DEPARTMENT OF MATERIALS AND CONSTRUCTION

C. H. Scholes, *Chairman*

TEMPERATURE VARIATION AND MOISTURE RETENTION OF CONCRETE CURING METHODS

Phillip L. Melville, *Associate Research Engineer*, and R. W. Czaban, *Graduate Assistant*, *Virginia Council of Highway Investigation and Research*

SYNOPSIS

It was postulated that, as stated by the Bureau of Reclamation, "the object of curing is to prevent or replenish the loss of necessary moisture during the early, relatively rapid stage of hydration" of portland-cement concrete. Moisture being integrally related to temperature, the evaluation of concrete-curing methods was made as a function of their ability to control water content and thermal variations. Electrical methods were chosen to secure desired data. The Bouyoucos plaster block and copper-constantan thermocouple were selected by process of elimination. Instrumentation included a specially designed and built A. C. ohmmeter for moisture and a standard potentiometer for temperature. Proper calibration was empiric, and for moisture contents between 1 and 6 percent, the relative error was less than ±5 percent. For temperatures between 0 and 135 F. the equipment manufacturer's guaranteed temperature accuracy was ±1.155 F. A pilot investigation was made on an 8-in.-concrete slab (2 by 3½ ft.) conveniently located on the grounds of the University of Virginia. Results indicated that the approach was practical and reliable. Data were gathered on the variations in temperature and moisture as a function of the distance from the surface of the slab.

Using the experience gained, the same method of investigation was utilized on a paving project on Route 58 in southeastern Virginia to evaluate the relative merit of the four curing methods: liquid-membrane seal, liquid-membrane seal covered with a limewash, waterproofed paper, and damp burlap. For the purpose of comparison, slabs without any artificial curing were included in the project. Virginia road specifications were followed when applicable. Test sections were repeated and placed in regular and air-entrained concrete. Results indicate that overall variations in temperature and moisture were larger and more frequent near the surface while the bottom of the slab varied little and infrequently. A relation was established between the overall variations and climatic conditions. No major difference in the effectiveness of the curing methods on the regular and air-entrained concrete could be observed. From the results, the order in which the methods proved themselves best able to retain moisture was, on the average: waterproofed paper, damp burlap, liquid-membrane seal with limewash, liquid-membrane seal, no cure. Records indicate the average order of effectiveness to maintain low and uniform temperatures to be: liquid-membrane seal with limewash, damp burlap, waterproofed paper, no cure, liquid-membrane seal.

● It is recognized that without proper curing, the desired properties of hardened concrete may not be fully developed. In addition to the easily observed loss of strength due to improper curing, a reduced durability is frequently encountered and diagnosed as follows: low resistance to wear and adverse chemical reactions, poor water-tightness, and inadequate resistance to weathering.

The following definition of curing, by the Bureau of Reclamation (*8*), has been adopted for this investigation: "The object of curing is to prevent or replenish the loss of necessary moisture during the early, relatively rapid

stage of hydration." Curing is not always considered as providing sufficient moisture to the exclusion of other considerations. Some investigators have asked whether the distribution and condition were not at least as important as the quantity of available moisture. In other words, would it not be possible for concrete to be improperly cured even with a large supply of water available when not at the proper place or in the proper form in the concrete? Furthermore, is free moisture at all needed, and, if so, how much? The investigation reported in this paper is not concerned with these questions. Instead, since standards for curing methods are currently based on so-called water-retention tests, it was postulated that the efficiency of the individual curing methods was a direct function of the quantity of free moisture in the concrete.

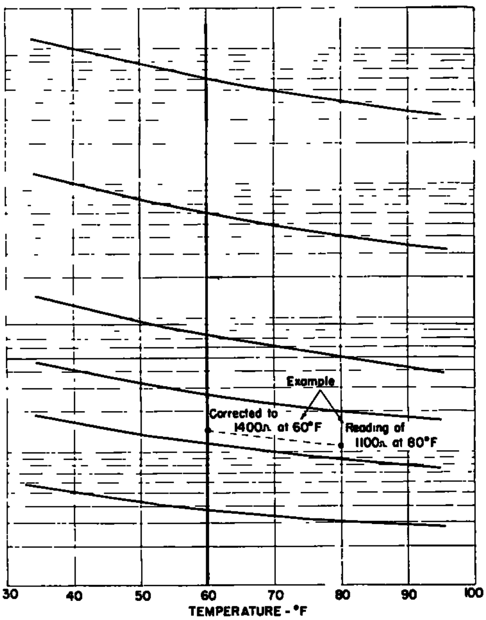

Figure 1. Chart for correcting resistance of plaster block units for temperature.

The only other factor which was surveyed was temperature. It is known that the gain of strength at early ages and other properties of concrete are related to temperature. No attempt was made to analyze the function of heat, since it was considered a parameter in the equation of curing with moisture as only variable. It would be remembered that if heat accelerates hydration of cement, as illustrated by the efficiency of steam curing (*34*), it is a well-accepted view that moderate and uniform temperatures are advisable to obtain so-called sound concrete. Thus, curing might be expressed by the following mathematical function:

$$C = f(M_t)$$

where M is the free moisture at temperature t. It is believed that everything in this paper could be extrapolated, with minor adjustments, to apply to any concrete member, but the investigation was limited to curing of highway-pavement slabs.

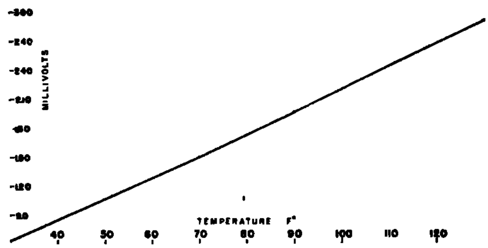

Figure 2. Calibration chart for copper and constantan thermocouples (L & N) 38 calibration (Leeds & Northrup).

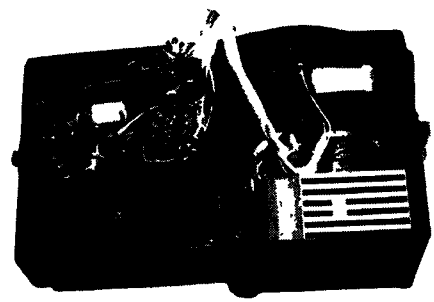

Figure 3. Inside view of A. C. ohmmeter.

LABORATORY INVESTIGATION

The electrical-resistance method was chosen as best suited to measure moisture with the desired accuracy and continuously through the experiments. A rather exhaustive study of various systems was undertaken, since none was recommended for concrete by previous investigators (*48*). By the process of elimination, the unit developed at the Michigan Agricultural Experiment Station by George J. Bouyoucos and A. H. Mick, was selected to

measure moisture in concrete as was done by the Michigan State Highway Department in coöperation with the Bureau of Public Roads (*37*).

Resistance varies with temperature as well as with moisture, and it was therefore neces-

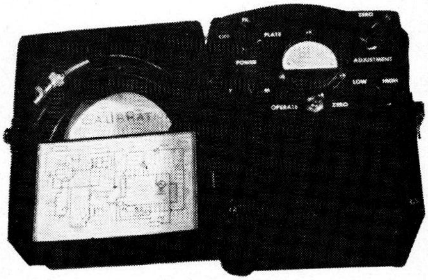

Figure 4. Outside view of A. C. ohmmeter.

over-all were used to obtain a desired accuracy of ±1.55 F. Readings were made with a Leeds & Northrup portable temperature indicator using the calibration shart shown on Figure 2 (*27*).

For the determination of moisture, a portable A.C. ohmmeter was designed and built by a student in electrical engineering at the university. It is shown in Figures 3 and 4. "The fundamental idea in the design of the instrument is that an alternating current (needed to equalize the effect of polarization), when passed through a given area of the concrete, should, when returned to the meter and rectified, give an indication of the mobile ions in the concrete. This was achieved by generating an alternating current with a battery driven feed-back oscillator, by recti-

TABLE 1
PART LIST FOR A. C. OHMMETER

Quantity	No.	Description	Specifications
1	SW-1	Switch	Double pole, triple throw, rotary
1	SW-2	Switch	Triple pole, double throw, rotary
1	SW-3	Switch	Double pole, double throw, toggle
1	SW-4	Switch	Double pole, double throw, rotary
1	SW-5	Switch	Single pole, normally closed, push type
3 ft.	Cable	3 wires	Rubber covered
1	R-1	Resistor	1.5 meg, ½ watt ± 10%
1	R-2	Potentiometer	2,000 ohm, ½ watt, WW ± 10%
1	R-3	Resistor	400 ohm, 1 watt ± 10%
1	R-4	Resistor	15,000 ohm, ½ watt, precision ± 1%, WW (with lugs)
1	R-5	Resistor	2,000 ohm, ½ watt, precision ± 1%
1	R-6	Resistor	14,000 ohm, ½ watt, precision ± 1%
1	R-7	Resistor	50 ohm, ½ watt, precision ± 1%, WW
1	R-8	Resistor	15,000 ohm, 1 watt ± 10%
1	R-9	Resistor	1,200 ohm, 1 watt ± 10%
1	R-10	Potentiometer	1.0 meg., 1 watt, WW
1	C-1	Condenser	1,000 mm F, paper, 600 V
1	C-2	Condenser	.05 MF, paper, 400 V
1	C-3	Condenser	2.0 MF, paper, 50 V
1	C-4	Condenser	.01 MF, paper, 400 V
1	VT-1	Tube	3V4
2	B-1	Battery	1.5V Flashlight
1	B-2	Battery	45V
2	RE-1 to 2	Crystal diode	Germanium
1	T-1	Transformer	Interstage 2–3
1	M-1	Microammeter	0–200 microamps

sary to convert the resistance, as measured, to a base temperature, in this case 60 F. The chart of Figure 1 for making the conversion was obtained experimentally by Bouyoucos, using soils as test media (*5*). After careful study, it was postulated that the curves could also be used for concrete.

