PROGRESS REPORT OF COMMITTEE ON CURING OF CONCRETE PAVEMENT SLABS[1]

F C LANG, *Chairman* AND FRED BURGGRAF

Engineer of Tests and Inspection, Minnesota Highway Department
Research Engineer Highway Research Board

In the 1929 report of this investigation, it was stated that "By good curing of concrete is meant the setting up of favorable conditions for chemical action during the setting and early hardening period" It now appears that favorable conditions are also necessary to minimize the bad effects of certain physical changes that take place, particularly in volume

The object of this investigation is to disclose distinctive characteristics of well cured concrete, and how these characteristics are affected by different curing methods In other words, what are favorable conditions during the early setting and hardening period, that will produce concrete of optimum strength and durability In the 1929 report the committee stated its opinion that information on (1) Moisture retention during curing (2) Strength (3) Volume changes (4) Surface condition (5) Permeability and Absorption and (6) Resistance to natural destructive agencies, would indicate whether or not the necessary favorable conditions had been set up

This year a large volume of data has been studied Most of these data, have been accumulated in the process of comparing the results secured by different curing methods, rather than in study of the fundamental factors of the problem This report will present certain facts developed by the various research projects concerning, (1) Flexural and Compressive Strength (2) Surface Condition and (3) Volume change The conclusions that the Committee have drawn from the facts are based upon the commonly accepted assumption that covering the pavement with wet burlap for a period and then with wet earth, straw or similar material constitutes a favorable condition

Before proceeding to a discussion of these more definite conditions, some indications with respect to moisture conditions and effects of climate upon curing conditions should be noted

RELATION OF INITIAL MIXING WATER RETAINED IN SPECIMEN DURING CURING PERIOD TO STRENGTH

Due to the lack of sufficient data, definite conclusions cannot be drawn yet, concerning the factor of moisture retention There is,

[1] This is a progress report and the conclusions therein are based upon information available at the present time They may be extended or revised later when more complete and extensive information becomes available

however, evidence to indicate that the amount of mixing water retained in the concrete during the curing period is an important index of the effectiveness of curing methods. For similar curing methods the strength appears to be a function of the amount of initial mixing water retained

Figure 1 illustrates this tendency by data from the laboratories of the Bureau of Public Roads, Portland Cement Association and Iowa Highway Commission These data are not considered sufficient to determine the relative values of different curing methods, since certain field tests offer contradictory evidence as to the relation between

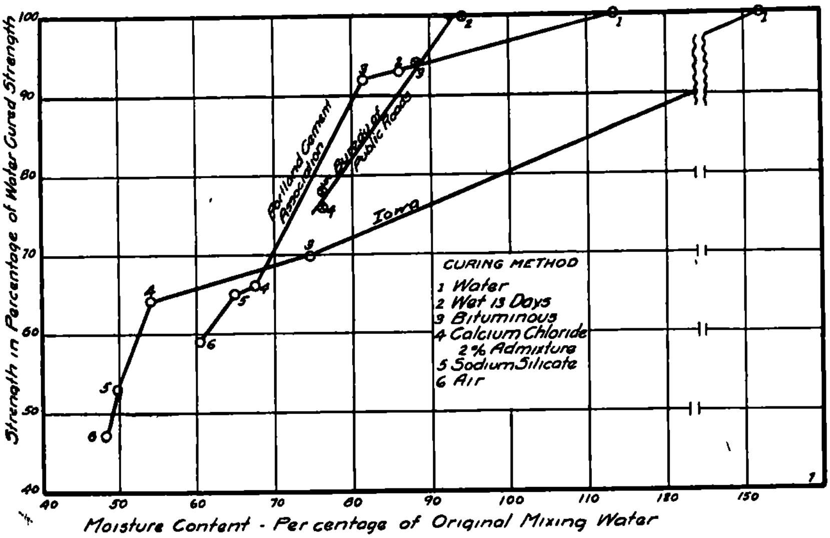

Figure 1 Relation of Strength to Amount of Mixing Water Retained

Iowa Laboratory tests on 2 by 4 inch mortar cylinders, 1 2, age 28 days

Portland Cement Association Laboratory tests on 6 by 12 inch concrete cylinders; soaked before testing, age 28 days.

