EFFECTIVENESS OF MEMBRANE CURING ON CONCRETE SURFACES

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The data obtained for this research were taken from 19 sidewalk-sized test slabs (26 by 24 by 8 in. thick). Variables investigated included three environments (73 F and 25 percent RH, 100 F and 30 percent RH, and 140 F and 25 percent RH), four curing methods (white pigmented curing compound, monomolecular film followed by white pigmented curing compound, water-soluble linseed oil, and no curing compound), and three wind velocities (0, 8 to 10, and 18 to 20 mph). Constants included mix design (5 sacks per cubic yard of concrete), mixing temperature, mixing procedure, placement, finish, and cure time. In all cases adequate strengths were obtained, but curing temperatures of more than 100 F resulted in a significant reduction in the strength of the top portion of all concrete slabs, even though adequate curing methods were used. At temperatures of more than 100 F, the surfaces cured with the combination monomolecular film (one application before final finish) followed by white pigmented compound showed a high abrasion loss compared to the surfaces cured with either water-soluble linseed oil or white pigmented compound by itself. Thus, there appear to be no surface strength benefits from the one application of the film before finishing. Evaporation of water from the surface of the slabs was significantly retarded with the use of any of the curing compounds. Evaporation rates measured experimentally in this study did not agree with the values predicted by the PCA chart, especially the rates when wind was present. Thus, the validity of a portion of the PCA chart is questioned.

•THE surface properties of portland cement concrete pavement are affected by the combined effects of wind velocity, air temperature and relative humidity, concrete temperature, and type of curing compound. Properties of concrete, such as resistance to freezing and thawing, strength, water tightness, wear resistance, and volume stability, improve with age so long as conditions are favorable for continued hydration of the cement. The improvement is generally rapid at early ages but continues at a slower rate for an indefinite period. For proper cement hydration, there must be the continued presence of moisture and a favorable temperature (1). Hydration virtually ceases when concrete dries below a relative vapor pressure (relative humidity) of about 0.80 (2). At this pressure the water-filled capillaries begin to empty. Because hydration occurs only in these water-filled spaces, hydration ceases when the capillaries begin to empty; therefore, the effective curing time is confined to that period during which the relative humidity in concrete remains above 80 percent. If saturated concrete is placed in saturated air, it will not lose weight; however, if it is placed in air in which the vapor pressure is even slightly below that of saturated air, the concrete will lose water by evaporation. When the vapor pressure of the atmosphere changes, the moisture content of the concrete changes also; it rises with a rise in humidity and vice versa. Concrete sealed against evaporation must initially contain

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about 0.5 gram of water per gram of cement to ensure full hydration, though complete hydration is seldom if ever achieved because self-desiccation progressively reduces the space available for hydration products (2).

Because of increased labor costs and rapid construction pace, an increasing number of concrete highway pavements are being cured with membrane-forming curing compounds (ASTM Designation C 309). Although it is recognized that the moist-curing methods (ponding, sprinkling, and wet coverings) best ensure continued cement hydration, membrane-cured concretes have given creditable performance (3, 4). Field and laboratory tests have been conducted to evaluate several combinations of curing and protective treatments for concrete. A study conducted by the Virginia Highway Research Council evaluated concrete panels cured with white pigmented liquid membrane and white polyethylene sheet, both with and without subsequent treatments using linseed oil (5). On some concrete panels a monomolecular film was used to reduce evaporation prior to regular curing. Results showed linseed oil (in mineral spirits) to be the most satisfactory of the several alternatives practically available for improved durability. Application of the linseed oil following curing with a white pigmented resin-based compound of the type specified by the Virginia Department of Highways was again shown to be satisfactory. Finally, procedures for the use of monomolecular film were initiated on days when there was high evaporation potential, when there was delayed application of curing, or when there were equipment breakdowns.

Reports by Pennsylvania Department of Transportation and Kansas State University have also found, during evaluation of concrete protective sealants and curing compounds, that linseed oil proved superior to all other products as a concrete protective material (6, 7).

Field and laboratory tests conducted at Utah State University demonstrated that a monomolecular film served as a suitable evaporation retarder on the surface of the concrete, and it can be applied before finishing. A typical material that will serve as a suitable evaporation retarder is composed of molecules having a long hydrocarbon chain, which is hydrophobic, attached to a hydrophillic alcohol terminal group. The long hydrophobic chain orients itself vertically above the surface of the bleed water (8). If sufficient molecules are present, they form a tightly compressed, effective film. Water molecules may not possess sufficient energy to escape through this long chain film; hence, the evaporation is significantly retarded.