For the determination of temperature, selected 20-gauge-duplex copper-constantan-thermocouple wires having enamel, double-wrapped glass-fibre, silicone-impregnated insulation on each wire and glass-fibre brand

fying (with two germanium crystals) and measuring with a microämmeter the amount of current returned to the meter from an electrical-resistance unit" (*41*).

The meter was built in a portable case according to the circuit specifications of the Berkeley Scientific Co. (*10*). Due to availability, a 3V4 was substituted for a 3Q4 tube, since both have the same electrical characteristics. In calibrating with precision resistors it was found necessary to make several changes. The resulting diagram is

shown in Figure 5 and a list of parts in Table 1. Further checking showed that temperature did not affect the meter and that the aging of the dry-cell batteries did not perceptibly change the readings so long as enough power was supplied to the 3V4 tube to "zero" the microämmeter. The final calibration for the high and low ranges of the meter is shown in Figure 6. It is accurate to ±0.05 percent.

No standard procedure was available to calibrate the moisture units for concrete. The general practice used for soils served as a guide. The units (having been soaked 24 hr. in water) were cast in 6- by 12-in. concrete cylinders and, along with a thermocouple, were placed as near as possible to the center

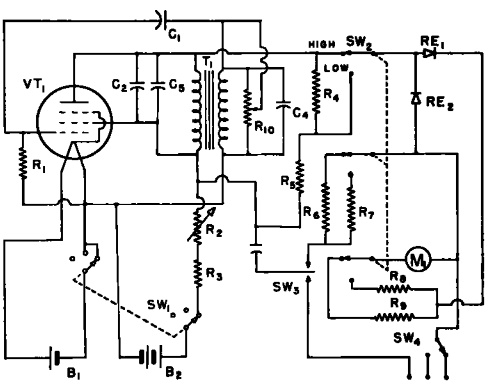

Figure 5. Circuit diagram for A. C. ohmmeter.

of the specimen. Readings were started after the concrete had set enough for the cylinders to be handled. At each reading, the resistance of the moisture unit, internal temperature. and weight of the cylinder were recorded. These readings were continued approximately on a logarithmic time scale until the changes in cylinder weights were negligible or until the resistance of the moisture unit was out of the range of the ohmmeter. The specimens were then placed in an electric oven at 110 C. and dried to constant weight. The percents moisture based on the oven-dry weight were plotted on an arithmetic scale against corresponding readings from the ohmmeter on a logarithmic scale.

A number of specimens were manufactured during the investigation and several were subjected to cycles of wetting and drying to obtain a profusion of calibrations. Sundry mixes were used to try to localize any variations which might be due to the materials used, composition of the mix, or other factors, such as air-entrainment. All mixes were designed in accordance with current practices of the council (*32*, *56*).

No correlation was established between the type of concrete and the moisture readings. The data are shown in Figure 7 for all the calibration specimens through several cycles of wetting and drying. It might at first glance

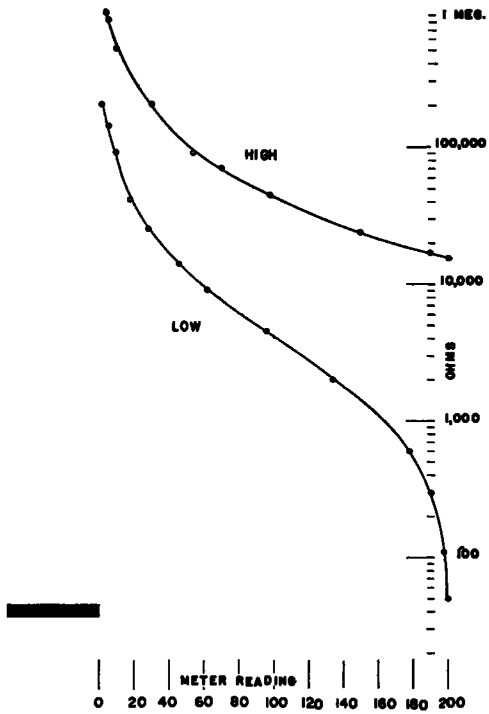

Figure 6. Calibration chart for A. C. ohmmeter.

appear that the points are too scattered to warrant any reliable average curve. The units measured moisture at one point in the cylinders (approximately the center) while weight determinations gave the average moisture content for the entire specimen. In addition, it is suspected that the dessication at the end of the first cycle may damage the plaster blocks, resulting in erroneous subsequent readings as the distribution of the individual calibration curves would indicate: the points were well grouped for the original drying cycle and almost all the values more than ±½ percent

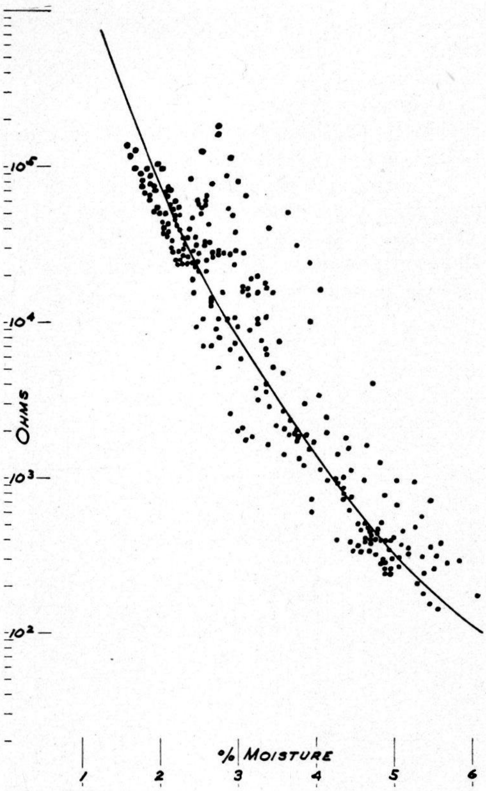

Figure 7. Distribution of points used in determining the mean calibration curve.

moisture from the mean calibration were obtained from subsequent cycles.

The range of the A. C. ohmmeter was from 100 ohms to 1 megohm. A mathematic approach was used to deduce the remainder of the curve from the known part (*49*). Two general equations fit reasonably well the existing data, if used within the limitations of the tests, one being an exponential and the other a hyperbolic function. If we have

$$\bar{y} = log_{10}y$$

we can write either:

$$(x + \tfrac{3}{8}) = 100.5e - (0.348\bar{y} + 2.04)$$

where *e* is Napier's constant, or:

$$\bar{y} = -0.87 + \frac{20.4}{x} - \frac{17.7}{x^2}.$$

It is interesting to speculate as to why the plaster blocks, which had been tried with indifferent success by many a previous investigator, gave such encouraging results which prompted the pilot and the field studies. It appears that the high-pH medium in which the electrodes were embedded will not change appreciably in alkalinity in the presence of concrete since the latter is also basic. It is likely that enough lime was available through the experiment to buffer the pH of the medium and regulate the flow of

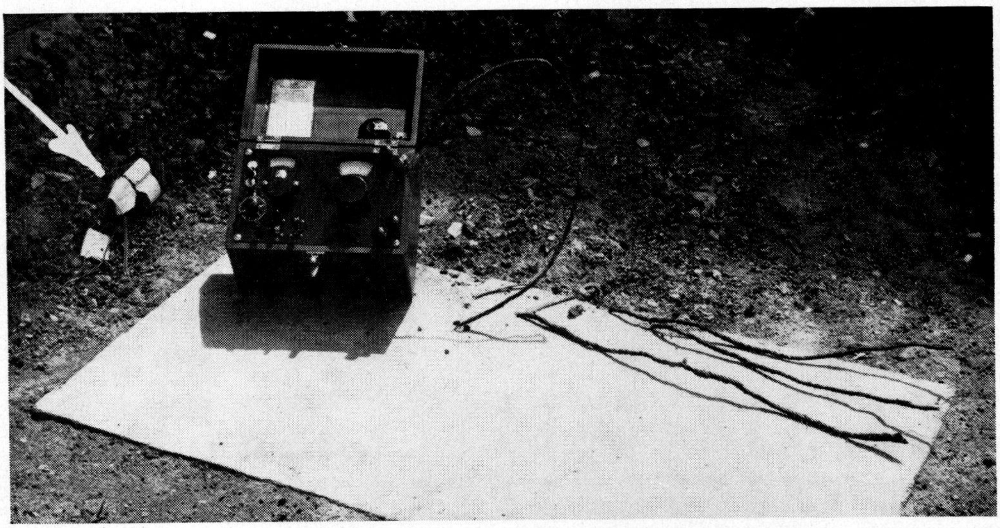

Figure 8. Concrete slab for pilot study (thermocouples connected to potentiometer; arrow points to leads of plaster blocks).