Bureau of Public Roads Field tests on 6 by 6 by 24 inch beams for strength and 6 by 12 by 24 inch slabs for moisture loss, laid on wet subgrade, age 7 and 21 days

strength and curing method, but they do indicate that the retention of the original mixing water or addition thereto after placing constitutes a favorable condition for development of strength. The relation between laboratory and field tests will be further discussed later

It may be found possible through further research to define the relation between strength and retention of mixing water, so that specifications can be based thereon Such a specification would furnish a valuable basis for measuring the value of proposed curing methods To correlate such a specification with field conditions will require research on the influences of absorptive or semi-absorptive subgrades.

The effects of subgrade character and condition upon curing have not been extensively studied, but the data shown graphically in Figure 2 indicate that the subgrade factor, here as in all phases of highway construction is important and must be carefully investigated before complete information on curing processes can be obtained

CLIMATIC CONDITIONS GREATLY INFLUENCE THE EFFICIENCY OF CURING AND LIMIT THE USE OF SOME METHODS

The chief factors that influence the rate of evaporation are relative humidity, temperature and wind velocity, and these factors are so inter-

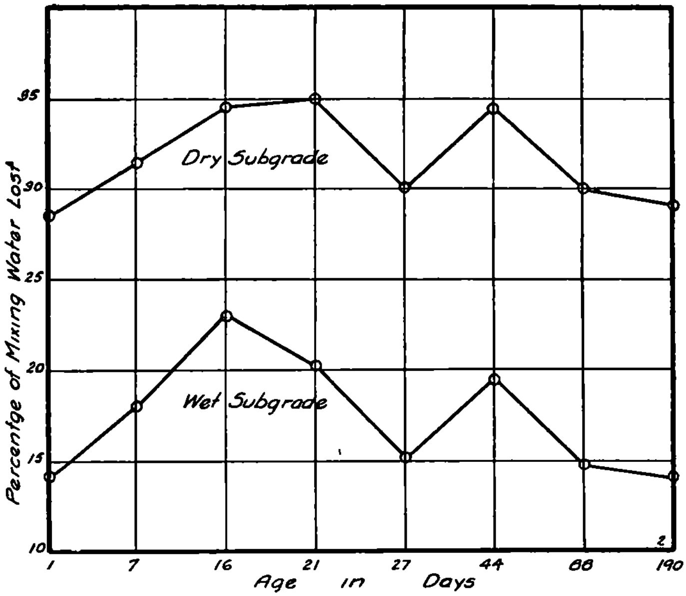

Figure 2. Effect of Subgrade Condition upon Moisture Losses of Slabs Cured by Surface Application of Calcium Chloride

No burlap protection during first 24 hours. Data furnished by Bureau of Public Roads.

dependent that it is impossible to make, with any degree of accuracy, a comparison between evaporation rates in different localities, based on a single factor However, since the rate of evaporation depends primarily on the capacity of the air to absorb additional moisture, which is measured by the relative humidity, a comparison of temperature and humidity records from various localities will reveal interesting information This comparison is interesting in connection with the study of data showing the lowest humidity for a given temperature at which calcium chloride will absorb enough moisture to dissolve itself The deliquescence curve representing these data is shown in Figure 3, which also

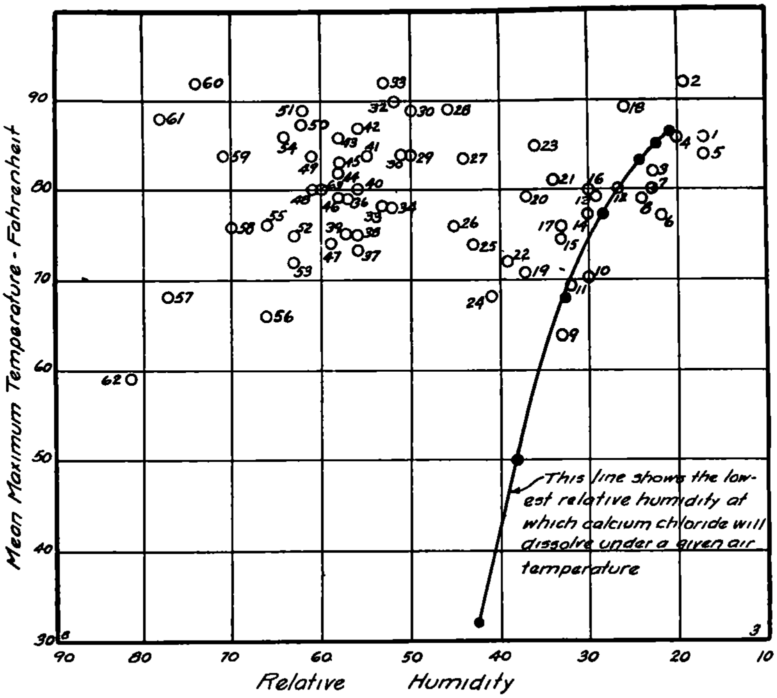

Figure 3. Relation of Lowest Relative Humidity and Temperature at Which Calcium Chloride Will Dissolve

