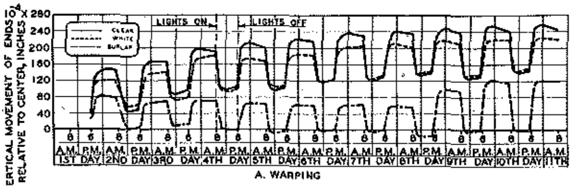
Fig. 2—Beam end being subjected to wear test

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 slab ends after the heat source is removed. The time at which these various phenomena occur is 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.

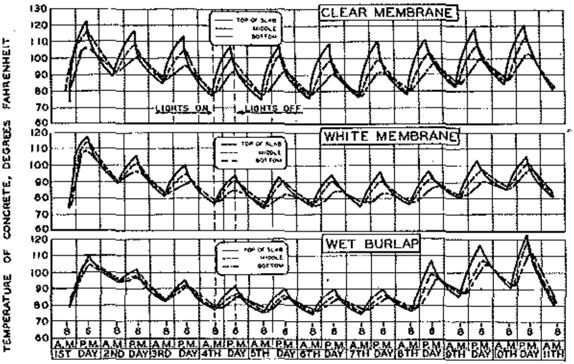
Evaporation of moisture does exert a direct compensatory influence on the warping of the slab, however, through its cooling effect on the surface. This is well illustrated by the warping curves of Fig. 6, which show consider-

TABLE 4—SUMMARY OF WEAR TESTS

Curing method	Penetration, in.			
	1 min.	3 min.	5 min.	10 min.
Clear membrane	0.032	0.067	0.092	0.138
White membrane	0.026	0.060	0.075	0.123
Wet burlap	0.025	0.048	0.071	0.117

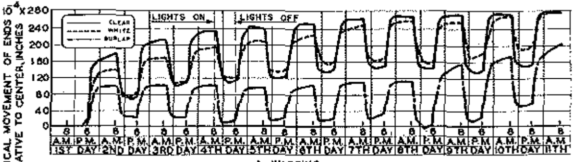


A. WARPING

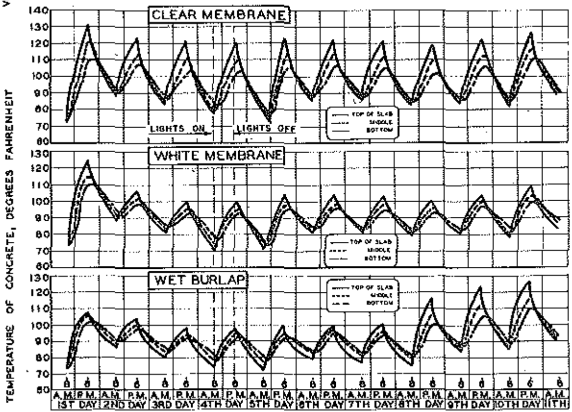


B. TEMPERATURE GRADIENTS.

Fig. 3—Temperature gradients and warping in beams of Series 1—Waterproofed subgrade



A. WARPING



B. TEMPERATURE GRADIENTS

Fig. 4—Temperature gradients and warping in beams of Series 2—Dry Sand subgrade

ably lower temperatures during the first day for the air-cured beam than for the membrane-cured one. The same graphs also demonstrate that the warping pattern is fairly 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 equaled after the first day and subsequently exceeded those in the latter.

The third factor to be considered in the interpretation of the warping data is autogenous shrinkage, or the contraction in absolute volume of the cement-water system accompanying the hydration reactions. Differential autogenous shrinkage may arise from (1) heterogeneity of the concrete and (2) different rates of hydration 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 air-entraining concrete has resulted in much better control of segregation and bleeding, the surface layer of finished concrete still is likely to differ materially from the bottom, especially in cement content, porosity, and volume response to changes in temperature and moisture. Some investigators have observed that a residual upward curl remains in concrete slabs dried from both surfaces, even when no temperature gradient exists.[2,3] Apparently this differential volume change does not progress far in concrete kept continuously moist after finishing. Once allowed to dry, however, the slab cannot be restored to its initial flat condition by addition of water to the top surface.