A concrete problem that is affected by surface properties of the concrete involves plastic shrinkage. Plastic shrinkage cracking is usually associated with hot-weather concreting and may develop whenever the rate of evaporation is greater than the rate at which water rises to the surface of the recently placed concrete (bleeding) (4). Although plastic shrinkage cracking is normally associated with hot-weather concreting, experience in Virginia has shown that spring and fall are more critical periods because of the occurrence of higher winds and lower humidities than are common in the summer (5). This evaporation causes the concrete to shrink, thus creating tensile stresses at the drying surface. Liquid-membrane curing compounds are utilized to retard or prevent evaporation of moisture from the concrete. Without the application of these curing compounds, stresses will develop before the concrete has attained adequate strength, and surface cracking may result (1, 6, 7). Plastic shrinkage cracks vary in length from a few inches (2 to 3) to a few feet (3 to 7) and are often almost straight, without any definite pattern (8). With regard to their depth, the term "surface cracks" is misleading; in fact widespread plastic cracking in pavement, extending to a depth of 4 in., has been observed (6). Therefore, unless the cracks are quite shallow and narrow, they can weaken the pavement, permit penetration of moisture, and render the reinforcement vulnerable to corrosion (9).

If the rate of evaporation exceeds the rate at which bleeding water rises to the surface, then plastic shrinkage and plastic shrinkage cracking are likely to occur. This has been shown experimentally (10). However, field investigations have shown that characteristics of the concrete do not have a major influence on plastic shrinkage or plastic shrinkage cracking (6). This has led to the preparation, by the Portland Cement Association (PCA), of a chart indicating the interrelation among air temperature, relative humidity, concrete temperature, wind velocity, and rate of evaporation of surface

moisture (11). PCA states that evaporation rates above about 0.2 lb/ft^2/hour may cause plastic shrinkage cracking and that at rates below 0.1 plastic shrinkage cracking will probably not occur (11).

From the foregoing it can be seen that proper curing is very important, especially where high winds, elevated temperatures, and low humidities occur simultaneously. To more definitely assess the interrelations among wind, temperature, humidity, and curing method on concrete pavement surfaces, we conducted a laboratory study.

EXPERIMENTAL PROGRAM

The data obtained for this research were taken from 19 sidewalk-sized test slabs (26 by 24 by 8 in. thick). Variables investigated included three environments (73 F and 25 percent RH, 100 F and 30 percent RH, and 140 F and 25 percent RH), four curing methods [white pigmented curing compound (WPC), monomolecular film followed by white pigmented curing compound (MMF plus WPC), water-soluble linseed oil (LO), and no curing compound (Table 1)], and three wind velocities (0, 8 to 10, and 18 to 20 mph). Constants included mix design (5 sacks per cubic yard of concrete), mixing temperature, mixing procedure, placement, finish, and cure time (Table 2).

For control purposes, flexural strength tests were performed on two 6- by 6- by 36-in. beams from each batch of concrete (ASTM Designation C 78-64). The specimens were moist-cured prior to testing. Also, compressive strength tests were made on two 6- by 12-in. cylinders from each batch. The specimens were moist-cured and tested in accordance with ASTM Designation C 39-64. Analysis of the strength results indicates a coefficient of variation of 6 percent for flexural strength and 11 percent for compressive strength.

After 28 days of curing, a minimum of three cores [4 in. (diameter) by 8 in.] were taken from each slab and subjected to diagnostic analyses including the following:

1. Dynamic modulus of elasticity (ASTM Designation C 215-60)—the torsional sonic modulus was determined for each case,
2. Bulk density by absolute volume of the top 3 in. and bottom 3 in. of each core (ASTM Designation D 1188-68),
3. Abrasion coefficient of the finished surface of the cores (ASTM Designation C 418-68), and
4. Splitting tensile strengths on the top 3 in. and bottom 3 in. of each core (ASTM Designation C 496-66).

The steel forms (72 by 27 by 8 in.) for the slabs had two wooden dividers to separate the concrete into three slabs. These three slabs were in turn each subdivided into halves, one-half being covered with a curing compound and the other half without curing compound. In each of these halves, as shown in Figure 1, there was a smaller metal box (6 by 4 by 4 in.) that was inside a wooden box. These smaller metal boxes were designed to be lifted out and weighed periodically on a 10,000-gram balance. Concrete was placed in the forms in three layers, vibrated in place, and finished, and the proper cure was applied to the surface. The wind generator was turned on prior to the placement of the third layer and turned off only during the application of the curing compounds. The weighings of the boxes continued until the water loss became negligible, which was normally after 50 hours. As a method of control, weighings were taken from identical boxes under steady conditions (0 mph). The wind was channeled across the surface of the blocks to prevent the wind from spreading. No significant change in wind velocity could be measured between the first and last block. As a check to ensure that the relative humidity did not vary along the slab lengths, three control sections were monitored along each slab row. Evaporation data from each control section were virtually identical. It should be noted that this test is not designed to duplicate the ASTM water retention test; rather it is an attempt to measure total water loss from the time of placement.