It will not dissolve under temperature and humidity conditions to the right of the curve. The numbered circles refer to the cities listed in Table I and indicate the prevailing atmospheric conditions in these localities The circles in most cases show the average temperature and humidity for May, June, July, August and September, for several years

Figure 4

The outlined area is the region in which most of the time calcium chloride will not dissolve upon exposure to the air The numbered circles show the location of the cities listed in Table I.

shows the temperature and humidity conditions in different localities of the United States in their relation to the deliquescence curve The identification of localities, and the temperature and humidity data are given in Table I

TABLE I

PREVAILING TEMPERATURE AND HUMIDITY CONDITIONS AT VARIOUS LOCALITIES THROUGHOUT THE UNITED STATES

Identification number	Place	Mean maximum temperature*	Humidity	
			Per cent	Time taken
1	Independence, California	86	17	Noon
2	Fresno, California	92	19	5 P M
3	El Paso, Texas (a)	82	23	2 P M
4	Phoenix, Arizona (a)	86	20	6 P M
5	Tucson, Arizona (a)	84	17	6 P M
6	Tonopah, Nevada	77	22	5 P M
7	Winnemucca, Nevada	80	23	5 P M
8	Modena, Utah	79	24	6 P M
9	Santa Fe, New Mexico (a)	64	33	6 P M
10	Grand Junction, Colorado (a)	70	30	6 P M
11	Pueblo, Colorado (a)	69	32	6 P M
12	Boise, Idaho	80	27	6 P M
13	Roswell, New Mexico (a)	79	29	8 P M
14	Pocatello, Idaho	77	30	Noon
15	Lander, Wyoming	75	33	6 P M
16	Salt Lake City, Utah	80	30	6 P M
17	Spokane, Washington	76	33	5 P M
18	Red Bluff, California	89	26	5 P M
19	Baker, Oregon	71	37	5 P M
20	Denver, Colorado	79	37	6 P M
21	Lewiston, Idaho	81	34	Noon
22	Helena, Montana	72	39	6 P M
23	Sacramento, California	85	36	5 P M
24	Yellow Stone Park, Wyoming	68	41	Noon
25	Cheyenne, Wyoming, and Havre, Montana	74	43	6 P M
26	Rapid City, South Dakota	76	45	8 P M
27	Amarillo, Texas	84	44	7 P M
28	Abilene, Texas	89	46	7 P M
29	Dodge City, Kansas	84	50	7 P M
30	Fort Worth, Texas	89	50	7 P M
31	Evansville, Indiana	84	51	Noon
32	San Antonio, Texas	90	52	Noon
33	Del Rio, Texas	92	53	Noon
34	North Platte, Nebraska	78	52	7 P M
35	Huron, South Dakota	78	53	8 P M

* Mean maximum temperature is the average for several years of the months of May, June, July, August and September

(a) Average of March, April, May and June

TABLE I—*Concluded*

Identification number	Place	Mean maximum temperature*	Humidity	
			Per cent	Time taken
36	Los Angeles, California	79	57	Noon
37	Devils Lake, North Dakota	73	56	7 P M
38	St Paul, Minnesota	75	56	8 P M
39	Bismark, North Dakota	75	57	7 P M
40	Omaha, Nebraska	80	56	7 P M
41	Wichita, Kansas	84	55	7 P M
42	Birmingham, Alabama	87	56	Noon
43	Oklahoma City, Oklahoma	86	58	7 P M
44	Kansas City, Missouri	82	58	7 P M
45	Atlanta, Georgia	83	58	Noon
46	Des Moines, Iowa	79	58	7 P M
47	Providence, Rhode Island	74	59	Noon
48	Columbus, Ohio	80	61	8 P M
49	Nashville, Tennessee	84	61	7 P M
50	Palestine, Texas	88	62	7 P M
51	Shreveport, Louisiana	89	62	8 P M
52	Madison, Wisconsin	75	63	8 P M
53	Portland, Maine	72	63	Noon
54	Little Rock, Arkansas	86	64	7 P M
55	Albany, New York	76	66	8 P M
56	San Francisco, California	66	66	Noon
57	Nantucket, Massachusetts	68	77	Noon
58	Lansing, Michigan	76	70	8 P M
59	Raleigh, N Carolina	84	71	8 P M
60	New Orleans, Louisiana	92	74	7 P M
61	Tampa, Florida	88	78	8 P M
62	Eureka, California	59	81	5 P M
63	Springfield, Illinois	81	60	7 P M

