EVALUATION OF CURING CONTINUOUSLY REINFORCED CONCRETE PAVEMENT

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A field evaluation of curing continuously reinforced concrete pavement with white-pigmented liquid membrane and white translucent polyethylene (paper) curing agents was made on Wisc-15 in Walworth and Waukesha Counties, Wisconsin. Physical properties of the concrete were investigated, and it was concluded that the curing method does not significantly affect tensile or compressive strength of the modulus of elasticity. Data show that the temperature drop experienced by the concrete during the first 24 hours was not significantly affected by the curing agent. Strain readings on the reinforcing bars indicate that the steel stress was nearly equal in paper- and membrane-cured sections at a temperature of 64 F (18 C). The only significant performance difference between the two curing methods, as of 1 year of age, appears to be in the realm of transverse cracking, i.e., membrane curing allowed the pavement to crack earlier and to crack more at early ages. Both membrane and paper curing produced acceptable crack-spacing distributions when climatological conditions were favorable, although neither curing agent contributes to acceptable crack-spacing distributions during hot weather paving conditions. No cold weather paving was performed on this project.

•ALTHOUGH Wisconsin allows liquid membrane curing for conventionally reinforced and nonreinforced concrete pavements, polyethylene (paper) curing has been required for continuously reinforced concrete pavements (CRCP). Recent increases in the mileage of CRCP placed in Wisconsin and the use of liquid membrane curing for CRCP in surrounding states prompted concern in Wisconsin about the advisability of continuing the requirement of paper curing for CRCP.

A survey of the practices of seven neighboring states revealed that six of these northern states allowed the liquid membrane curing compound to be used for CRCP during the normal construction season with special requirements for paper and protection during cold weather paving. None of these seven states differentiated between curing methods for CRCP and regular reinforced concrete pavements. On consideration of this information and other factors about the performance of pavement and the method of curing, the engineering research advisory committee of the Division of Highways decided that a field investigation should be conducted to determine the influence of the type of curing on the performance of CRCP.

The CRCP highway chosen for this investigation was a four-lane divided highway scheduled to be built as a portion of Wisc-15 from just west of county trunk highway F in Waukesha County to Wisc-20 near East Troy in Walworth County. Paving operations began in late July 1972 and continued into October. The selected test sections were constructed during July and August 1972.

This paper discusses the testing program and the results obtained up through a 1-year period subsequent to construction.

PROCEDURES

Test Sections

Eight test sections, each 500 ft (152 m) long and two lanes wide, were established

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for this research project. Four test sections were cured with 4-mil white translucent paper and four with white-pigmented liquid membrane. The test sections were located so that a test section with one type of curing agent was approximately opposite another test section cured with the other agent. This way some of the variables (such as cut, fill, soil type, water table depth, soil support, grade, and alignment) not pertinent to the research program were averaged out. The final curing scheme was developed primarily on the basis of field considerations. Material properties and performance characteristics evaluated were concrete tensile and compressive strength, modulus of elasticity, concrete temperatures, steel stress, pavement cracking, pavement serviceability, and pavement surface friction.

Concrete Tensile Strength

For each test section (except VI) thirty 6- by 12-in. (15 by 30 cm) concrete cylinders were cast for use in the tensile strength test (splitting test). For approximating duplication of actual pavement conditions, the cylinders for each test section were (a) half (15 cylinders) membrane-cured and half paper-cured, (b) insulated on the sides for the first day to prevent loss of hydration heat so as to maintain a cylinder temperature like that of the pavement, and (c) cured in the environment of their respective test section. Curing half of the cylinders with one curing agent and half with the other curing agent produced a paired test. The object of pairing was to determine if a significant difference in some concrete property exists between the cylinders because of the curing agent used; all other variables are the same for both groups of cylinders.

Concrete Compressive Strength

Twelve concrete cylinders were cast per test section (except VI) for use in the standard compression test. These cylinders were insulated on the sides for the first day, cured in the test section environment, and cured with the curing agent of their respective test section. Compression tests were not paired because the cylinders were cured by only one method per test section.

Modulus of Elasticity

Four 4- by 4- by 16-in. (10 by 10 by 41 cm) concrete beams were cast per test section (except VI) for determining the modulus of elasticity at various ages. These beams were cured in the environment of their respective test section with half of the beams per test section (2 beams) membrane-cured and half paper-cured, which produced a paired test for the sonic modulus of elasticity. Because the sonic test used to find the modulus of elasticity is a nondestructive test, these beams were to be used repeatedly at ½, 1, 3, 7, and 28 days; however, 22 of the beams were stolen from the curing site and thereby limited the number of further tests.