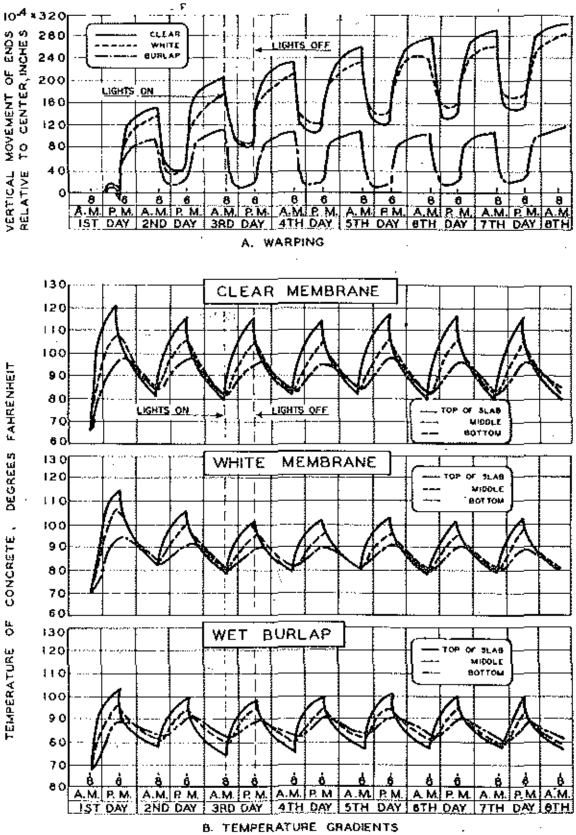


Fig. 5—Temperature gradients and warping in beams of Series 3—Saturated sand subgrade

The total warping at any instant is the resultant of the effects produced by temperature gradient, 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 Fig. 3 through 6 also emphasize the significance of the time of taking initial or base measurements. Obviously results may vary widely, depending upon the particular time chosen for reference measurements. In these experiments, the first readings were taken 5 to 6 hours after finishing and curling may have already begun. From the data shown, it seems unlikely that slabs poured on bright summer mornings would ever actually be warped concave downward after the concrete had hardened except under the most unusual temperature and moisture 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 differentials 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.

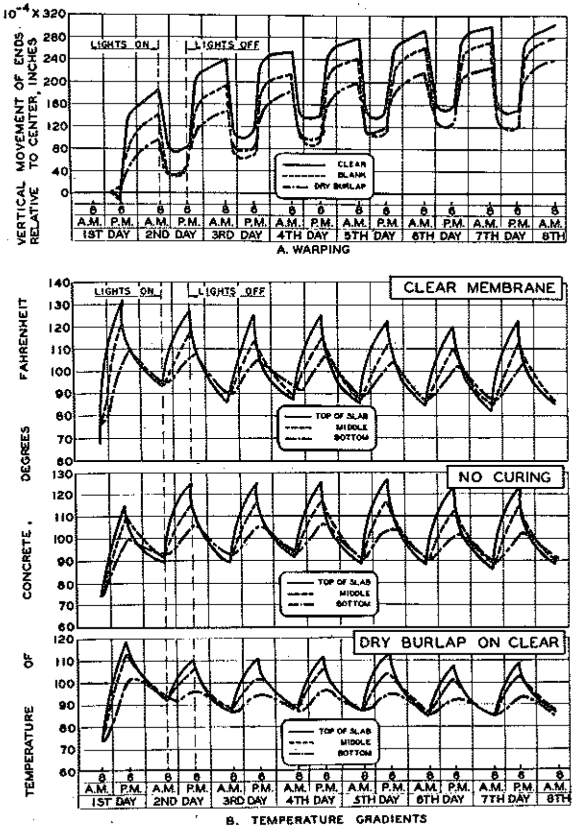


Fig. 6—Temperature gradients and warping in beams of Series 4—Saturated sand subgrade

Temperature control—The use of white-pigmented membrane reduced maximum temperatures about 15 degrees below those attained in beams cured with clear compounds. The reduction in temperature differential is reflected in correspondingly lower deflections of the slab ends. It should be kept in mind 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 and resulted in a 26 percent decrease in warping when compared with beams cured with clear compound only. White-pigmented compound gave comparable results.