The United States map (Figure 4) shows the area (derived from Figure 3) in which calcium chloride used as a surface curing agent is probably not effective, since there is not normally enough moisture in the air to dissolve the salt

This area is a region in which great care must be taken either to conserve the initial mixing water or to supply additional water in order to assure satisfactory curing conditions The normal climatic conditions within this area are very adverse to good curing of concrete

Curing methods can best be evaluated when the atmospheric conditions are not such in themselves as to set up favorable curing conditions It is to be noted in Tables II and III that in some of the field investigations the results with practically no curing are nearly as good as if wet earth or straw curing had been employed This is probably due to the damp weather which prevailed for some time immediately after the placing of the concrete To illustrate this point the data reported from

TABLE II

Field Data—Summary of Flexural Tests of Concrete Made and Cured in the Field

Ratios of strengths for various curing methods to the strengths of concrete cured with wet earth or straw

Source of data	Cured with wet earth or straw	Ages of tests	Average strength of all ages, expressed as a percentage of the strength of corresponding concrete cured with wet earth or straw. Figures in parentheses are the numbers of specimens tested						
			Minimum curing	Hunt process	Curcrete	Miscellaneous bituminous	Sodium silicate (after 24 hours)	Calcium chloride admixture (2 per cent)	Calcium chloride surface
	days	*days*							
Iowa Highway Department (s)	9	7–28–90–365	81(442)	93(332)	98(446)		90(333)	91(433)n	95(450)
Ohio Highway Department	9	4–7–28					92(30)	93(27)	94(30)
Pennsylvania Highway Department	10	10–14–90–365						90(32)d	
Missouri Highway Department	7 and 28	7–28	82(10)			89(10)c	82(10)e		98(10)r
Missouri Highway Department	10	21–28–91					92(18)b		92(18)
Minnesota Highway Department	2 and 6	7–28	94(12)g				85(8)f	93(12)	94(12)
New Jersey Highway Department	10	28			104(14)			94(6)	
New Jersey Highway Department	10	7–28	86(16)	103(16)	101(16)		85(16)	86(16)	95(16)
Rhode Island Highway Department	10	7–14–28						104(13)	106(12)
Connecticut Highway Department	10	4–7	83(6)					110(22)	
Connecticut Highway Department	10	4–7–14						103(9)	
Illinois Highway Department	14	28–60	87(30)			98(15)a			102(30)h
Wisconsin Highway Department (s)	7	28–90			101(18)		91(18)	91(18)	99(18)
Washington Highway Department	10	14–28	87(8)	97(32)					
Tennessee Highway Department	10	3–7–14–28	92(432)	97(336)	95(336)		93(240)	91(216)q	96(624)
Tennessee Highway Department	10	3–7–14–28	78(96)o	94(192)o	91(96)o		90(96)o	90(48)p	88(48)o

West Virginia Highway Department	10	28	85(28)		99(12)		83(6)		92(10)
Portland Cement Association	7 and 14	7-14-28-90	75(20)				75(20)L	85(88)	92(15)i
Portland Cement Association									84(20)j
Bureau of Public Roads	7	4-8-15-29					101(57)	101(39)	
Bureau of Public Roads	14	3-7-14-28-90-180-365	82(56)				83(56)k	74(56)k	
Bureau of Public Roads	13	3-7-21-180	82(16)m		96(16)		79(16)	77(16)	90(16)
Average of Project Averages			84(1172)	97(908)	99(954)	94(25)	87(924)	92(1051)	95(1329)