Concrete Temperatures

Six to eight thermocouples were installed per test section to measure air, concrete (top, middle, and bottom), and "under the paper" temperatures. Temperatures were recorded every 2 hours during the first 30 to 48 hours after concrete placement.

Steel Stress

Three steel bars with strain gauges were embedded in the concrete to measure steel strain in the vicinity of a crack. Cracks were forced to develop at the desired location by sawing the pavement transversely 1 to 1½ in. (2.5 to 3.8 cm) deep to form a plane of weakness. Before paving, these instrumented bars were placed in position by first removing a section of longitudinal reinforcing steel and then "lapping-in" the instrumented bar. The lead wires attached to the gauges were bundled together and put inside a conduit (to protect the lead wires during paving), which was temporarily attached to the reinforcing bar. The bar was then allowed to pass through the slip-form paver along with the other longitudinal reinforcing steel (Fig. 1). After the passage of the paving train, a small amount of concrete was excavated to enable removal of the conduit housing the

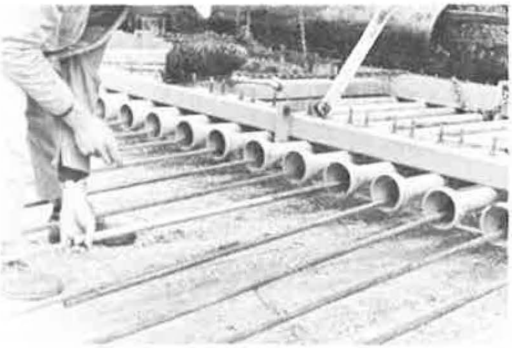


Figure 1. Gauged bar passing through slip-form paver.

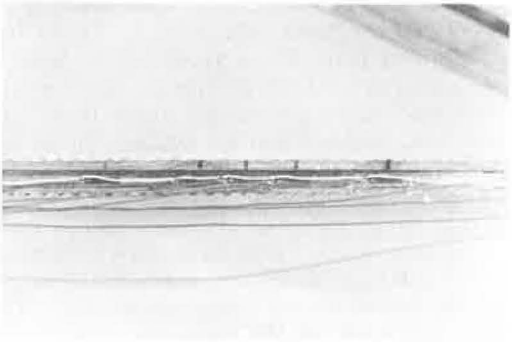
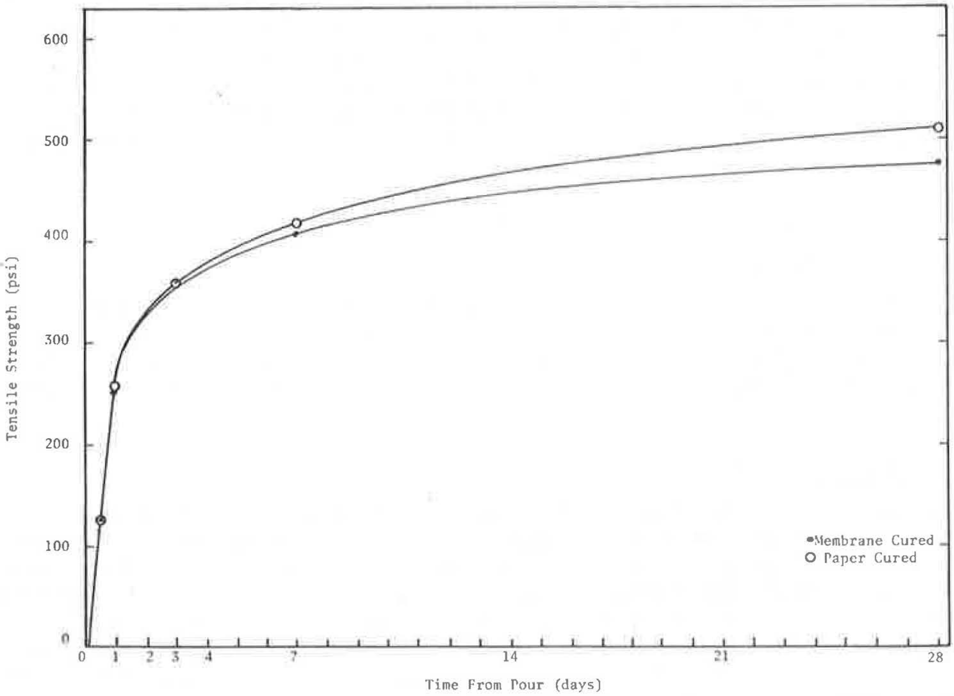


Figure 2. Reinforcing bar with attached strain gauges and lead wires.

Figure 3. Concrete tensile strength (average of all sections) versus time.



lead wires. Then the lead wires were fished under the pavement through a plastic conduit previously buried in the base course.