Table 1. Curing methods.

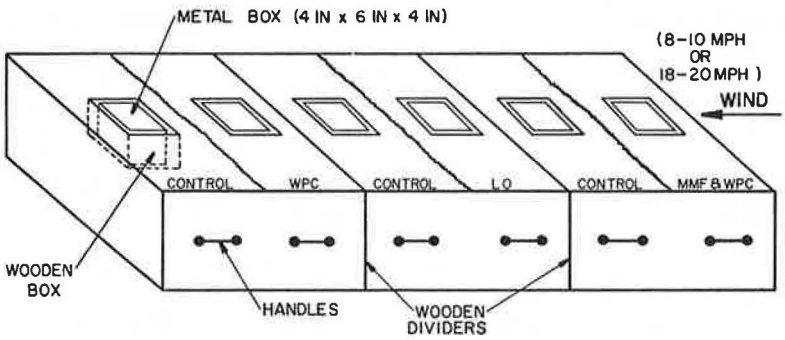
Curing Method	Description
WPC	A white pigmented curing compound, resin-based (ASTM Designation C 309), was sprayed on the test slabs after finishing and after the water sheen had disappeared from the surface (180 ft^2/gal).
MMF plus WPC	A monomolecular film was sprayed on the surface of the test slabs prior to finishing (200 ft^2/gal). After finishing, as soon as the water sheen had disappeared from the surface, the same white pigmented curing compound as used in the WPC curing method was sprayed on the surface.
LO	A water-soluble linseed oil applied to the surface upon completion of the finishing operation (200 ft^2/gal).
Control (no cure)	The slab surface was allowed to cure without application of any curing compound.

Table 2. Concrete mix designs and strengths.

Batch Code	Percent Absolute Volume: Cement	Water	Fine Aggregate[a]	Coarse Aggregate[b]	Air	Slump (in.)	Initial Unit Weight (lb/ft^3)	7-Day Compressive Strength (psi), ASTM Designation C 39	7-Day Flexural Strength (psi), ASTM Designation C 78
36	8.9	13.9	22.5	51.7	3.0	3/4	150	3,760	546
37	8.8	13.9	22.3	51.3	3.7	3/4	144	3,940	674
38	8.8	13.9	22.3	51.3	3.7	3/8	144	4,330	674
39	8.8	13.9	22.3	51.3	3.7	1 3/8	144	3,120	674
40	8.8	14.0	22.6	51.8	2.8	1 1/4	148	4,060	645
41	8.8	14.0	22.6	51.8	2.8	1	148	4,220	645
42	8.8	14.0	22.6	51.8	2.8	1 1/2	148	3,440	645
43	8.8	14.0	22.4	51.5	3.3	1	148	3,840	679
44	8.8	14.0	22.4	51.5	3.3	1	148	3,920	679
45	8.8	14.0	22.4	51.5	3.3	2	148	3,440	679
46	8.8	14.0	22.4	51.6	3.2	7/8	147	3,960	701
47	8.8	14.0	22.4	51.6	3.2	1 3/4	147	4,140	701
48	8.8	14.0	22.4	51.6	3.2	1 3/4	147	3,520	701
49[c]	8.8	13.9	22.4	51.4	3.5	1 1/2	149	3,280	—[c]
50	8.9	13.9	22.5	51.7	3.0	2 3/4	148	3,220	663
51	8.9	13.9	22.5	51.7	3.0	1 1/8	148	3,540	663
52	8.9	13.9	22.5	51.7	3.0	1 3/8	148	3,200	663
53	8.9	13.9	22.5	51.7	3.0	3/4	148	3,080	646
54	8.9	13.9	22.5	51.7	3.0	1 1/4	148	3,900	646
55	8.9	13.9	22.5	51.7	3.0	2 1/4	148	3,250	646
56[c]	8.8	14.0	22.6	51.8	2.8	1 5/8	147	3,010	—[c]

[a]Siliceous river-run fine aggregate with a fineness modulus of 2.86.
[b]Siliceous river-run coarse aggregate with a fineness modulus of 6.90 (maximum size 1 in.).
[c]Only cylinders made for these batches.

Figure 1. Concrete slab setup.



RESULTS AND DISCUSSION

To determine the effect of moisture loss, measurements of water loss from the surface of test slabs were recorded by the periodic weighing of the boxes during the initial curing period (first 50 hours).