(a) Blown Asphalt (b) Applied at 7 hours (c) Average of thick and thin asphalt (d) Average of 1 2 3 and 1 2 4 Concrete wet burlap protection for 24 hours (e) Specimens removed from forms at 24 hours and all sides coated with undiluted commercial sodium silicate (f) Sodium silicate applied 8 hours after placing concrete Diluted 1 to 1 with commercial solution (g) After the forms were removed the sides and ends of all beams in all the series were thoroughly sealed with an emulsified asphalt which dried very quickly (h) 3 pounds of calcium chloride per square yard (i) Beams molded and cured in concrete forms (j) Beams molded and cured in wood forms (k) Forms removed at end of 24 hours and specimens grouped and edges banked with earth (L) Undiluted sodium silicate (m) Placed on dry subgrade Other values on wet subgrade (n) Wet burlap for 48 hours (o) These specimens received no rain during first 10 days (p) These specimens received no rain during first 5 days (q) 3 day strengths not included (r) Specimens removed from forms at 24 hours, 3 sides and both ends coated with thick asphalt $CaCl_2$ sprinkled on surface (s) Specimens in this investigation tested wet

TABLE III

FIELD DATA—SUMMARY OF COMPRESSIVE TESTS OF CONCRETE MADE AND CURED IN THE FIELD

Ratios of strengths for various curing methods to the strengths of concrete cured with wet earth or straw

Source of data	Cured with wet earth or straw	Ages of tests	Average strength of all ages, expressed as a percentage of the strength of corresponding concrete cured with wet earth or straw. Figures in parentheses are the numbers of specimens tested							
			No curing	Hunt process	Curcrete	Miscellaneous bituminous	Sodium silicate (after 24 hours)	Calcium chloride admixture (2 per cent)	Calcium chloride surface	Type of specimen
	days	*days*								
Highway Departments										
Iowa	9	8–29–90–365	80(159)	91(120)	98(160)		90(120)	100(158)c	96(160)	1
Ohio	9	7–28					86(18)	96(20)		2
Ohio	9	90					87(9)d	84(10)	92(9)	3
Pennsylvania	10	10–14–90–365						105(16)e		2
New Jersey (f)	10	28			108(14)			121(6)		1
New Jersey (f)	10	28			107(19)			118(9)		2
New Jersey (f)	10	28			111(23)			101(8)		3
New Jersey	10	28	90(6)b	103(6)	94(6)		93(6)	104(6)	95(6)	3
North Carolina	10	75–130					116(16)	118(23)g		3
North Carolina	10	120							93(22)	3
Georgia	10	210					96(9)		94(8)	3
Rhode Island	10	7–14–28						111(5)h		2
Wisconsin	7	90			102(6)		92(6)	88(6)	103(6)	3
Wisconsin	7	28–90			84(12)		77(12)	98(12)	92(12)	2
Washington	10	28		94(49)i						2
Tennessee (a)	10	365	101(32)	87(28)	95(28)		83(20)	102(24)	97(52)	3
Tennessee	10	365	83(4)m	86(16)m	100(8)m		81(8)m	138(4)n	96(4)m	3
West Virginia	10	28	94(8)		97(6)		92(3)		95(5)	2

California	7	11-28-240 (j)		91(16)	94(16)					3
California	12 and 14	14-21-28-90 (1-3-5 years)	84(35)							3
California	10	14-28-90-180-365		77(27)	86(27)	87(27)k	80(25)			3
Bureau of Public Roads (L)	7	28-120-180-365					93(28)	90(28)		4
Bureau of Public Roads (L)	7	180-365					108(14)	103(10)		4
Bureau of Public Roads (L)	7	7-14-28					99(18)	97(18)		5
Bureau of Public Roads (L)	7	8-15-29					98(15)	134(8)		5
Bureau of Public Roads (L)	7	28-90-365					102(30)	93(25)		3
Bureau of Public Roads	14	365					89(11)	89(11)		3
Average of Project Averages			88(244)	91(262)	98(325)	87(27)	93(368)	103(407)	95(284)	