The instrumented bars were made from $7\frac{1}{2}$ ft (2.3 m) lengths of deformed reinforcing steel [60 ksi yield (414 MPa)]. These lengths of reinforcing steel were cut in half longitudinally (Fig. 2), a groove $\frac{3}{8}$ by $\frac{1}{8}$ in. (9.5 by 3.2 mm) was milled in each half of the bar, eleven to thirteen 0.5-in. (12.7 mm) foil strain gauges were installed in the groove with lead wires protruding about 10 ft (3.05 m) out of one end, and the bar was epoxied and spot welded together again. These bars were subjected to tensile tests before placement to check gauge operation and to establish the apparent modulus of elasticity. [This was not 29×10^6 psi (200 GPa) because of Poisson's effect on the compensating strain gauge mounted transversely in the groove.]

On one of the three bars the epoxy broke, which allowed the bar to separate longitudinally during placement through the slip-form paver and resulted in problems that could not be corrected or compensated for. Therefore, two of the three instrumented steel bars embedded in the concrete were capable of giving good strain readings. One gauged bar was in membrane-cured section VII and one was in paper-cured section II.

Crack Counts

Crack counts (and diagrams) were taken at 1, 3, 7, 28, and 90 days and 1 year. (Annual crack counts are planned for the future.) Any visible crack that extended at least $\frac{1}{3}$ of the distance across both lanes [8 ft (2.44 m)] was included as a full crack. Crack spacings were measured to the nearest 0.1 ft (30.5 mm) along the outside edge of the pavement; test section termini were used as reference points. Crack counts on the paper-cured sections were omitted while the paper was in place but were conducted as soon as it was removed.

RESULTS

Concrete Tensile Strength

The t test showed that there was no significant difference in the concrete's tensile strength for 210 concrete cylinders, at any particular age, because of the curing agent. For general informational purposes, Figure 3 shows average tensile strengths versus time. This curve has a shape similar to that of a typical compressive strength versus time curve.

Concrete Compressive Strength

Inasmuch as the compressive strength cylinders were not paired, the membrane-cured cylinders were not exposed to the same environment as the paper-cured cylinders and a t test was inappropriate. However, from the results it was clear there was little or no difference in compressive strength because of curing. If there was a strength difference it could not be highly significant because there was no difference in tensile strength that was due to the curing agent. [This would of necessity exist if there was a compressive strength difference because tensile strength is "more or less directly related" to the compressive strength (1).] If, due to curing, there was a compressive strength difference, it would have to be relatively large before it significantly affected the pavement because compressive strength plays little part in the direct behavior-performance of CRCP (2). But compressive strength is an indicator of other characteristics of the concrete, i.e., tensile and flexural strength, which do have a direct behavioral effect.

Modulus of Elasticity

The t test results applied to the sonic modulus of elasticity (E) data reveal that there was no significant difference in E, from 12 hours to 28 days, because of the curing agent employed. The variation of E with time or strength (Fig. 4) is included in this report because little is known about the value of E at early ages. This is a vital factor whenever stress-strain phenomena during the first few days of pavement life are studied.

Figure 4. Modulus of elasticity (average of all sections) versus time.