Figures 2 through 7 show the water loss measurements versus log time. The figures are representative of each compound's ability to retain water when exposed to the various temperatures and wind velocities. By comparison, it is clearly shown that the portion of the slab without any curing compound (no cure), exhibits considerably higher water loss than any of those with a curing compound. At the early stages of concrete curing, all curing compounds appear to retard water evaporation at nearly the same rate, but a noticeable difference is seen in the later stages of curing. Further comparison of the six figures shows that it is clearly evident that no significant benefits were obtained by adding MMF, in the particular manner employed in this research, before WPC. Though this statement seems inconsistent with other reports, it should be noted that a single application was used, at the heaviest rate recommended by the manufacturer. Perhaps two or more applications would produce better results, as it is hypothesized that insufficient film was present to form an effective barrier. Consistently, the LO and WPC retarded the rate of evaporation better than MMF plus WPC (except at 73 F and 18 to 20 mph). In fact, at least a 15 percent reduction in water loss was noted with the use of LO and WPC over MMF plus WPC at 73 F and 8 to 10 mph (Fig. 2), and this reduction was 30 percent at 140 F and 8 to 10 mph (Fig. 6). Therefore, on the type of concrete used in this study, having little or no observable bleeding, these laboratory results do not show any reason to use a single application of MMF prior to finishing as an evaporation retarder.

There is another interesting finding relating to the effects of wind. In Figures 2, 4, and 6 the evaporation rates for specimens cured without any compound (no cure) at the specified temperature—but without wind—are shown by dashed lines. Note the effect of wind when compared with no wind in the same environment. Without wind the evaporation during the first several hours is considerably reduced, and with wind none of the curing compounds reduced the evaporation rate to that experienced without cure at 0 mph (Fig. 6). This dramatizes the strong influence of wind on evaporation.

Values were obtained from the PCA chart for the conditions employed in this study. In order to compare the PCA values with the experimental values determined in this research, water loss values for the first few hours were plotted against time, and evaporation rates were determined. Figures 8 and 9 show typical results obtained. PCA values (11) and the experimental values are given in Table 3. As can be seen, the values determined from this research are not quite as high as the values obtained from the PCA chart (except at 140 F). Because the values at 140 F from the PCA chart had to be extrapolated, no real comparison could be made here. Note that the values obtained from the PCA chart for steady conditions (0 mph) are nearly the same as those obtained experimentally in this study. However, significant differences were found at increased wind velocities, which casts doubt on the validity of the PCA chart.

The effects of wind on the curing of the top of the concrete are shown in Figure 10. Top splitting tensile strength is plotted against curing temperature for the four curing methods. These four methods were grouped at each particular wind velocity because no distinguishable difference was statistically established for any of the curing methods. Because review of the strength data indicates that the concretes used were of similar strengths, it is concluded that wind apparently affects the strength of the concrete at 73 F and 25 percent RH. The increased wind (18 to 20 mph) must reduce the available water (evaporation from the surface) so as not to allow the concrete to obtain as high a surface strength (compared to 8- to 10-mph conditions).

Figures 11 (8 to 10 mph) and 12 (18 to 20 mph) show a comparison of abrasion loss and temperature under wind conditions. As can be seen, an increase in abrasion loss is noted with increased wind conditions. Also, no apparent abrasion benefit is obtained with the use of these curing compounds because the no-cure specimens had essentially the same losses as the cured specimens. A comparison of the four methods of cure (MMF plus WPC, WPC, LO, and no cure) indicates that, at 140 F, MMF plus WPC

Figure 2. Effect of curing method on evaporation of water from surface of concrete slabs (73 F and 8 to 10 mph).

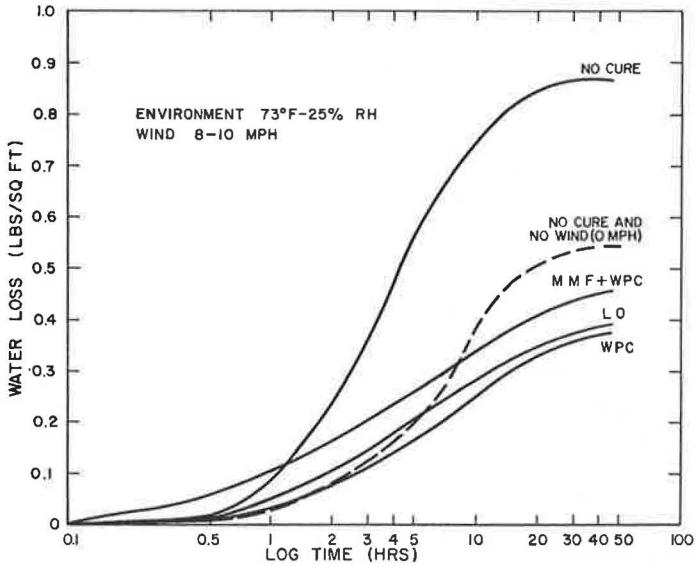


Figure 3. Effect of curing method on evaporation of water from surface of concrete slabs (73 F and 18 to 20 mph).