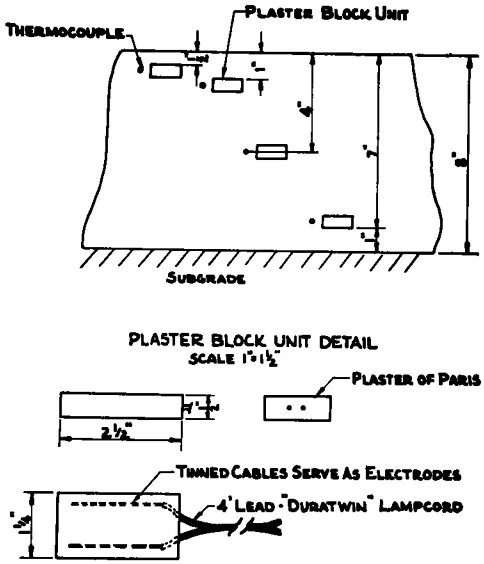

Figure 9. Location of units in slab.

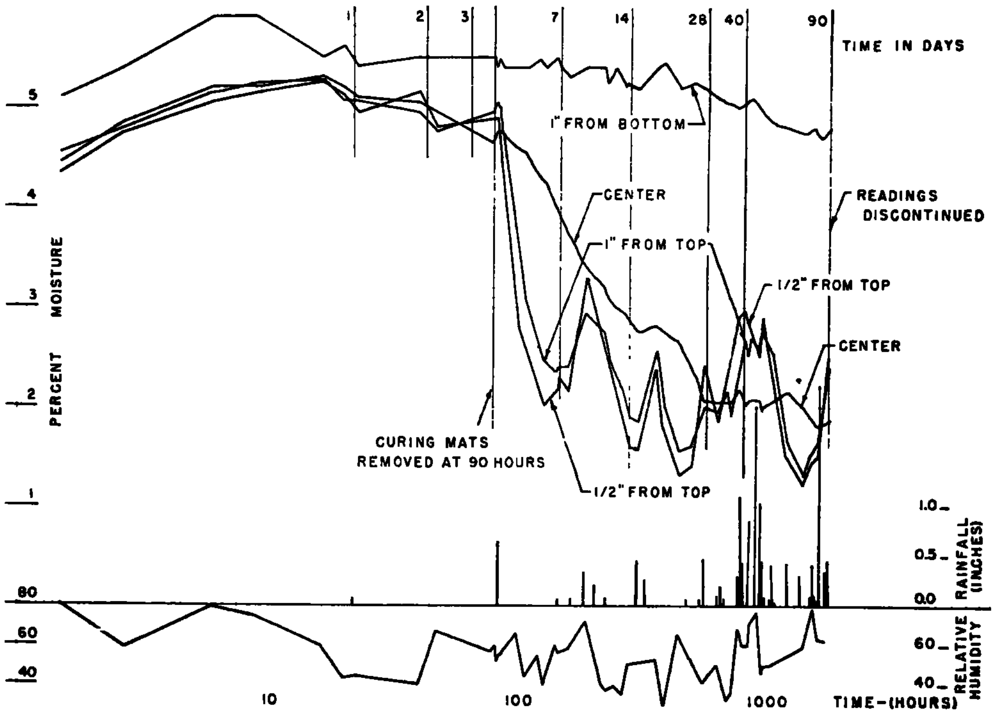

Figure 10. Time versus moisture content for pilot slab.

ions during resistance readings. The extreme care exercised in preparing and placing the units as well as the quality of the electrical equipment undoubtedly contributed to the success of the project.

PILOT STUDY

Before attempting a large-scale field investigation of curing methods, a pilot slab was placed outside the laboratory on the grounds of the university. The simulated pavement was 8 in. thick and 3½- by 2-ft. in area and is shown in Figure 8.

Four moisture-temperature units were embedded in the slab as shown in Figure 9 to study variations in moisture as a function of depth from the surface. Instrument readings, which had been started immediately after placing, were continued for 90 days. For the first 90 hr., the slab was covered with saturated cotton mats. The concrete was air-entrained and otherwise designed to meet requirements for Class A of the Virginia Department of Highways.

Figure 10 shows time-moisture curves for the units placed in the slab. As expected, the amplitude of moisture variation was a function of the depth of embedment. Both the

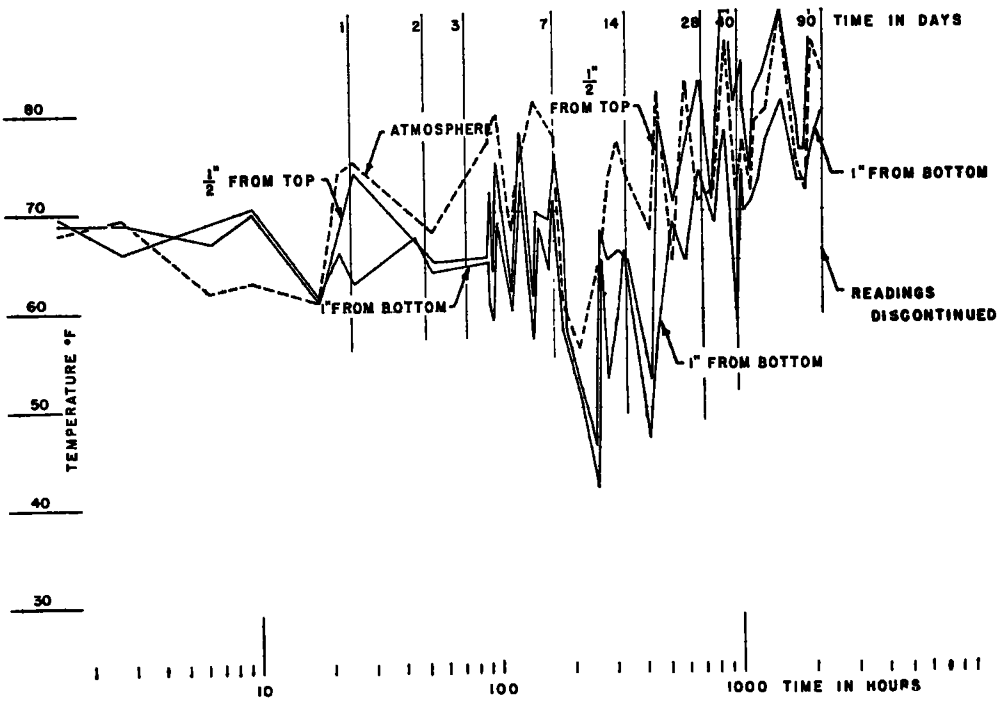

Figure 11. Time versus temperature for pilot slab (at time of readings).

TABLE 2
DESCRIPTION OF TEST SECTIONS

Group No.	Section No.	Treatment	Time of Pour		Type Concrete
			Date	Hour	
1	1	No cure	9/11/51	9:30 A.M.	Ordinary
	2	Membrane		10.45 A.M.	
	3	Paper		11:30 A.M.	
	4	Burlap		1:45 P.M.	
	5	Membrane + limewash		3:00 P.M.	
2	6	Membrane	9/12/51	11 00 A.M.	Ordinary
	7	Membrane + limewash		11:30 A.M.	
	8	Paper		1 30 P.M.	
	9	Membrane		4:00 P.M.	
	10	Burlap		4·30 P.M.	
3	11	Paper	9/19/51	10:00 A.M.	Air-entrained
	12	Burlap		10 30 A.M.	
	13	No cure		11 00 A.M.	
	14	Membrane + limewash		11:30 A.M.	
	15	Membrane		12:00 A.M.	
4	16	Paper	9/20/51	9:00 A.M.	Air-entrained
	17	Burlap		9:20 A.M.	
	18	No cure		9:40 A.M.	
	19	Membrane + limewash		10:00 A.M.	
	20	Membrane		10 30 A.M.	

losses due to evaporation and the gains in moisture due to precipitations were magnified in the readings obtained with the units nearest the surface. The temperature data shown in Figure 11 are only for the top and bottom units, since the intermediate ones averaged the thermal behavior of the extremes.

The information gathered in the making of the pilot slab and the moisture-temperature data were considered reliable and accurate enough to warrant the undertaking of a field project.

FIELD INVESTIGATION

After both the laboratory investigation and the pilot slab study proved the practicability

of measuring the moisture content at any one point in a concrete slab *in situ*, the highway department selected a field project to compare several means of curing pavement concrete on the basis of their relative abilities to retain moisture. The project chosen was located in Southampton County (Project No. 1787-04), Route 58, east of Emporia, in southeastern Virginia.

Each curing treatment was applied to a complete slab, twice in ordinary and twice in air-entrained concrete. This gave a total of four complete groups placed on different days.

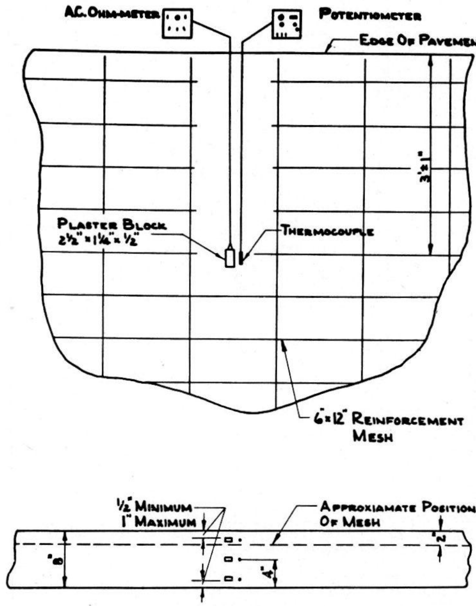

Figure 12. Details for placing units.

The experimental slabs are identified by section and station in Table 2. The pavement was 8 in. thick with contraction joints spaced every 50 ft. A longitudinal joint along the centerline divided the pavement into 12-ft. lanes.

The five different curing methods which were compared were:

A = No treatment
B = Liquid-membrane seal
C = Liquid-membrane seal followed by limewash
D = Waterproof paper
E = Damp burlap.