(a) Tested moist (b) Damp burlap 24 hours (c) Wet burlap for 48 hours (d) Sodium silicate applied at 6 hours (e) Average of 1 2 3 and 1 2 4 concretes Wet burlap protection for 24 hours (f) Grouped as one Test in general average (g) Average of over 2000 additional cores drilled from pavement at approximately 4 months averaged 3852 pounds per square inch (1 2 4 mix) (h) Wet burlap 24 hours (i) Specimens allowed to remain in forms and top coated Immersed before test (j) All specimens immersed before testing (k) Bitumuls placed directly on concrete Imperial Valley Tests (L) Grouped as one test in general average (m) These sections received no rain during first 10 days (n) This section received no rain during first 5 days

Type of Specimen 1, Beam Ends 2, 6 × 12 Cylinders 3, Pavement Cores 4, Test Slab Cores 5, Special Made Cylinders the Tennessee project have been divided into two parts in Tables II and III A considerable number of specimens (Note (o) Table II, (m) Table III) received no rain during the first 10 days which was duly reflected in the lower strength of the minimum cured specimens, but in the case of the variously cured specimens the strengths were in general not materially lowered

FLEXURAL AND COMPRESSIVE STRENGTH

The following facts were disclosed by study of test data from 36 sources as reported in the ninth Proceedings of the Highway Research Board and confirmed by additional tests from five sources

1 Concrete cured with surface treatments of calcium chloride, or bituminous coatings (Hunt process and Curcrete) generally showed a small range in results and gave strengths 90 per cent or more of the strength of concrete cured with wet earth or straw

2 In these tests sodium silicate surface treatment and calcium chloride used integrally showed strengths both above and below 90 per cent of the strength of concrete cured with wet earth or straw Some relatively low strengths appear particularly in the laboratory tests, which are in general lower than the field tests

Conclusions

In view of the facts given in the foregoing paragraphs the committee concludes that

1 Surface coatings of calcium chloride or the bituminous materials covered by the tests reported are satisfactory as respects strength, for use as curing agents

2 Further information is needed as to the factors that influence the efficiency of sodium silicate surface covering as respects strength before definite recommendations can be made

3 Further information is needed as to the factors that influence the efficiency of calcium chloride used integrally as respects strength before definite recommendations can be made

Discussion of strength data

Summaries of the experimental data from all the Projects are shown in Tables II to VI

Figures 5 and 6 show the average strengths of field specimens from all sources, for various curing methods

On account of the uncorrelated nature of the test data on strength available from the different sources it has only been possible to make comparisons of general nature For instance the amount of moisture in the test specimens at the times of test was generally an uncontrolled variable, although it is now well known that this factor can cause varia-

TABLE IV

LABORATORY DATA—SUMMARY OF FLEXURAL TESTS OF CONCRETE MADE AND CURED IN THE LABORATORY

Ratios of strength tests of various curing methods to the strengths of concrete cured with wet earth or straw

Source of data	Cured with wet earth or straw	Ages of tests	Average strength of all ages, expressed as a percentage of the strength of corresponding concrete cured with wet earth or straw Figures in parentheses are the numbers of specimens tested						
			No curing	Hunt process	Curcrete	Miscel-laneous bitu-minous	Sodium silicate (after 24 hours)	Calcium chloride admixture (2 per cent)	Calcium chloride surface
	days	*days*							
Minnesota Highway Department (a)	3 and 10	7–14–21–28–90	90(30)					80(30)	93(30)
Minnesota Highway Department (b)	Moist room	3–7–14–28–90						91(48)	
Illinois Highway Department (c)	10	28	86(9)						95(9)
Illinois Highway Department (c)	14	28	87(6)			94(6)d			98(6)
Pennsylvania Highway Department	8	28				86(8)e	80(8)f	75(8)	
Pennsylvania Highway Department	28	28	69(4)				58(4)g	66(4)	
Pennsylvania Highway Department	28	7–14–28–90						85(12)	
Ohio State Thesis	10	7–28	84(12)				93(12)h	79(12)	114(12)
Portland Cement Association (L)	13	14–28–90–365	74(16)	110(16)	103(16)		74(16)i	71(16)j	99(16)k
Average of Project Averages			82(77)	110(16)	103(16)	90(14)	76(40)	78(128)	100(73)

(a) All specimens placed in constant temperature 70°F and Humidity (70 per cent) storage until test (b) Moist room storage until test (c) Specimens in forms until tested (d) Asphalt penetration 80 (e) Hot tar (f) Sodium silicate applied at 9 hours Forms removed next day and 1 (S S) to 3 (Water) solution applied to all surfaces (g) Sodium silicate applied at 9 hours Forms removed next day and 3 (S S) to 1 (Water) solution applied to all surfaces (h) Beams painted with a 37 degree Baumé solution (i) Specimens removed from forms at end of 24 hours and given 3 brush coats of sodium silicate (j) Specimens were not protected with burlap during first 24 hours Removed from forms at end of 24 hours (k) Specimens left in forms until tested (L) All specimens soaked before test