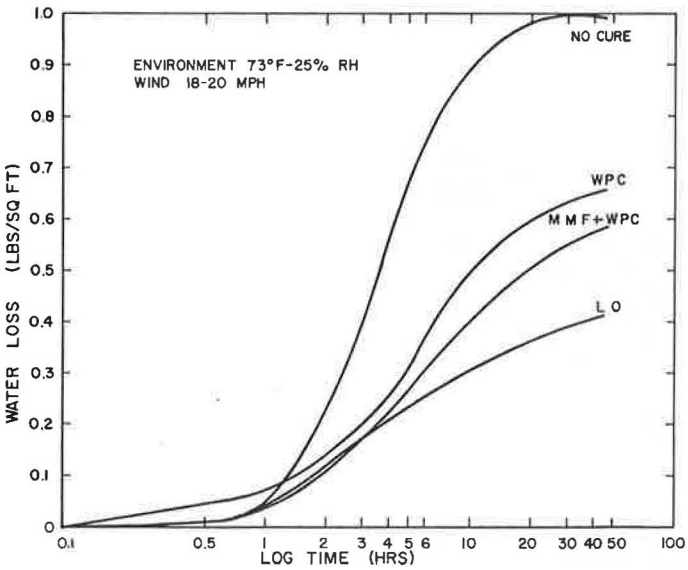


Figure 4. Effect of curing method on evaporation of water from surface of concrete slabs (100 F and 8 to 10 mph).

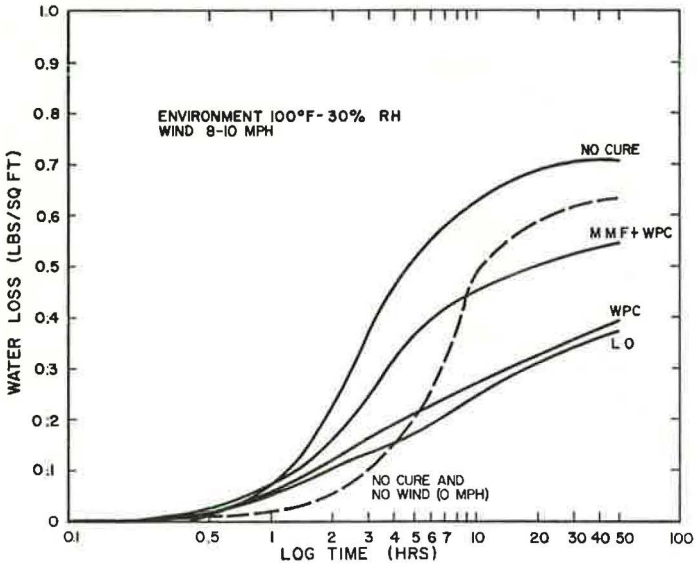


Figure 5. Effect of curing method on evaporation of water from surface of concrete slabs (100 F and 18 to 20 mph).

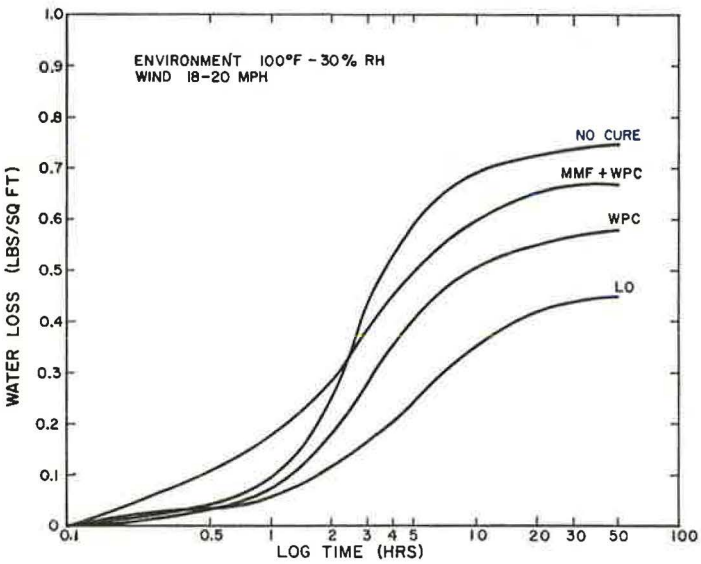


Figure 6. Effect of curing method on evaporation of water from surface of concrete slabs (140 F and 8 to 10 mph).