Treatment B was applied by the contractor with a mechanical sprayer in accordance with current specifications. In Group 2 there are two membrane and no no-cure sections, due to a misunderstanding on the part of the operator. The limewash coating in C, sprinkled with a watering can, was a solution of one part of lime to two parts of water. The waterproofed paper in D was rolled on in two 11- by 50-ft. blankets and 2-ft. strips overlapping the edges and the centerline of the slab. Finally, sand was used for weighing down the outside edges and the centerline strips. In F, burlap weighing 6.7 oz. per sq. yd. was

Figure 13. Placing of center moisture-temperature unit in est slab. Note wire-mesh reinforcement removed to avoid interferences.

placed across the slab with a minimum 6-in. overlap. Small piles of sand were placed on the burlap to hold it secure. The burlap was maintained in a moist condition by sprinkling at least three times daily. In all cases, except as noted below, the treatments were started before midnight of the day of placing and were continued for a period of at least 72 hrs. The limewash in Sections 1, 2, and 4 was not sprinkled on until 9:00 A. M. of the following day. *Virginia Road and Bridge Specifications* (1947) were followed whenever applicable for the above treatments. Especially, the liquid-

Figure 14. Marking used for identification of typical test section. The A. C. ohmmeter is ready to be connected with lead wires at edge of slab.

membrane seal was sprayed under the department inspector's direct supervision and in full compliance with current specifications.

Three units were placed in each test slab as shown in Figure 12. Each plaster block was soaked in water for at least 2 hr. previous to embedment to bring its moisture content to approximately that of the fresh concrete. The bottom units were inserted in the first course; some 6 sq. ft. of wire-mesh reinforcement was removed before placing the center and top units to eliminate possible interference (Fig. 13). When the top units had been placed in each slab, it was necessary to maintain close watch on the finishing operations to prevent any dislocation. Extreme care was exercised in the placing of all units in order to secure a minimum of variation in the depth of embedment, but in no way were the contractor's forces delayed in their work.

After a complete group of units had been placed, a slump test (ASTM designation C 143) was made. For Groups 3 and 4, the entrained-air content was determined with a Washington Airmeter (ASTM designation

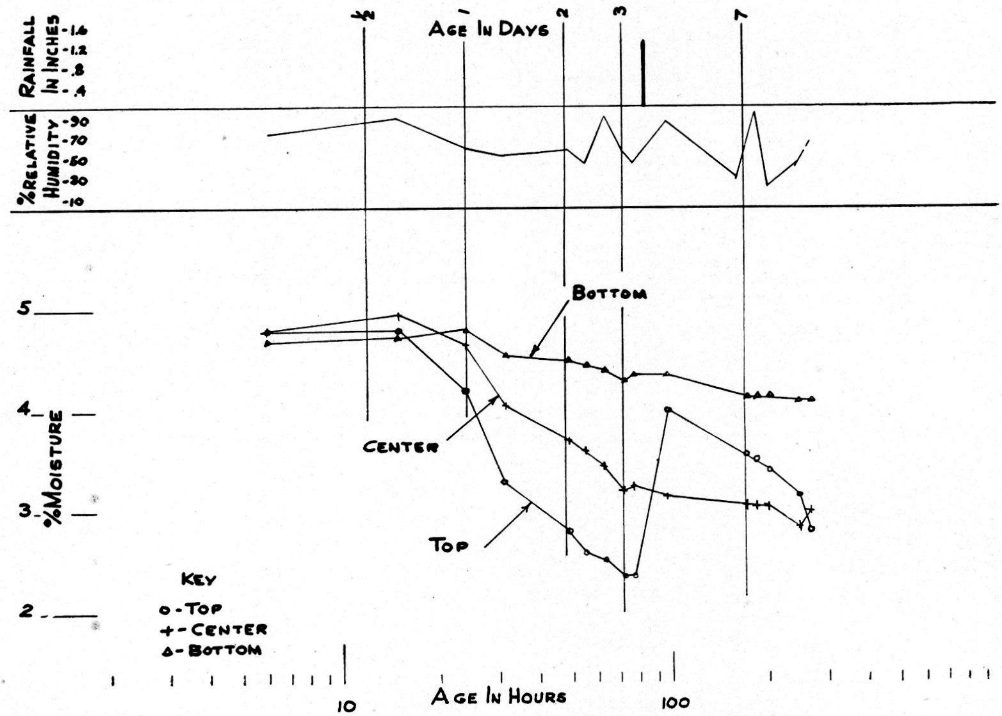

Figure 15. Moisture versus age for Test Section 1; treatment, none. Station, 90908.

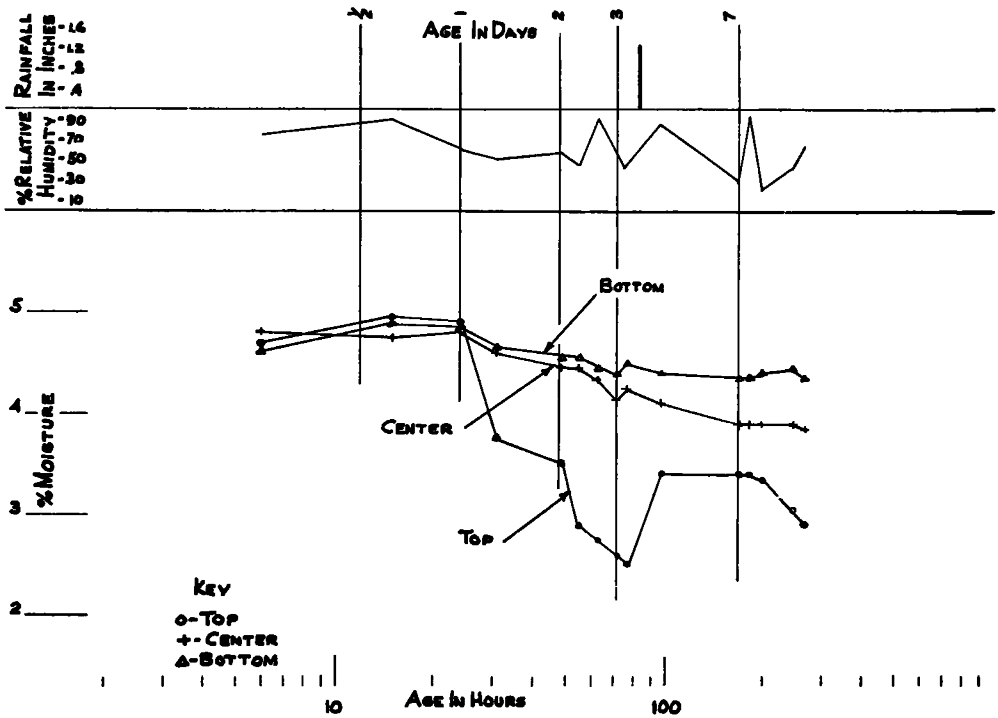

Figure 16. Moisture versus age for Section 2; treatment, membrane. Station, 91008.

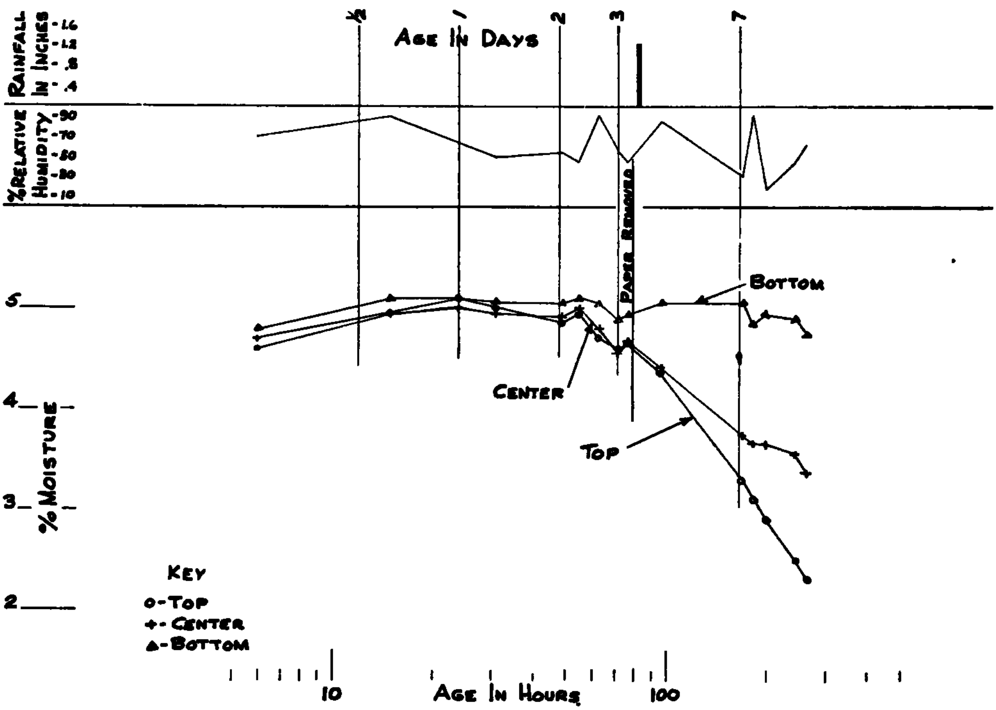

Figure 17. Moisture versus age for Section 3; treatment, paper. Station 91059.