TABLE V

LABORATORY DATA—SUMMARY OF COMPRESSIVE TESTS OF CONCRETE MADE AND CURED IN THE LABORATORY

Ratios of strength tests of various curing methods to the strengths of concretes cured with wet earth, straw, or water

Source of data	Cured with wet earth or straw	Ages of tests	Average strength of all ages, expressed as a percentage of the strength of corresponding concrete cured with wet earth or straw. Figures in parentheses are the numbers of specimens tested						
			No curing	Hunt process	Cur-crete	Miscellaneous bituminous	Sodium silicate (after 24 hours)	Calcium chloride admixture (2 per cent)	Calcium chloride surface
	days	*days*							
Portland Cement Association (c)	13	14-28-90-365	71(16)	102(16)	98(16)		71(16)d	72(16)e	117(16)f
Minnesota Highway Department (a)	3 and 10	7-14-21-28-90	86(18)					93(18)	
Minnesota Highway Department (b)	Moist room	3-7-14-28-90						106(29)	
Pennsylvania Highway Department (i)	28	28	75(3)				58(3)h	68(3)	
Pennsylvania Highway Department (g)	Wet sand	2-7-28-90-365						109(25)	
Pennsylvania Highway Department	8	28				98(6)j	93(6)k	94(6)	
Pennsylvania Highway Department	28	7-14-28-90						94(12)	
Portland Cement Association	3	120	80(24)						
Average of Project Averages			78(61)	102(16)	98(16)	98(6)	74(25)	91(109)	117(16)

(a) All specimens placed in constant temperature (70°F.) and Humidity (70 per cent) storage until test. (b) Moist room storage until test. (c) All specimens soaked before test. (d) Specimens removed from forms at end of 24 hours and given 3 brush coats of sodium silicate. (e) Specimen removed from forms at end of 24 hours then in air of laboratory at 50 per cent humidity until test. (f) Specimens left in forms until tested. (g) Specimens stored in wet sand during storage period. (h) Sodium silicate applied at 9 hours. Forms removed next day and 3 (S.S.) to 1 (Water) solution applied to all surfaces. (i) Standard Curing method was Wet Sand Storage for 28 days. (j) Hot Tar. (k) Sodium Silicate applied at 9 hours. Forms removed next day and solution of 3 parts of water and 1 part of sodium silicate applied to all surfaces.

TABLE VI

FLEXURAL AND COMPRESSIVE STRENGTHS FROM INVESTIGATIONS, WHICH DID NOT INCLUDE A WET EARTH OR WATER METHOD OF CURING AS A STANDARD

Source of data	Ages of tests	Average strength of all ages, expressed as a percentage of the strength of corresponding concrete under minimum curing. Figures in parentheses are the numbers of specimens tested						
		Minimum curing	Curcrete	Sodium silicate (after 24 hours)	Calcium chloride admixture (2 per cent)	Calcium chloride surface	Type of tests	Place of tests
	days							
Illinois Highway Department	29	100(3)				118(3)	Transverse	Field
Illinois Highway Department	14–28	100(6)		101(6)a		123(6)	Transverse	Lab
Missouri Highway Department (d)	6–14	100(73)b	135(72)	104(73)c			Transverse	Field
Kentucky Highway Department (i)	7–14–21–28	100(60)g				101(60)	Transverse	Field
Minnesota Highway Department (h)	3–7–14–21–28–90	100(96)			97(96)	117(96)	Transverse	Lab
Illinois Highway Department	29	100(6)				118(6)	Cores Comp	Field
Missouri Highway Department (e)	7–16–27–184	100(96)b	109(161)	100(166)			Cores Comp	Field
Minnesota Highway Department (h)	3–7–14–21–28–90	100(48)			115(48)		Cast 6 × 12	Lab
Kentucky Highway Department (i)	7–14–21–28	100(60)g				101(60)	Cast 6 × 12	Field
Kentucky Highway Department	135	100(20)				100(20)	Cores Comp	Field
Missouri Highway Department (f)	21–28–90			90(31)	87(30)	100(27)	Transverse	Field
Missouri Highway Department (j)	21–28–90	100		96(31)	93(30)	112(27)	Transverse	Field
Missouri Highway Department	41			92(10)	85(9)	100(5)	Cores Comp	Field
Missouri Highway Department (j)	41	100		103(10)	95(9)	112(5)	Cores Comp	Field