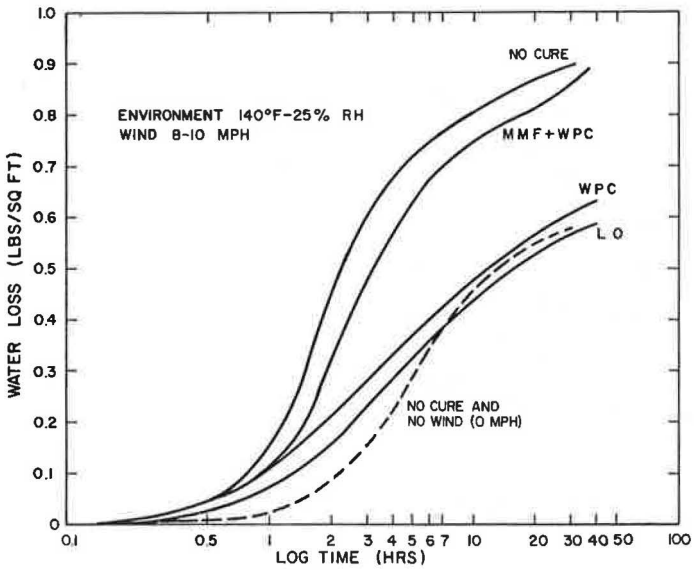


Figure 7. Effect of curing method on evaporation of water from surface of concrete slabs (140 F and 18 to 20 mph).

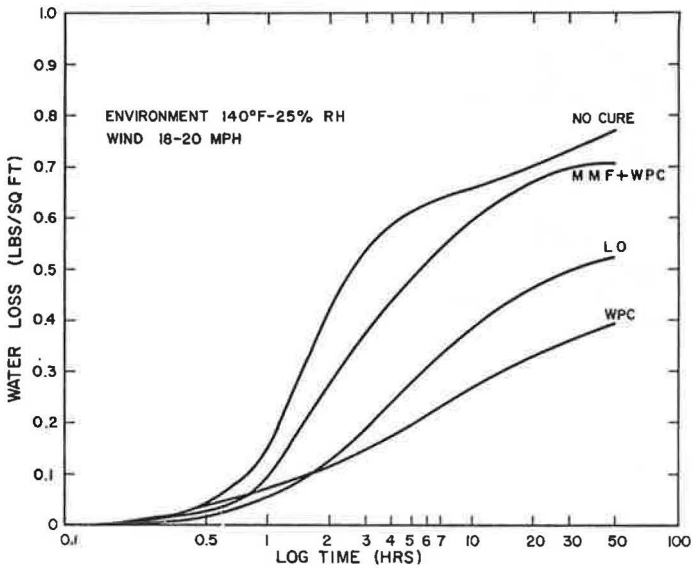


Figure 8. Determination of evaporation rate (73 F and 8 to 10 mph).

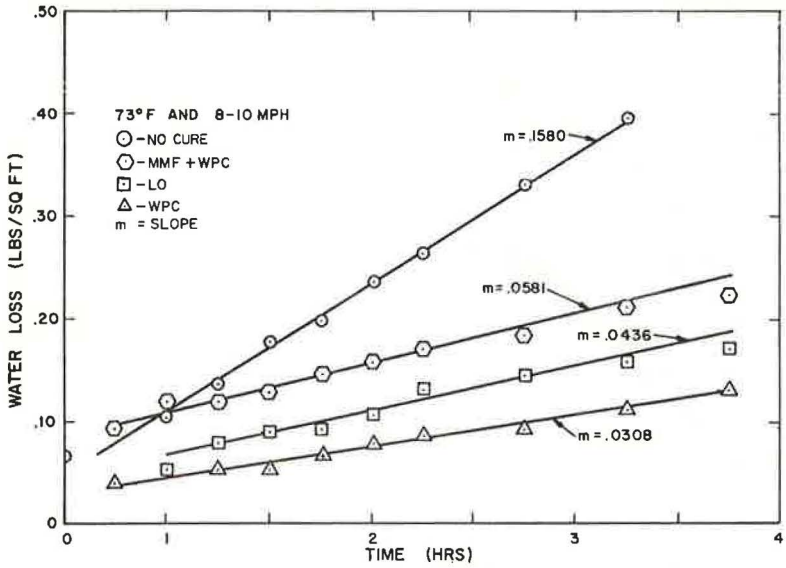


Figure 9. Determination of evaporation rate (140 F and 8 to 10 mph).

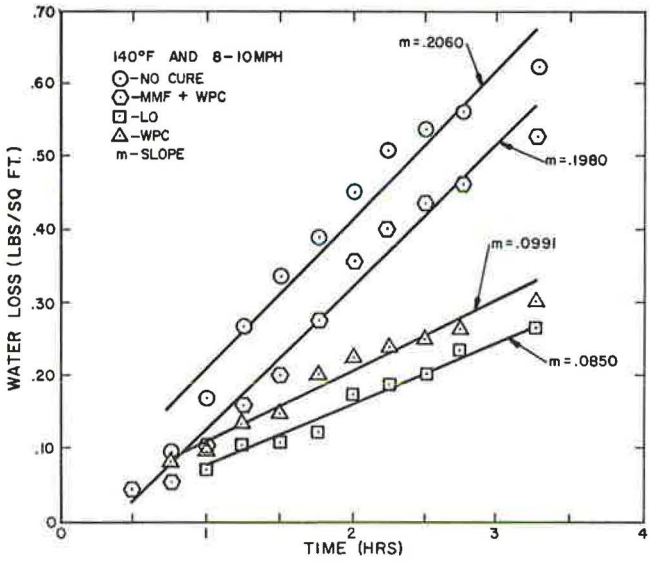


Table 3. Comparison of evaporation rates.