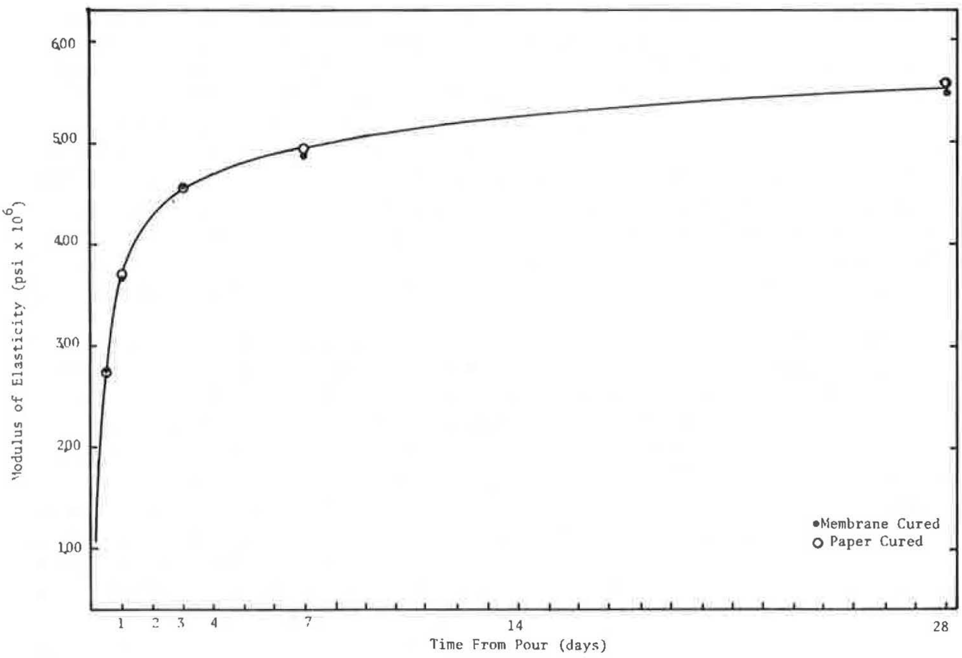
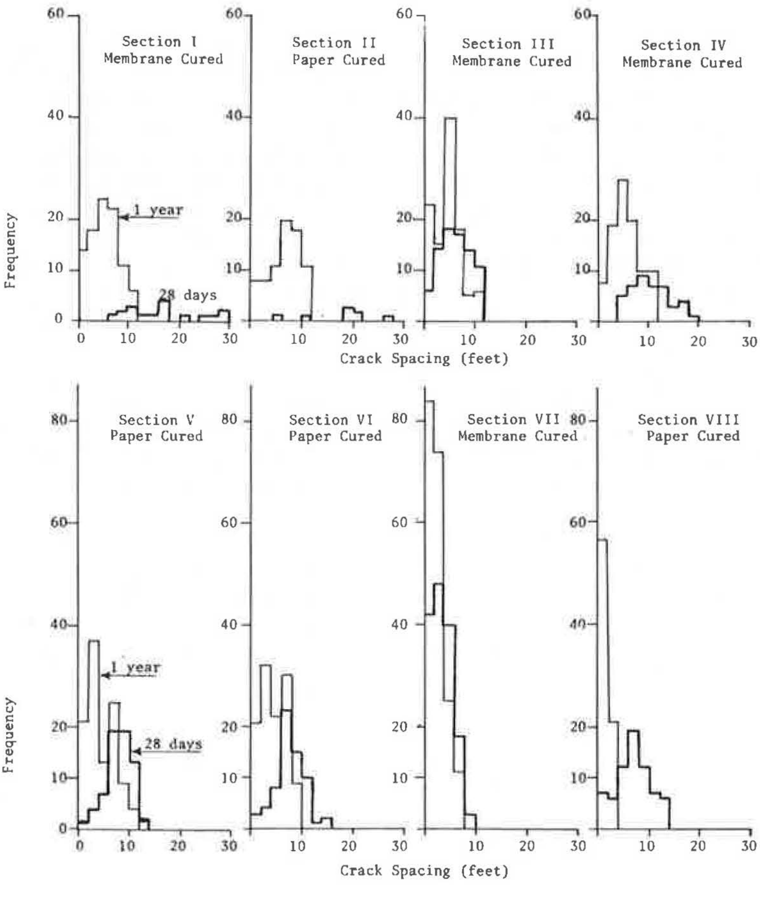


Figure 5. Crack-spacing distributions at various ages.



Concrete Temperature

The amount of early transverse cracking is related to temperature change between the maximum and minimum slab temperatures (averaged over the slab depth) experienced by the pavement during the first 24 hours (3). To directly compare the temperature drop experienced by the pavement as influenced by the curing agent required paired temperature data. Pairing of concrete temperature data would have been possible if, for each test section, a corresponding section had been constructed and instrumented with thermocouples at the same time but cured by the alternate method. Because there was no pairing of temperature data, direct comparisons of concrete temperatures are misleading inasmuch as test sections were not exposed to the same ambient temperatures. A meaningful comparison of concrete temperatures can only be made by first adjusting the temperature data to reflect approximately equal ambient exposure conditions.

Ambient temperature exposure was estimated from collected data, and the average membrane-cured section experienced about a 62 percent cooler exposure during the first 24 hours than the average paper-cured section. But the average membrane-cured section realized a concrete temperature drop of 16 deg while the average paper-cured section had only a 10-deg temperature drop. This disparity in temperature change during the first 24 hours amounts to a 60 percent greater temperature drop in the average membrane-cured section, which, for practical purposes, equals the 62 percent cooler exposure experienced by the average membrane-cured section. Thus when the data are adjusted for equal ambient temperature conditions, there appears to be no significant difference between membrane and paper curing when one considers their ability to insulate concrete against falling temperatures, within the range considered.

Average high concrete temperature for all membrane-cured sections was the same as for all paper-cured sections, i.e., 94 F (34 C). (No adjustment of this temperature was necessary after considering the various factors.)