Strength and abrasion resistance—The data of Table 3 indicate that satisfactory flexural strengths were obtained except in the two membrane-cured beams of Series 1. There is no apparent explanation for the anomaly that lower strengths were developed in beams cast on a waterproofed subgrade than in those cast on a dry subgrade and cured by identical procedures. As was to be expected, the strengths 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 tests presented in Table 4 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 traffic and weather long before it is worn out.

FIELD STUDIES

Studies of field curing were of three types differing in purpose and method of approach. The first was intended to provide temperature data; the second was concerned with the practicability of the use of white-pigmented curing compounds on pavements; and the third consisted of the acquisition and interpretation of data on the condition of recently constructed concrete pavements cured with clear membrane compounds.

Temperature study

On September 9, 1947, temperature measurements were made on five pavement slabs placed at intervals between 7:30 a.m. and 3:30 p.m. inclusive. This two-lane pavement was 22 ft wide, 9 in. thick and constructed according to current Michigan State Highway Department design which, in the present instance, provided for 100-ft contraction joints with load transfer dowels, no expansion joints, and 86 lb of steel reinforcement per 100 sq ft.

Surface temperatures at all five stations are charted in Fig. 7, and both top and bottom temperatures at the first station appear in Fig. 8. The short vertical lines drawn through the curves indicate the time of application of the clear membrane.

Considering first the graph of top and bottom temperatures at the single station, Fig. 8, the following facts may be noted:

1. Between 12 noon and 1:00 p.m. a vertical temperature difference of about 20 F had already been established, and this difference was maintained until the top surface began to cool at 3:00 p.m.

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

3. The temperature difference decreased rapidly after the maximum temperature in the top surface was reached at 3:00 p.m., then vanished at about 6:00 p.m. after which a reversal occurred and the difference increased in the opposite direction gradually to 7 F at 2:00 a.m.

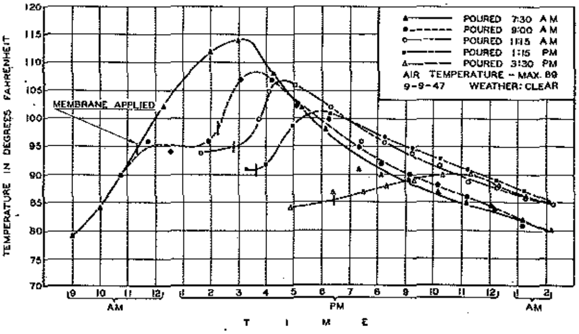


Fig. 7—Surface temperatures of pavement slabs placed at different times of the day.

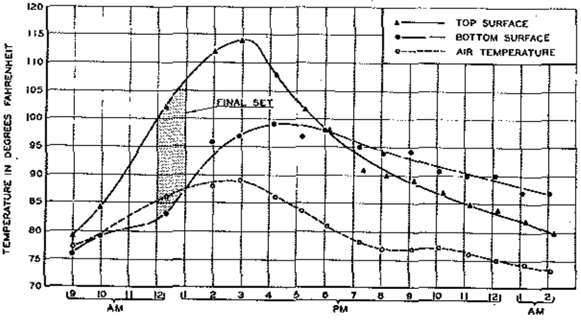


Fig. 8—Temperatures of pavement slab placed at 7:30 a.m.

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 be made to determine the conditions existing in the first slab of the day's pour at midnight of the same day.

In this particular pavement the concrete was fully restrained until the 100-ft, weakened-plane contraction joints opened by cracking. Therefore, the tensile stress in the slab before the ends were freed is given by

$$S_t = Eet \quad \text{(1)}$$

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 average temperature of the slab.

The thermal coefficient of expansion of concrete containing natural aggregates is close to 5×10^{-6}, and the dynamic modulus and flexural strength may be taken from Table 1 as 4.5×10^6 and 300 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. Substitution in Eq. (1) shows 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. 8 it seems certain that the joints should have cracked by midnight.