Air Temperature (deg F)	Relative Humidity (percent)	Wind Velocity (mph)	Curing Compound	Evaporation Rate ($lb/ft^2/hour$) Experimental	PCA[a]
73	25	0	None	0.047	0.040
73	25	10	None	0.158	0.22
			MMF plus WPC	0.058	–
			WPC	0.031	–
			LO	0.044	–
73	25	20	None	0.186	0.38
			MMF plus WPC	0.062	–
			WPC	0.058	–
			LO	0.029	–
100	30	0	None	0.037	0.03
100	30	10	None	0.136	0.14
			MMF plus WPC	0.085	–
			WPC	0.065	–
			LO	0.045	–
100	30	20	None	0.182	0.24
			MMF plus WPC	0.111	–
			WPC	0.107	–
			LO	0.057	–
140	25	0	None	0.054	0.00[b]
140	25	10	None	0.206	0.00[b]
			MMF plus WPC	0.198	–
			WPC	0.099	–
			LO	0.085	–
140	25	20	None	0.235	0.00[b]
			MMF plus WPC	0.128	–
			WPC	0.031	–
			LO	0.048	–

[a]Concrete temperature of 80 F was used in all predicted values. [b]Extrapolated values.

Figure 10. Effects of wind on splitting tensile strength of concrete.

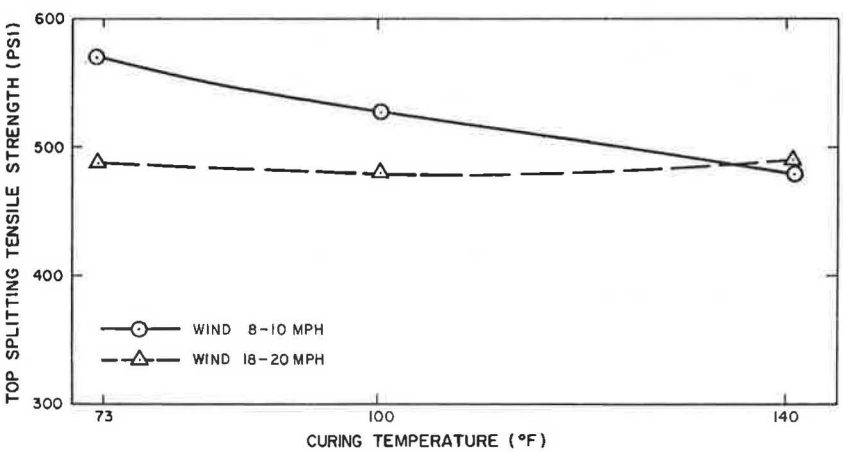


Figure 11. Effect of curing temperature and curing compounds on abrasion coefficient (0 and 8 to 10 mph).

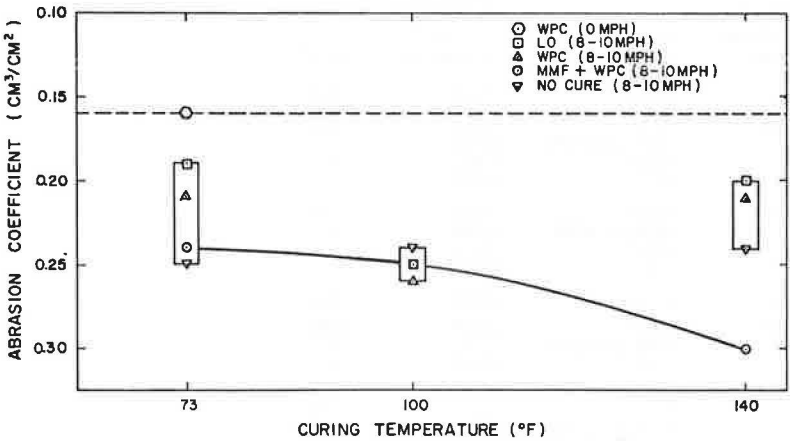
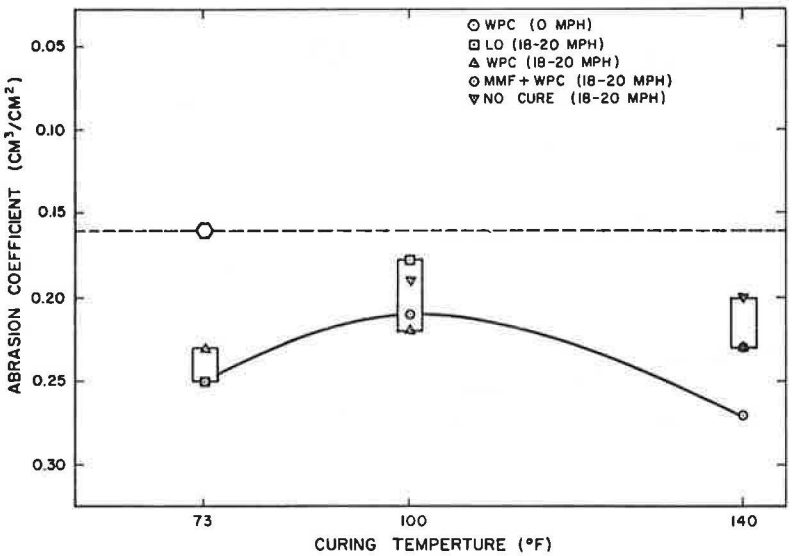