Cracking

Optimum average crack spacing is really nonexistent, but ideally there is an average crack spacing somewhere between 2 and 10 ft (0.6 and 3.0 m) that is considered optimum because it results in a pavement with the best balance of ride, structural performance, and pavement life for the imposed conditions. However, average crack-spacing tabulations often are unreliable because indicators of poor pavement performance potential are often masked. That is, very small or very large crack spacings may be numerous enough to cause future problems, but these adverse spacings are not revealed by a single average value. Therefore, a more reliable indicator of pavement performance potential is the crack-spacing distribution chart that shows the relative number of each crack spacing. In general, a normal distribution of crack spacings on the distribution chart indicates satisfactory cracking behavior, and a skewed distribution reflects unsatisfactory cracking behavior (4).

The results of 28-day and 1-year crack surveys (Fig. 5) reveal that five test sections have satisfactory crack-spacing distributions at 28 days. [Three unsatisfactory sections are I(M), II(P), and VII(M). M and P refer to membrane and paper curing respectively.] Six text sections have satisfactory crack-spacing distributions at 1 year, and VII(M) and VIII(P), perhaps V(P) too, exhibited unsatisfactory cracking behavior at 1 year.

Fortunately, for a comparison, section VII was poured within a day: One section was paper-cured and another membrane-cured. A crack-spacing distribution of the paper-cured portion, near the poorly distributed crack spacings in section VII, shows a skewed distribution at 28 days for that day's pour. Thus, it appears the distribution of cracks was influenced primarily by the environment rather than by the curing method. Two sections (also V) with badly skewed crack distributions experienced the highest average concrete temperatures of all the sections tested: 90 F (32 C).

That the progress of aging alters the position and shape of the distribution curve is shown in Figure 5. The shift to the left does not imply a detrimental effect, especially if a normal distribution is retained or developed as in sections I and II.

A brief summary of the amount of cracking at 28 days (Table 1) shows that the average crack spacing is large when compared to the expected stabilized value [2 to 10 ft (0.6 to 3.0 m)], which other researchers have indicated should be reached near or before 5 years of age (5). The range of the crack spacings and standard deviation at 28 days is also large for both types of curing. However, the results of the 3-month survey show the average crack spacing and standard deviation to be nearly equal for both types of curing and to be within the expected range of values.

A 1-year survey reveals that cracking has not changed significantly since the 3-month survey. The discrepancy at 28 days in the average crack spacing between the paper- and membrane-cured sections apparently equalized sometime before 3 months and established a difference in the amount of early cracking (Fig. 6). Whether the difference in early cracking is caused by the curing method or different ambient conditions between the sections requires further delineation.

The difference in cracking between the paper- and membrane-cured sections can best be studied by adjusting the curve representing the membrane-cured sections (Fig. 6) to reflect equal environmental conditions between it and the curve representing the paper-cured sections. This enables the cracking-versus-time curves to be compared on an equal basis. This adjustment was estimated from available data (based on air temperature, relative humidity, solar radiation, and wind speed) and is shown in Figure 6 as a dashed line. If the adjusted curve for membrane curing had nearly equaled the curve for paper curing, it would seem reasonable to assume that the ambient conditions had caused the earlier cracking in the membrane sections. However, because the two curves are more divergent at early ages, it appears logical that the difference in cracking is likely because of differences produced by the curing methods inasmuch as other prime factors have been somewhat equalized by the adjustment. The membrane-cured sections are the more prolific early cracking pavements—possibly because of greater early drying shrinkage. Note that the difference between the curves in Figure 6 becomes constant after about 2 months of age.

Researchers have stated that prolonged moist curing delays the advent of shrinkage, but the effect of curing on the total magnitude of shrinkage is slight (6). Therefore, it seems plausible that paper curing could have delayed the advent of shrinkage (more initial cracking in the membrane-cured section), even though in finality the shrinkage may be equal. Because the effect of curing on the total magnitude of shrinkage is slight, the disparity in cracking at later ages is probably not caused by shrinkage differences brought about by curing agents. However, this disparity in cracking may indirectly result from shrinkage inasmuch as more cracking will occur for a given strain at early ages than for the same strain at later ages (Fig. 7). (In Fig. 7, cracking strain is the strain required to cause rupture of the concrete. It is derived by dividing the tensile splitting stress at any particular age by the modulus of elasticity at the same age.)

Crack Load Transfer Efficiency

An important quality of good pavement is its ability to transfer a load across a crack or joint from one slab to another. In CRCP there are basically two elements that are functional in load transfer: longitudinal steel and aggregate interlock. Joint or crack load transfer efficiency decreases as a function of the number of heavy loadings and crack width (4), i.e., for high load transfer efficiency the crack width should be as small as possible.

In general, the smaller the crack spacings are, the smaller the crack widths; hence, one would assume that small crack spacings are desirable for load transfer in CRCP (not so small, however, that they detract from other structural qualities).