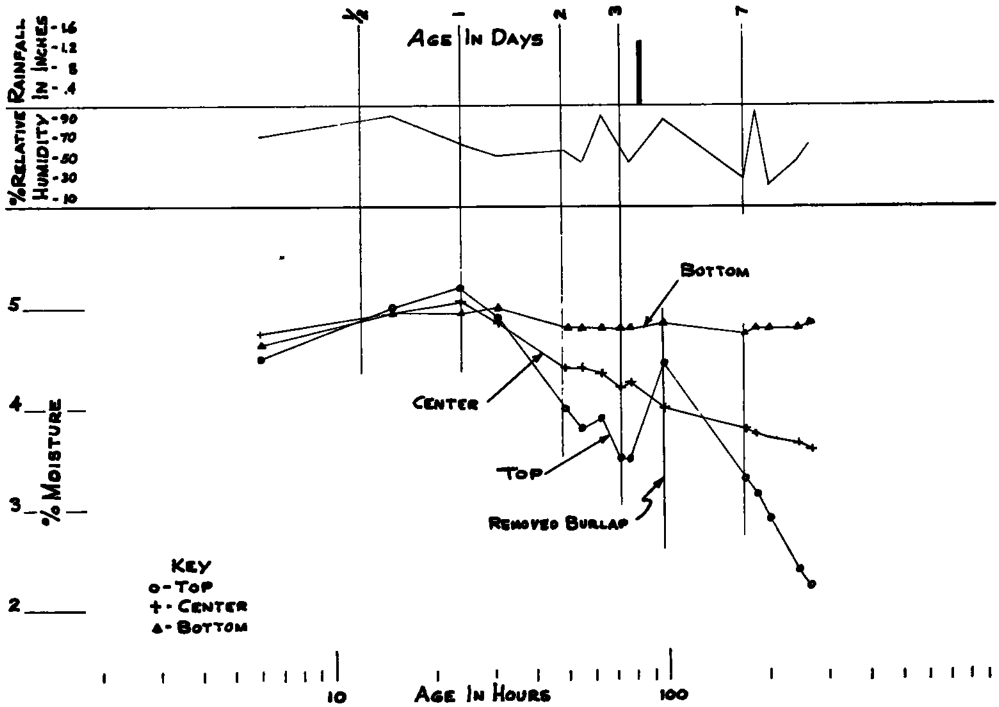

Figure 18. Moisture versus age for Section 4; treatment, burlap. Station, 91258.

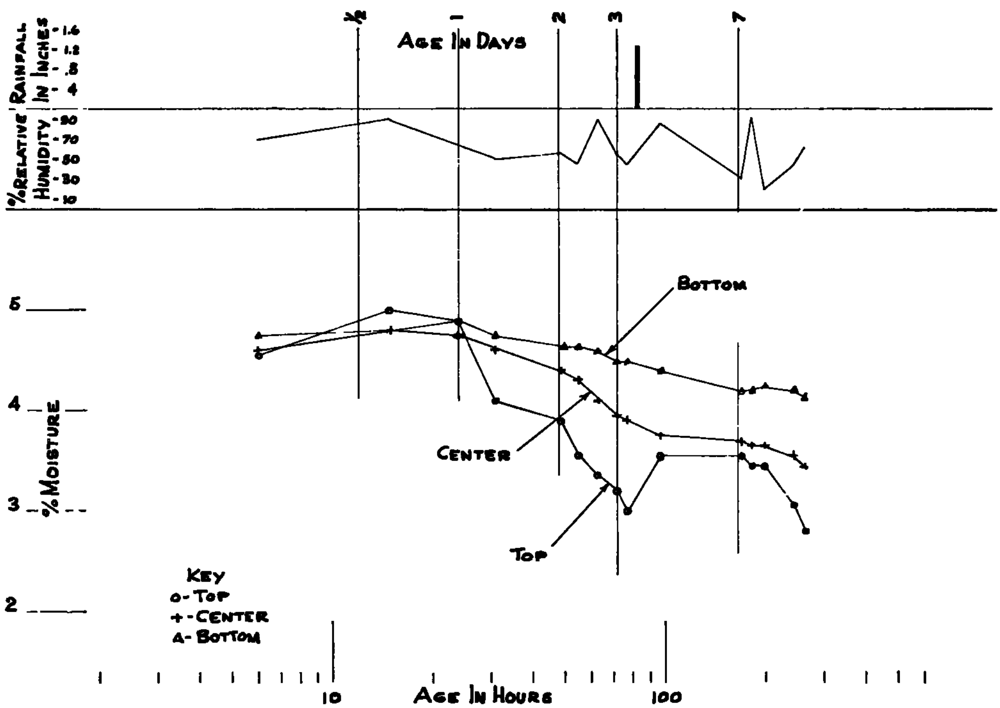

Figure 19. Moisture versus age for Section 5; treatment, membrane plus limewash. Station, 91318.

C 185). Finally, one check cylinder was made for each group following the same procedure used in the laboratory studies. All the materials used fully passed the requirements of *Virginia Road and Bridge Specifications*

After several months, two cores were drilled from each test section. They were tested in compression to try to establish a relation between strength and curing of the concrete.

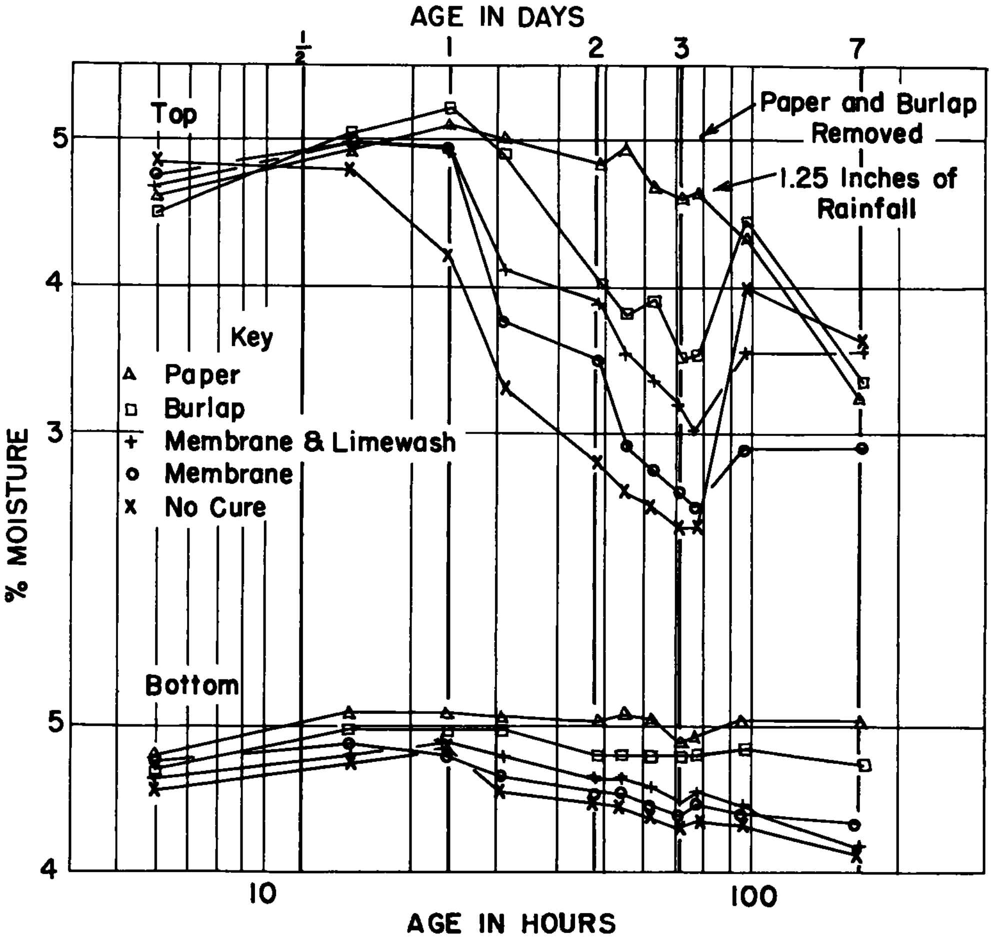

Figure 20. Moisture versus age for slabs in test sections.

Readings were started as soon as possible after brooming of the freshly placed concrete and continued during the 72-hr. curing period with an average of three readings per 24 hr: one in the morning, one in the afternoon and one around midnight. Proper identification was etched in the fresh concrete at the test points (Fig. 14). Three-in. cast-iron pipes, 2 ft. long, driven vertically at these locations along the edge of the slab, were used as terminal boxes to protect the lead wires.

RESULTS

Since the results of the field study are too bulky for presentation *in extenso*, Sections 1 to 5 were selected as representative of the whole, in view of the good check between groups.

The relationship of the moisture content as a function of the distance from the surface of the pavement is first shown in Figures 15 to 19. The curing treatments are evaluated by comparing the moisture content in the top

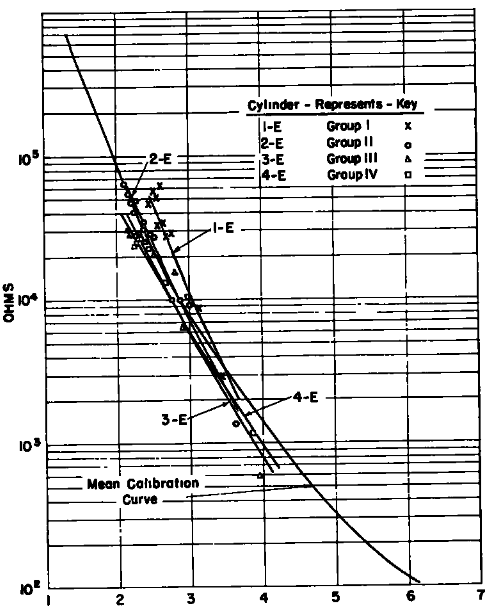

Figure 21. Check calibration curves for field investigation.

and bottom units in Figure 20. The check calibration curves for the field cylinders, as compared with the mean calibration curve developed in the laboratory, are shown in Figure 21. It is felt that their relationship verified the validity of the mean calibration curve.