Figure 12. Effect of curing temperature and curing compounds on abrasion coefficient (0 and 18 to 20 mph).



statistically exhibited a significantly larger abrasion loss. Apparently, the MMF plus WPC did not seal the surface against water loss so well as the other methods at this elevated temperature and wind condition. As indicated by the water loss measurements, there must be sufficient water loss to cause a reduction in surface strength, hence an increase in abrasion loss.

There were no significant differences in the dynamic moduli of all the slabs, and similarly there were no significant differences in bulk densities of the top and bottom of the cores taken.

CONCLUSIONS

The study data support the following conclusions:

1. In all cases adequate strengths were obtained. But, curing temperatures in excess of 100 F resulted in a significant reduction in the strength of the top portion of all concrete slabs, even though adequate curing methods were used. With the simulated wind conditions of 8 to 10 mph and 18 to 20 mph, this reduction in strength was even more pronounced.
2. At temperatures in excess of 100 F, the surfaces cured with the MMF plus WPC showed a high abrasion loss compared to the surfaces cured with either LO or WPC by itself. Thus, there appear to be no surface strength benefits from the one application of the MMF before finishing.
3. Evaporation of water from the surface of the slabs was significantly retarded with the use of any of the curing compounds (MMF plus WPC, LO, and WPC). LO and WPC tended to retard the evaporation more than MMF plus WPC. Thus, the laboratory results do not show any advantage to the particular way in which MMF was used as an evaporation retarder. Conversely, the use of an adequate curing compound was shown to be advantageous.
4. Evaporation rates measured experimentally in this study did not agree with the values predicted by the PCA chart, especially the rates when wind was present. Thus, the validity of a portion of the PCA chart is questioned.

ACKNOWLEDGMENT

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REFERENCES

1. Recommended Practice for Curing Concrete. ACI Jour., Vol. 68, April 1971, pp. 233-243.
2. Powers, T. C. A Discussion of Cement Hydration to the Curing of Concrete. HRB Proc., Vol. 27, 1947, pp. 178-188.
3. Carrier, R. E., and Cady, P. D. Evaluating Effectiveness of Concrete Curing Compounds. Jour. Materials, Vol. 5, No. 2, June 1970, pp. 294-302.
4. Recommended Practice for Hot Weather Concreting. ACI Jour., Vol. 68, July 1971, pp. 489-503.
5. Newlon, H. H., Jr. Random Cracking of Bridge Decks Caused by Plastic Shrinkage. Virginia Highway Research Council, Dec. 1966, 7 pp.
6. Lerch, W. Plastic Shrinkage. ACI Jour., Vol. 53, No. 2, Feb. 1957, pp. 797-802.
7. Cordon, W. A., and Thorpe, J. D. Control of Rapid Drying of Fresh Concrete by Evaporation Control. ACI Jour., Vol. 62, No. 8, Aug. 1965, pp. 977-984.
8. Shalon, R., and Ravins, D. Studies in Concreting in Hot Countries. Proc., Symposium on Concrete and Reinforced Concrete in Hot Countries, Israel Institute of Technology, Haifa, 1960, 45 pp.

9. Shalon, R., and Ravins, D. Plastic Shrinkage. ACI Jour., Vol. 65, No. 4, April 1968, pp. 282-291.
10. Hansen, T. C. Effect of Wind on Creep and Drying Shrinkage of Hardened Cement Mortar and Concrete. Materials Research and Standards, Jan. 1966.
11. Curing of Concrete. Concrete Information Bull., Portland Cement Association, Chicago, 1966, 5 pp.