For high load transfer efficiency the concrete should possess a high degree of aggregate interlock, which is affected by crack width. Cores taken at transverse cracks in the pavement revealed that early formed cracks had less fractured coarse aggregate than cracks that appeared at later ages. If a low percentage of fractured coarse aggregate (and therefore a higher percentage of protrusions) is coincident with better interlock, it would appear that early cracking of CRCP would be desired. Because the results obtained in this study indicate that the membrane-cured concrete cracked more at early ages, it follows that such curing might be favored for more desirable load transfers at cracks.

Table 1. Average crack spacing.

	Membrane-Cured CRCP		Paper-Cured CRCP	
Age	Avg Crack Space	Standard Deviation	Avg Crack Space	Standard Deviation
1 month	10.7	5.4	14.3	9.2
3 months	5.3	2.4	5.5	2.5
1 year	4.5	2.4	4.7	2.6

Figure 6. Average number of cracks as a function of time.

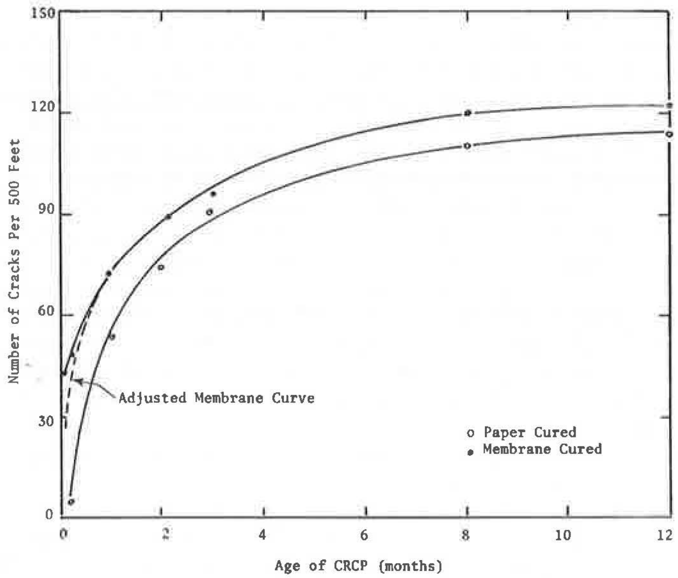
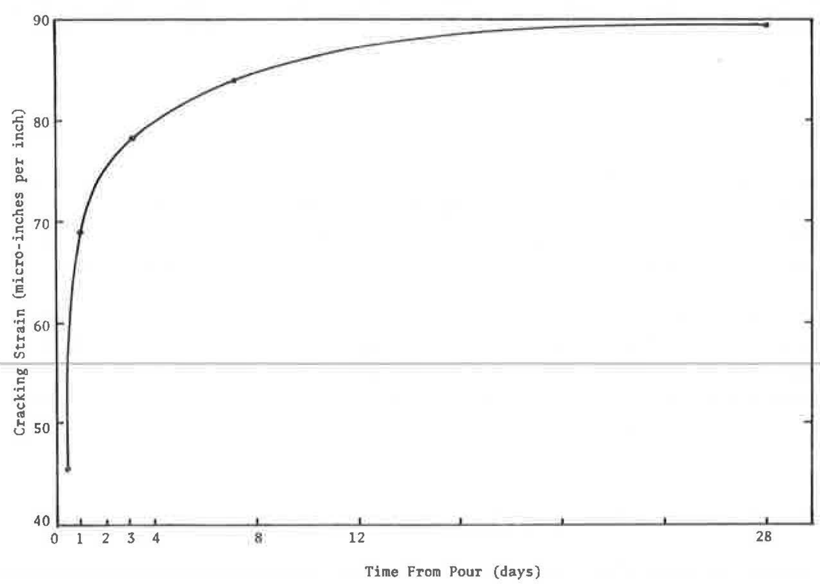


Figure 7. Concrete cracking strain at various ages.



Steel Stress

As stated previously, three steel bars instrumented for strain readings were placed in the concrete. As of November 1972, only two of these bars were performing satisfactorily: one in section II(P) and the other in VII(M).

Steel stress measured on September 14, 1972, is shown for comparison (Fig. 8). At 27 and 42 days of pavement age, for the membrane- and paper-cured sections respectively, the steel stress was nearly the same, i.e., 44,000 psi (304 MPa) at an average concrete temperature of 64 F (18 C). This was true in spite of the fact that there was a marked difference in the amount of cracking in the two sections, i.e., II(P) had approximately 30 cracks and VII(M) had 141 cracks. For the bar embedded in the membrane section, there was a secondary stress peak 10 to 12 in. (24 to 30 cm) from the center gauge that was caused by an additional crack that developed in that section (Fig. 8 insert). The variation in steel stress with distance from the forced crack was reasonably equal between the two sections, except for the effect of the secondary crack. In both bars the maximum stress occurred about 1 in. (2.5 cm) from the midpoint of the bar where the crack was expected to occur. This offset could be the result of longitudinal movement of the bar while it was passing through the paver, inaccurate location of the saw cut, and the crack not extending vertically downward from the location of the saw cut.