Table 3 gives the percent moisture in top units of the test slabs at the end of the 72-hr. curing period. These values are tabulated below on the basis of difference in moisture from that in the no-cure sections.

Treatment	Group				Avg. of 1, 3, 4
	1	2[a]	3	4	
Waterproofed paper	2.25	1.88	1.90	2.25	2.13
Damp burlap	1.15	1.38	1.10	1 50	1.25
Membrane plus limewash	0.85	0.68	0.55	1.50	0.97
Membrane	0.25	0.00	0.25	0.55	0.35
No cure	0.00	—	0.00	0.00	0.00

[a] Moisture content at 50 hr. on account of heavy rain before 72 hr.

TABLE 3

MOISTURE CONTENT IN TOP UNITS OF TEST SLABS AT END OF 72-HR. CURING PERIOD

Treatment	Group			
	1	2[b]	3	4[b]
	percent	*percent*	*percent*	*percent*
Waterproofed paper	4 60	4.95	4 20	4.55
Damp burlap	3 50	4 45	3 40	3.80
Membrane plus limewash	3 20	3 75	2 85	3.80
Membrane	2.60	2 65, 3 60	2 55	2 85
No cure	2 35	[a]	2.30	2.30

[a] Group 2 contained two test sections of membrane curing, leaving out a no-cure section.

[b] Represents moisture content at 50 hr. because of heavy rain occurring before end of 72-hr. curing period.

Table 4 lists the maximum losses in moisture content for the top units in the test slabs during the 72-hr. curing period. For comparison, these values are expressed as relative percentages of moisture loss with the no-cure section representing 100 percent change.

Treatment	Group				Avg. of 1, 3, 4.
	1	2	3	4	
Paper	20.4	37.5	47.9	32 7	33.6
Damp burlap	69.4	37.5	54.2	53 1	58.8
Membrane plus lime wash	73.5	125.0	70 8	49.0	64.5
Membrane	96.0	100.0	95.8	85.7	92 5
No cure	100 0	—	100 0	100.0	100.0

TABLE 4

MAXIMUM LOSS IN MOISTURE CONTENT IN TOP UNITS OF TEST SLABS DURING 72-HR. CURING PERIOD

Treatment	Group			
	1	2	3	4
	percent	*percent*	*percent*	*percent*
Paper	0.50	0 45	1.15	0.80
Burlap	1 70	0.45	1.30	1.30
Membrane plus limewash	1.90	1 50	1.70	1.20
Membrane	2 35	1.10, 1.30	2 30	2 10
No cure	2 45	[a]	2.40	2 45

[a] Group 2 contained two test sections of membrane curing, leaving out a no-cure section.

Table 5 lists the maximum temperatures reached in the top units during the 72-hr. curing period. These values are tabulated below on the basis of number of degrees Fahrenheit above that reached in the membrane-plus-limewash sections.

Treatment	Group				Average
	1	2	3	4	
Membrane	11	24	9	18	15.5
No cure	2[a]	—	8	14	8 0
Paper	8	10	2	10	7.5
Damp burlap	0	3	7	1	2.8
Membrane plus limewash	0	0	0	0	0

[a] Shade of large tree protected slab.

Table 6 shows the maximum temperature differential in degrees Fahrenheit between the

top and bottom units at any one time during the 72-hr. curing period. For the purpose of comparison, these values are expressed as degrees Fahrenheit of temperature differential above that in the waterproof paper sections.

Treatment	Group			
	1	2	3	4
Membrane	6	5	0	8
No cure	4	—	5	4
Membrane plus limewash	1	1	3	−1
Damp burlap	2	1	3	3
Paper	0	0	0	0

Table 7 lists the temperature variations in degrees Fahrenheit for the top units throughout the 72-hr. curing period. The values are also tabulated below on the basis of degrees Fahrenheit variation above that of the membrane-plus-limewash sections.

Treatment	Group			
	1	2	3	4
Membrane	5	17	−1	15
No cure	−1	—	2	14
Damp burlap	1	1	3	7
Paper	3	3	−9	6
Membrane plus limewash	0	0	0	0

Atmospheric wet- and dry-bulb temperatures were recorded at readings. In order to correlate weather conditions with the data, the corresponding humidity and precipitation were plotted on the time-moisture curves. Figure 22 shows a typical temperature relationship, for the various treatments, in the top units of Sections 1 through 5. The core strengths did not indicate any relation between the curing methods and the compressive strength of the hardened concrete.

RESULTS AND CONCLUSIONS

From the data presented in this report and under the conditions investigated, the following conclusions may be drawn: (1) It is possible and practical to measure continuously moisture and temperature at any point in a concrete slab during the curing period by electrical methods. (2) Bouyoucos plaster blocks and copper-constantan thermocouples with *ad hoc* electrical instruments give satisfactory readings. (3) No significant difference exists between the effects of the curing methods on air-entrained and non-air-entrained concrete slabs. (4) There is no apparent correlation between the compressive strength of the pavement concrete and the method used to cure it.

Considering only the moisture variable, it is observed from the data that: (5) The rating of the curing methods based on the highest to lowest amount of moisture retention is: waterproof paper, damp burlap, membrane plus limewash, liquid-membrane seal and no cure. (6) Moisture contents vary appreciably through the 8-in slabs as a function of depth. (7) Moisture variations are larger the nearer to the surface and decrease at an increasing rate

TABLE 5
MAXIMUM TEMPERATURES FOR TOP UNITS IN TEST SLABS DURING 72-HR. CURING PERIOD

Treatment	Group			
	1	2	3	4
	F.	F.	F.	F.
Membrane	107	107, 117[b]	97	100
No cure	98[a]		96	96
Paper	104	98	90	92
Burlap	96	91	95	83
Membrane plus limewash	96	88	88	82

[a] Shade of large tree protected slab.
[b] Group 2 contained two test sections of membrane curing leaving out a no-cure section.

TABLE 6
MAXIMUM TEMPERATURE DIFFERENTIAL BETWEEN TOP AND BOTTOM UNITS IN TEST SLABS DURING 72-HR. CURING PERIOD

Treatment	Group			
	1	2	3	4
	F.	F.	F.	F.
Membrane	13	13, 12[a]	7	14
No cure	11		12	10
Membrane plus limewash	8	8	10	5
Burlap	9	8	10	9
Paper	7	7	7	6

[a] Group 2 contained two test sections of membrane curing leaving out a no-cure section.

TABLE 7
TEMPERATURE VARIATION FOR TOP UNITS IN TEST SLABS DURING 72-HR. CURING PERIOD

reatment	Group			
	1	2	3	4
	F.	F.	F.	F.
Membrane	25	25, 39[a]	26	26
No cure	19		29	25
Burlap	21	16	30	18
Paper	23	18	18	17
Membrane plus limewash	20	15	27	11

[a] Group 2 contained two test sections of membrane curing leaving out a no-cure section.

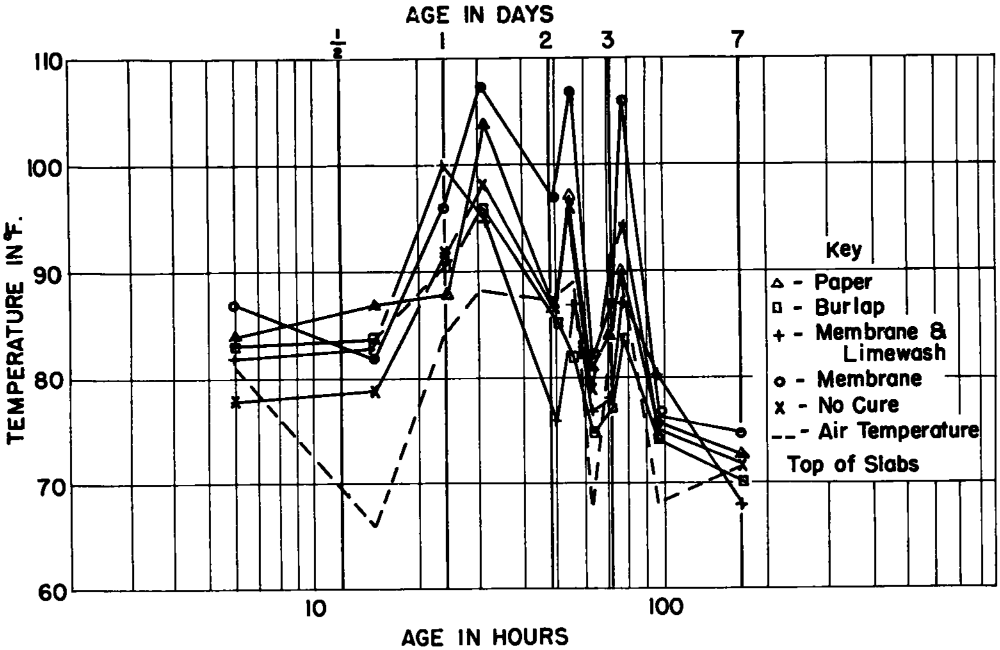

Figure 22. Temperature versus age for slabs in test sections.