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

$$t_w = T_t - T_b - (T_{ht} - T_{hb}) \quad \text{(2)}$$

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} = temperature in the top and bottom surfaces respectively at the time hardening takes place.

A reasonable approximation of the maximum warping stress due to vertical temperature difference in a slab of sufficient weight to prevent it from warping away from the subgrade except near the ends may be found from

$$S_w = \frac{Eet}{2} \quad \text{(3)}$$

where S_w = maximum warping stress,
E = modulus of elasticity of the concrete,
e = thermal coefficient of expansion of the concrete and
t = difference in temperature between the top and bottom surfaces of the slab.[6]

At midnight, then, $t_w = -5 - 20 = -25$ F, E and e are taken as 4.5×10^6 psi and 5×10^{-6} respectively and the warping stress due to temperature only is found from Eq. (3) to be 281 psi. Since the warping stress is directly proportional to the difference in temperature between the top and bottom of the slab, in the present case a reduction of 12 degrees in the difference would decrease the warping stress approximately 50 percent.

Finally, the subgrade resistance to slab movement after the ends are freed remains to be calculated. 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:

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

$$\text{or} \quad S_f = \frac{WLf}{288} \qquad (4)$$

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.

Assuming a friction coefficient, f, of 1.0, and the unit weight of concrete to be 150 lb per cu ft, the maximum frictional stress at the midsection is found from Eq. (4) to be 52 psi. This determination presupposes that a sufficient drop in temperature exists at the bottom of the slab to cause appreciable contraction at the subgrade surface and that dowel friction at the joints can be neglected.

Taking the maximum tension from subgrade resistance as 52 psi, the net warping stress due 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 is about 300 psi, the induced stresses in this example are dangerously near the rupturing point.

These conditions are by no means the most severe possible in hot weather concreting. The sun was far past the summer solstice 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 is only a rough approximation but points out the magnitude of the stresses that may be expected in summer concreting under a definite set of conditions and shows the need of adequate temperature and moisture control to minimize early cracking or incipient cracking of the pavement.

The temperature curves of the five slabs placed at different times of the same day (Fig. 7) require little comment. It may be observed, however, that the application of the membrane to the slab placed at 9:00 a.m. was unduly delayed with the result that the temperature did not rise above 96 F until after 2:00 p.m. and then reached a maximum of about 108 F between 3:00 and 4:00 p.m. Nevertheless, this slab may have fared worse than the first one because of excessive surface drying. The two slabs placed in the afternoon were in a much better position to come through the first 24 hours in a structurally sound condition than were the three placed during the morning, other things being equal.

The Grand Ledge curing experiment

The study of white membranes was made on the Grand Ledge Experimental Project as a part of a broader investigation planned primarily to evaluate new standards of pavement design. For use on pavements, the possible effects of the white pigment on operator vision and the change in general appearance due to weathering and traffic are important and the principal object of this study was to learn something of these effects.

Scope—Two consecutive 100-ft slabs in the south lane of the 22-ft 8-in. pavement were cured with a white compound and the corresponding slabs in the north lane with the clear compound furnished on the job. Both white and clear membranes were applied at the rate of 200 sq ft per gal.

Thermocouples were placed in the concrete at the top, middle and bottom of the slab in each lane and seven inserts 40 in. apart for clinometer warping measurements were set along the outside edge of both lanes of the pavement for 20 ft on each side of the common contraction joint. Initial readings were taken approximately 6 hours after the finishing operation, and at various intervals for 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. 9 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. 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. 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 ft back from the joint, as indicated by the increased slope at point 7.