A drastic change in steel stress occurred in II(P) at about five days (Fig. 9). This jump in steel stress indicates when the concrete ruptured (cracked) at the weakened plane and transferred its imposed load to the steel.

There is a greater change in steel stress with temperature in the paper-cured section than in the membrane-cured section. Hence, cyclic daily and seasonal temperatures will cause, at least in this case, greater cyclic (dynamic) steel stress in the paper-cured section. [The crack spacing affects the thermal strain (7) and that is certainly one reason why section VII(M), with the closer crack spacing, had less thermal stress variation than II(P). In view of this, the curing agent can influence the cyclic steel stress because the curing agent apparently has an effect on the amount of cracking.] The dynamic thermal stress superimposed on the steady-state stress may constitute an important factor in the fatigue life of CRCP reinforcing steel. However, more research is required before any statement can be made on CRCP steel fatigue or dynamic stress, especially as it relates to the effects of the curing agent.

The bond stress for bar 1 (Fig. 8) was calculated at slightly over 1,700 psi (11.9 MPa) between points a and b. Such stress implies slippage between the concrete and the bar. This slippage (as well as creep, shrinkage, and moisture) has an effect on the steel stress; thus, prediction of steel stress for other temperatures and pavement ages is not advisable.

Steel stress varies inversely with concrete temperature (Fig. 10). As a matter of reference, the steel stress at an average concrete temperature of 12 F (-11 C) [January 1973, section II(P)] was close to 46,000 psi (320 MPa).

Pavement Serviceability

Serviceability values obtained for various test sections before the pavement was opened to public traffic and again after 1 year are given in Table 2. These values indicate that the method of curing had no apparent influence on loss of ride quality. However, ride quality was somewhat better in driving lanes than in passing lanes. This difference may be due to construction procedures.

Pavement Surface Friction

Surface friction numbers given in Table 2 are computed as an average from four individual values obtained in each test section. A t test on the before traffic data (similarly stationed sections are considered as a pair) shows that the method of curing had no significant effect on these initial values. Friction values were obtained again after 1 year of service. A t test on the loss of friction during the first year reveals that there has been a significant loss of pavement friction for the membrane-cured sections compared to the paper-cured sections (8.3 and 4.4 respectively). Whether the higher loss

Figure 8. Variation in steel stress near a crack.

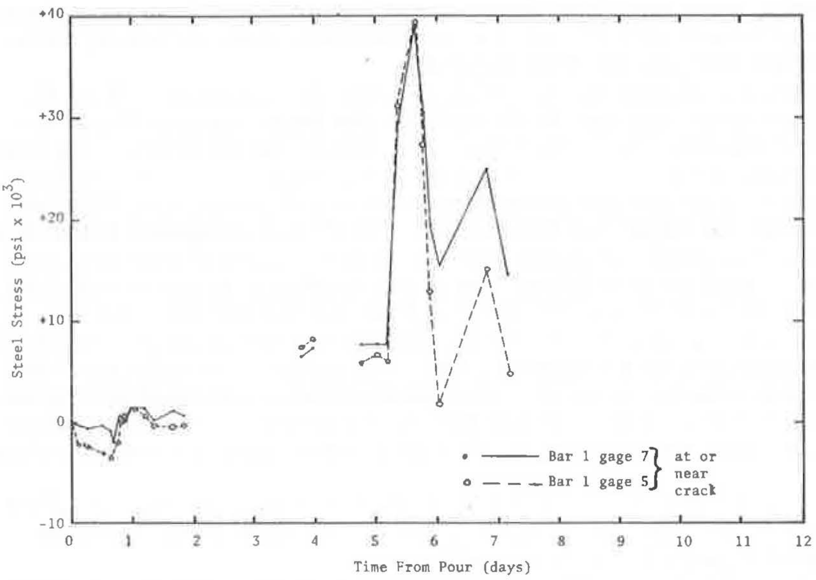


Figure 9. Time of cracking as revealed by steel stress.