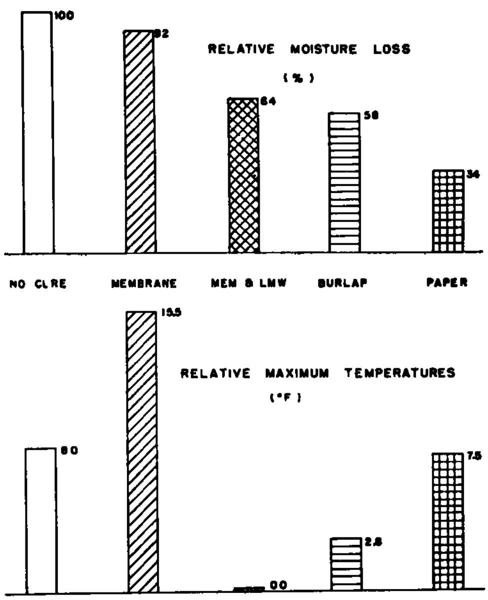

Figure 23. Summary of results for 72-hr. curing period in top of test slabs.

toward the bottom. (8) The amplitude of moisture variations through the curing period is least with the paper; then, in order, with damp burlap, membrane and limewash, membrane, and no cure.

Considering only the temperature variable, it is observed from the data that: (9) Lowest temperatures are obtained with membrane and limewash; then, in order, with damp burlap, paper, no cure and membrane. (10) Temperatures vary appreciably through the slabs as a function of depth. (11) The amplitude of temperature variations throughout the thickness of the slabs is least for paper, with membrane and limewash a close second, followed, in order, by burlap, no cure and membrane. (12) The amplitude of temperature variations near the surface of the slabs is least with membrane and limewash; then, in order, paper, damp burlap, no cure and membrane.

Considering only the climatic variables, it is observed from the data that: (13) Precipitations are most clearly reflected in the no-cure sections; then, in order, in the damp burlap, membrane, membrane with limewash, and paper. (14) Air temperatures are most clearly reflected in the membrane sections; then, in order, no cure, damp burlap, paper, and membrane and limewash. (15) Relative humidity is most clearly reflected in the moisture varia-

tions of the damp burlap; then, in order, paper, membrane with limewash, no cure, and membrane.

A summary of the data shown previously is presented in Figure 23. In conclusion, this investigation indicated that the waterproof paper was the most-efficient and the liquid membrane the least-efficient method of retaining moisture in the fresh concrete. In addition, the temperature conditions most commonly required in pavement curing were obtained as a function of the tone of the surface. In other words, the lighter the surface tone, the cooler the concrete. This explains the improvement in performance of the liquid-membrane seal when painted with a limewash. A similar result would be expected if the waterproofed paper had a white surface. The good performance of the damp burlap in maintaining a fairly low, uniform temperature may be explained by the cooling effect resulting from evaporation. Logically enough, the tone is also partially responsible for the moisture readings, since the rate of evaporation is a function of the temperature.

It is believed that much additional information on concrete curing may be obtained by using the methods developed in this investigation. It is expected that this same approach may prove of value in studying a number of problems where moisture and temperature in portland-cement concrete are of critical importance.

ACKNOWLEDGMENTS

The authors are grateful for the help of members of the faculty of the School of Engineering at the University of Virginia, who in one way or another made this project possible, and in particular, to F. T. Morse. H. W. Curtis and E C. McClintock, as well as to M. Cruser of the School of Physics and to David Redfield, student in electrical engineering. The coöperation of the field forces of the Virginia Department of Highways, E. C. Ramsey, inspector; A. T. Arnold, resident engineer; B. W. Butt, Suffolk District materials engineer; J. M. Hagen, Suffolk District engineer, was largely responsible for making the field project possible. Thanks are also due to the contractor, H. Scott of Franklin, Virginia, for his willingness to help the investigators, and to several individuals, among them Joe Smith of High Point, North Carolina, and Mr. and Mrs. Drew of Emporia, Virginia—who rendered valuable services. Finally, the constructive criticism offered by T. E. Shelburne, director of research, Virginia Council of Highway Investigation and Research, is gratefully acknowledged.

REFERENCES

1. ABRAMS, DUFF A.: Effect of Curing Condition on the Wear and Strength of Concrete. *Bulletin 2*, Structural Materials Research Laboratory, Lewis Institute, September, 1922.
2. BLANKS, R. F., MEISSMER, H. S., AND TUTHILL, L. H.: Curing Concrete with Sealing Compounds. *Proceedings*, American Concrete Institute, *42:* 493–512, 1946.
3. BLANKS, R. F., VIDAL, E. N., PRICE, W. H., AND RUSSELL, F. M.: The Properties of Concrete Mixes. *Proceedings*, American Concrete Institute, *36:* 436–475, 1940.
4. BODEN, O. G.: Canal Lining Cured by Sprayed Coats of White-Pigmented Compounds. *Proceedings*, American Concrete Institute, *38:* 449–451, 1942.
5. BOUYOUCOS, GEORGE J., AND MICK, A. H.: An Electrical Resistance Method for the Continuous Measurement of Soil Moisture under Field Conditions. *Technical Bulletin 172*, Michigan State College Agricultural Experiment Station, East Lansing, 1940.
6. BOUYOUCOS, GEORGE J.: Nylon Electrical Resistance Unit for Continuous Measurement of Soil Moisture in the Field. *Soil Science 67:* 319–330, 1949.
7. BOUYOUCOS, GEORGE J.: Methods for Measuring the Moisture Content of Soils under Field Conditions. PROCEEDINGS, Highway Research Board, Not Released for Publication, 1950.
8. Bureau of Reclamation, *Concrete Manual*, Government Printing Office, Washington, D. C., 1949.
9. BROWN, L. S.: *Unpublished Data*, Lone Star Cement Research Laboratory, 1940.
10. COLMAN, E. A.: *Manual of Instructions for Use of the Fiberglas Soil-Moisture Instrument*, U. S Forest and Range Experiment Station, Berkeley, Calif., October, 1948.
11. COPELAND, R. E., AND CARLSON, C. C.: Tests of the Resistance of Concrete Masonry Walls to the Penetration of Rain. *Proceedings*, American Concrete Institute, *32:* 485–494, 1936.
12. CRONEY, D., COLEMAN, J. D., AND CURRER, E. W. H. The Electrical Resistance Method of Measuring Soil Moisture. *British Journal of Applied Physics*, *2:* 85–91, April 1951.
13. CZABAN, R. W.: The Measurement of Mois-

ture Content in Concrete. *Virginia Journal of Science, 2:* (New Series) No. 4, September, 1951.

14. CZABAN, R. W.: An Investigation of Curing Methods of Pavement Concrete. Unpublished *Progress Report No. 2*, Council of Highway Investigation and Research, University of Va., August, 1951.
15. EDLFSEN, N. E.: A Review of Results of Dielectric Methods for Measuring Moisture Present in Materials. *Agricultural Engineering, 14:* 243–244, 1933.
16. GAUSE, G. R., AND TUCKER, J. J.: Method for Determining the Moisture Condition in Hardened Concrete. *Journal of Research*, National Bureau of Standards, *25:* 403–416, 1940.
17. GONNERMAN, H. F.: Review of Data on Bituminous Coatings and Relation of Temperature to Curing Methods. Report of Committee on Curing of Concrete Pavement Slabs, PROCEEDINGS, Highway Research Board, Part II, *13:* 35–49, 1933.
18. GONNERMAN, H. F.: Study of Methods of Curing Concrete. *Proceedings*, American Concrete Institute, *26:* 359–396, 1930.
19. Highway Research Board, Curing Concrete Pavements. *Wartime Road Problems*, No. 1, Washington, D. C., July, 1942.
20. JACKSON, F. H., AND BAUMAN, E. W.: A Study of Methods of Curing Concrete Pavements. *Public Roads, 11:* No. 2, January, 1931.
21. JACKSON, F. H., AND KELLERMAN, W. F.: Tests of Concrete Curing Materials. *Proceedings*, American Concrete Institute, *35:* 481–487, 1939.
22. JACKSON, F. H., AND WERNER, G.: Field Experiments in the Curing of Concrete Pavements. *Public Roads, 9:* 145–146, 1928.
23. KELLERMAN, W. F.: Curing Concrete. *Report on Significance of Tests of Concrete and Concrete Aggregates*, A. S. T. M., 2nd Edition: 89–93, 1943.
24. KREFIELD, W. J.: Incomplete Curing Weakens Concrete Surfaces. *Civil Engineering, 3:* 663–665, 1933.
25. LANG, F. C.: Intermittent Curing of Concrete. Report of Committee on Curing of Concrete Pavement Slabs, PROCEEDINGS, Highway Research Board, Part II, *13:* 66–82, 1933.
26. LANG, F. C., AND BURGRAFF, F.: Progress Report of Committee on Curing of Concrete Pavement Slabs. PROCEEDINGS, Highway Research Board, *10:* 370–401, 1931.
27. Leeds and Northrup, *Standard Conversion Tables* No. 31031, Leeds and Northrup Co., Philadelphia, November, 1948.
28. LEIGH, C. O.: An Investigation of Curing Methods of Pavement Concrete. Unpublished *Progress Report No. 1*, Council of Highway Investigation and Research, University of Va., March, 1951.
29. LONG, B. S., AND KURTZ, H. J.: Effect of Curing Methods upon Durability of Concrete as Measured by Changes in the Dynamic Modulus of Elasticity. *Proceedings*, A. S. T. M., *43:* 1051–1068, 1943.
30. MCMILLAN, F. R., AND LYSE, I.: Some Permeability Studies of Concrete. *Journal*, American Concrete Institute, *26:* 101–142, 1930.
31. MEISSNER, H. S., AND SMITH, S. C.: Concrete Curing Compounds. *Proceedings*, American Concrete Institute, *34:* 549–559, 1938.
32. MELVILLE, P. L.: Design of Concrete Mixes. Unpublished *Report*, Virginia Department of Highways, Research Section, Richmond, Va., July, 1947.
33. Menzel, Carl A.: Strength and Volume Change of Steam Cured Portland Cement Mortar and Concrete. *Proceedings*, American Concrete Institute, *31:* 125–148. 1935.
34. MENZEL, CARL A.: Studies of High Pressure Steam Curing of Concrete Slabs and Beams. *Proceedings*, American Concrete Institute, *32:* 51–64, 1936.
35. MORRIS, M.: The Use of Paper for Curing Concrete Pavements. PROCEEDINGS, Highway Research Board, Part II, *13:* 59–65, 1933.
36. MYERS, B.: Experiments in Curing Concrete Pavements. PROCEEDINGS, Highway Research Board, *19:* 284–295, 1939.
37. Nine Year Progress Report (1940–1949). *Report No. 137* Research Laboratory, Michigan State Highway Department, August, 1950.
38. POWERS, T. C.: A Discussion of Cement Hydration in Relation to the Curing of Concrete. PROCEEDINGS, Highway Research Board, *27:* 178–188, 1947.
39. POWERS, T. C., AND BROWNYARD, T. L.: Studies of the Physical Properties of Hardened Portland Cement Paste. *Proceedings*, American Concrete Institute, *43:* 249–336, 1947.
40. RAEGEL, F. V., WILLIS, T. F., AND WRAY, F. N.: *An Investigation of Methods of Curing Concrete Pavements*. Missouri State Highway Department, Jefferson City, Missouri, June, 1932.
41. Redfield, David D.: Alternating Current Ohmmeter for Soil Moisture, Temperature Measurement. *Unpublished*, University of Va., May, 1951.
42. RHODES, C. C., AND EVANS, J. R.: An Ap-