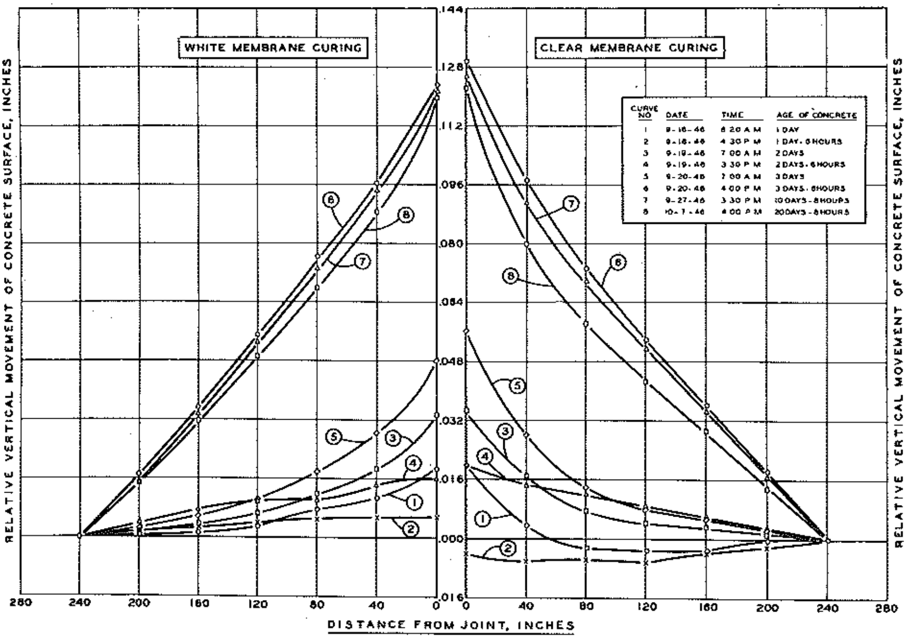
There was little difference in the warping of the slabs cured with white and clear membranes. It was late in the season and the highest temperatures measured in the tops of the slabs were only 97 F for the clear and 87 F for the white membrane, with a 10-degree differential in each case. Probably the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

The white membrane weathered away rapidly and uniformly without mottling or other unsightly weathering effects. Inspection 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 that their use would materially enhance the structural stability of concrete pavements cured with membranes.

Survey of postwar pavements

Condition surveys have been made of 29 concrete pavements built during 1946 and 1947, all of which were cured with clear membranes. The results



CURVE NO	DATE	TIME	AGE OF CONCRETE
1	9-18-46	8 20 A M	1 DAY
2	9-18-46	4 30 P M	1 DAY, 8 HOURS
3	9-19-46	7 00 A M	2 DAYS
4	9-19-46	3 30 P M	2 DAYS, 6 HOURS
5	9-20-46	7 00 A M	3 DAYS
6	9-20-46	4 00 P M	3 DAYS, 8 HOURS
7	9-27-46	3 30 P M	10 DAYS - 8 HOURS
8	10-7-46	4 00 P M	20 DAYS - 8 HOURS

Fig. 9—Early warping of 100-ft pavement slabs at a contraction joint

of these surveys have been given in detail in the basic report[1] and show that in all of the pavements built during the spring and summer months, early cracking, when occurring at all, was found predominantly in the morning pours. Pavements constructed in the fall did not, in general, exhibit this tendency.

For all of these 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 by effective temperature control.

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[4] and will not be repeated here. The results of the present investigation, however, permit a more quantitative evaluation of some of the factors enumerated by them, particularly with respect to stresses induced by differential heating. 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.

Efficiency

Efficiency as used here is 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.

Wet curing is unquestionably more efficient than membrane curing for hot weather concreting. The temperature-regulating effect of water is great 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.[5]

For cold weather construction, membrane curing has advantages 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 by the membrane 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 including (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. 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. It must be admitted 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 in the early days of membrane curing was 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 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 older more cumbersome methods.

SUMMARY

The more important findings of this investigation are given below. Some are derived from statements in the original report[1] but are included here for convenience.

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 continued hydrolysis and hydration reactions during curing.

2. 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 method of artificial curing used 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 placed 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 placed in hot weather exhibit concave upward warping only, the degree of which is determined largely by the magnitude 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, ideal conditions are extremely difficult to realize in practice and are seldom obtained on the job. For this reason, more uniformly satisfactory results are to be expected from the use of membrane curing compounds than from methods which demand constant attention and supervision during the entire curing period.

8. For fall or early winter construction in temperate climates, membrane curing preserves warmth in the slab through restriction of evaporation, and creates 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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