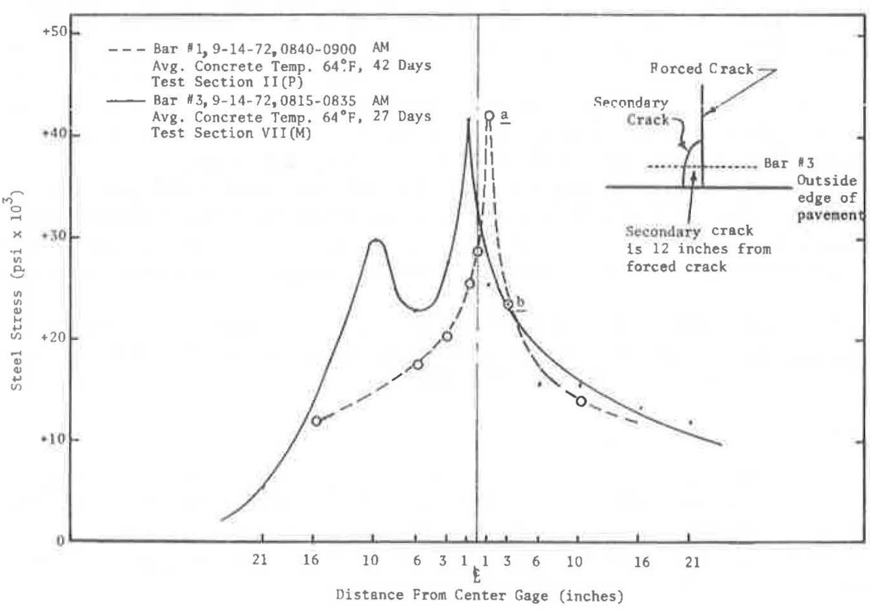


Figure 10. Variation in steel stress with temperature.

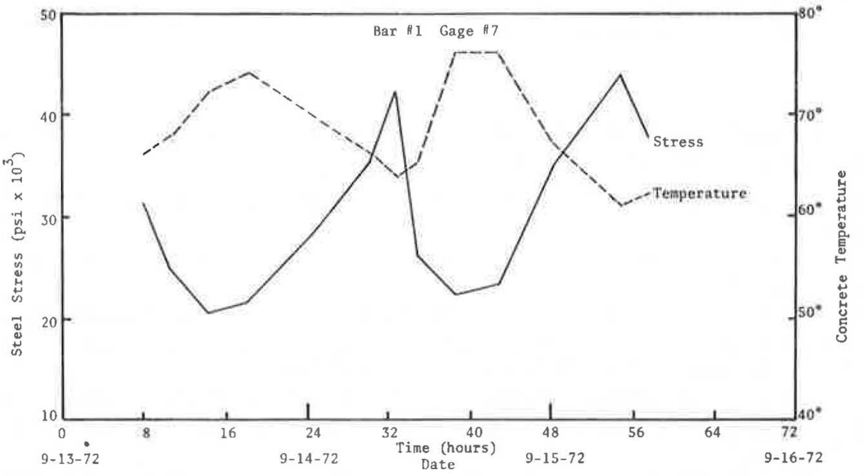


Table 2. Surface tests.

		Membrane-Cured Sections				Paper-Cured Sections			
Test	Occurrence	I	VII	III	IV	V	VI	II	VIII
PSI, by CHLOE profilometer	Before traffic	5.37	5.37	5.14	4.72	4.68	5.22	5.37	4.74
	1 year	5.18	4.94	5.00	4.64	4.71	5.20	5.16	4.80
Avg surface friction no.	Before traffic	51	54	60	56	57	52	56	50
	1 year	48	49	47	48	50	49	47	50

for the membrane-cured sections is actually related to the curing method is difficult to determine at this time particularly because other factors (such as climatic conditions at the time of placement) were also different.

CONCLUSIONS

The following conclusions are from data gathered for this particular paper and do not necessarily apply to the construction of all CRCP.

1. Concrete tensile strength as measured by splitting tests was not significantly affected by the curing method.
2. The modulus of elasticity as determined by sonic tests was not significantly affected by the curing method.
3. There was little or no difference in the effect of the two curing methods on the temperature drop experienced by the concrete during the first 24 hours after pouring.
4. Curing did not affect the average high concrete temperatures.
5. Both paper and membrane curing produced acceptable crack-spacing distribution patterns at 1 year. It appears that cracks appear earlier and more frequently at early ages with membrane curing.
6. Neither paper nor membrane curing produced acceptable crack-spacing distributions for hot weather concreting: near or above 90 F (32.2 C).
7. At pavement ages of 27 days for the membrane-cured section and 42 days for the paper-cured section, the steel stress at a concrete temperature of 64 F (18 C) was the same, i.e., 44,000 psi (303 MPa).
8. Initially, curing methods studied did not seem to affect surface friction characteristics significantly. However, at 1 year the membrane-cured sections lost an average of 8.3 surface friction numbers compared to 4.4 for the paper-cured sections.

As a result of this research study it was decided to treat CRCP with curing similar to that for other portland cement concrete pavements, i.e., unless otherwise provided, membrane curing would be used during the normal construction season and paper curing during cold weather concreting (after October 15).

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