praisal of the Membrane Method of Curing Pavement Concrete. *Bulletin 108*, Michigan Engineering Experiment Station, East Lansing, 1949.
43. RHODES, C. C.· Michigan's Experience in the Use of White Pigmented Membrane Curing Compounds. PROCEEDINGS, Highway Research Board, *30:* 260–282, 1950.
44. RICHARDS, L. S., AND WEAVER, L. R.: The Sorbtion Block Soil Moisture Meter and Hysteresis Effects Related to its Operation. *Jour. Amer. Soc. Agron.*, *35:* 1002–1011, 1943.
45. RUETTGERS, A., VIDAL, E. N., AND WING, S. P.: An Investigation of the Permeability of Mass Concrete with Particular Reference to Boulder Dam. *Proceedings*, American Concrete Institute, *31:* 382–416, 1935.
46. SAUL, A.: Principles Underlying the Steam Curing of Concrete at Atmospheric Pressure. *Research Note*, Cement and Concrete Association, Reprint 3, December, 1950.
47. SLACK, S. B.: Ohms of Resistance Measure Concrete Curing. *Engineering News-Record*, August 10, 1933.
48. SPENCER, R. W.: Measurement of the Moisture Content in Concrete. *Proceedings*, American Concrete Institute, *34:* 45–61, 1938.
49. STEINMETZ, CHARLES P.: *Engineering Mathematics*, McGraw Hill Book Co., New York, 1917.
50. SWAYZE, M. A.: Early Concrete Volume Changes and Their Control. *Proceedings*, American Concrete Institute, *38:* 425–440, 1942.
51. SWAYZE, M. A.: Finishing and Curing Concrete: A Key to Durable Concrete Surfaces. *Proceedings*, American Concrete Institute, *47:* Part I, 317–331, 1950.
52. TELLER, L. W., AND SUTHERLAND, E. C.: Structural Design of Concrete Pavements—Effects of Variation in Size, Shape, and Stress Resistance. *Public Roads*, *16:* No. 9, Nov. 1935.
53. TELLER, L. W., AND BOSBY, H. L.: The Arlington Curing Experiments. *Public Roads*, *10:* 217, 1930.
54. TIMMS, A. G., AND WITHEY, N. H.: Temperature Effects on Compressive Strength of Concrete. *Proceedings*, American Concrete Institute, *30:* 159–180, 1934.
55. TIMMS, A. G., AND WITHEY, N. H.: Further Studies of Temperature Effects on Compressive Strength of Concrete. *Proceedings*, American Concrete Institute, *31:* 165–180, 1935.
56. Virginia Department of Highways, *Road and Bridge Specifications*, Commonwealth of Virginia, Division of Purchase and Printing, Richmond, 1946.
57. WILSON, R., AND MARTIN, F. A.: Water Retained in Hardened Cement Pastes. *Proceedings*, American Concrete Institute, *31:* 272–279, 1935.
58. WUERPEL, C. E.: Moisture in Concrete Sand Measured by Electric Current. *Engineering News-Record*, July, 1935.

DISCUSSION

R. E. MADISON, *Technical Director, Truscon Laboratories*—We believe the authors have demonstrated the possibilities of a new and useful method for laboratory and field investigation in connection with the measurement of moisture contents and temperature in concrete. However, we do not believe that they have proved or demonstrated that one method of curing is superior to the other. They have merely obtained data on water-retention, as determined by the new apparatus and technique they have developed. In other words, they have not related the effects of the water losses or gains during the early curing period to the quality of the concrete obtained.

Since the paper mentions that "cores were drilled from the test sections," attempts were apparently made to relate what happened during the early curing period to compressive strengths. There also appears a statement to the effect that "the core strengths did not indicate any relation between the curing methods and the compressive strength of the hardened concrete," but no data are given.

We note the authors' specific reference to the effect that Virginia Road and Bridge Specifications were followed wherever applicable and that the liquid-membrane seal was applied in full compliance with specifications. Since such a high degree of precision has been brought to bear in this investigation, we believe that the authors should have obtained specific data on the actual coverage rate of the membrane seal. A scientific endeavor of this nature would seem to warrant more than a mere statement and should require actual data relating directly to the other data and measurements.

P. L. MELVILLE and R. W. CZABAN, *Closure*—The authors appreciate Madison's interest in their work. It was never intended to find out which curing method was "superior," as the study of criteria to determine superiority was not within the scope of this paper.

What was within the scope was the evaluation of several curing methods based on the amount of moisture retained under given temperature conditions during the first 72 hr. in accordance with current practice (ASTM Designation C156-44T).

The data on core strengths was omitted as it did not add much information and space limitations had to be met. As a matter of information, the means of eight compressive strengths at approximately 80 days were as follows: waterpoof paper: 5,660 psi.; membrane and limewash: 5,480 psi.; no cure: 5,450 psi.; damp burlap: 5,370 psi.; liquid membrane seal: 5,260 psi.; but the variations encountered within each treatment were often larger than the differences between treatments. It is possible that if coring and testing had taken place when the concrete was 72 hr. old (end of curing period) instead of several months, less erratic data would have been obtained and a correlation established between compressive strength and curing methods.

The liquid-membrane seal had been approved as meeting specifications by the Division of Tests of the Virginia Department of Highways and, as already stated, was mechanically applied under the state inspector's direct supervision in a manner believed typical of current field practice.

As a matter of information, 3,025 gal. of liquid-membrane seal was used for the entire paving project of 4.874 mi. (an average coverage of slightly less than 204 sq. ft. per gal. to be compared with the specification of 200 sq. ft. per gal.)

CURING CONCRETE PAVEMENTS IN KANSAS

R. L. Peyton, *Concrete Engineer, Kansas Highway Commission*

● The present specification for curing concrete pavements in Kansas requires the use of moist burlap covers for the first 24 hr., after which the pavement is covered with earth to a minimum depth of 4 in. The earth cover must be maintained in a moist condition for 10 days, left in place for 20 days and all traffic including construction traffic is excluded for a total of 30 days. The only exception to these requirements is in the case of city sections where earth cover is difficult to obtain economically. In such cases, cotton mats may be used in lieu of earth cover; all other requirements of the specification apply when this option is exercised.

This curing system precludes the use of membranes, either bituminous, nonbituminous, clear or pigmented. Paper covers, ponding, calcium chloride, and other types are also prohibited.

There is nothing new in these requirements; actually they are almost exactly the same as the curing specifications used in this state in 1924. Only the depth of cover has been changed from 2 in. to 4 in.

The operation of curing concrete pavements may be defined as the process necessary to protect the fresh concrete from adverse action of the elements and other physical forces during the period in which the concrete is hardening and gaining strength. When this definition is examined in detail, it is apparent that proper curing involves protection from both high and low temperature extremes, driving rain, drying winds and the prevention of damage by premature loading of the slab.

In Kansas it is believed no method of curing other than the one in use at present is sufficiently versatile to accomplish all of these things. This conclusion was arrived at after a period of about 25 yr., during which time practically all types of curing systems were used as standard procedure at one time or another. Observation of the results derived from the use of various curing systems coupled with some investigations of the efficiency of some of the more modern types of curing have convinced Kansas that the present method is better than anything else available. A short review of the various requirements used throughout this period of time will indicate to some degree why the state returned to this early method of curing concrete pavements.

From 1920 until 1930 the requirements were essentially the same as those now in force. It was during this period that the so-called old-fashioned concrete pavements were constructed. In 1931 curing requirements were