(a) Commercial solution of sodium silicate applied 10 hours after making Specimens remained in forms until tested (b) Wet burlap for 24 hours (c) Removed from forms and coated on all sides at end of 24 hours (d) All specimens placed on pavement after removal from forms (e) Cores drilled from pavement, capped and soaked before test (f) All specimens removed from forms after 24 hours (g) Wet burlap for 24 hours (h) All specimens placed in constant temperature (70°F) and Humidity (70 per cent) storage until test (i) All specimens removed from forms at 24 hours and placed next to pavement edge and dirt placed around three sides of the beams (j) Indirect comparison based on general average of other similar curing methods in which minimum curing was a standard tions in strength which may be equal to or greater than those caused by differences in curing

The term "minimum curing" is used in the tables and discussions to indicate that the concrete was allowed to harden under the prevailing

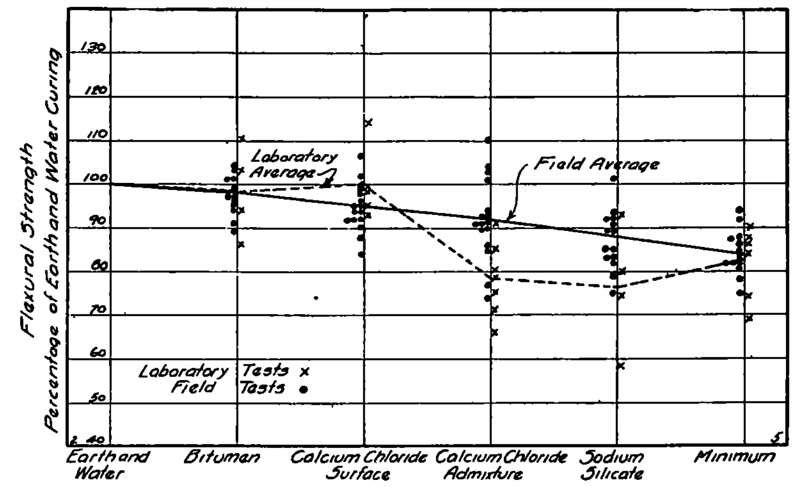

Figure 5. Relative Average Flexural Strengths of Concretes Cured by Various Methods for the Projects Reported in Tables II and IV

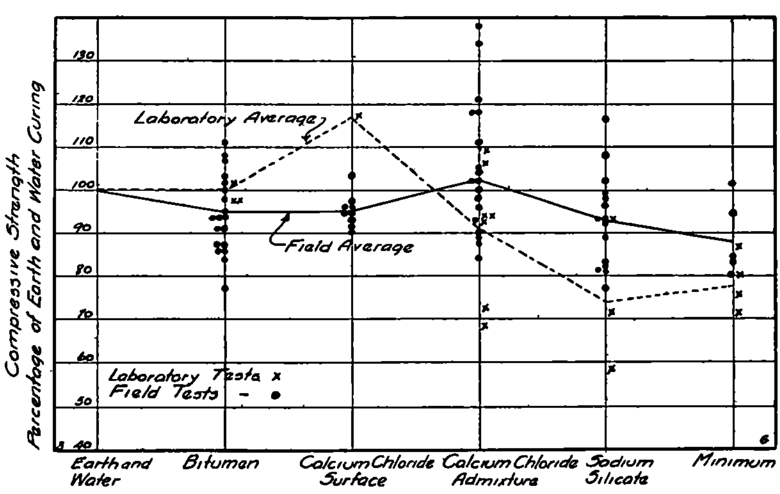

Figure 6 Relative Average Compressive Strengths of Concretes Cured by Various Methods for the Projects Reported in Tables III and V

atmospheric conditions of the tests without any attempt to conserve or to add to its moisture Needless to say, there were wide differences in the atmospheric conditions of the various series of tests In any of the individual field test projects, comparison of the minimum curing results with those of wet curing will give some indication of the extent to which all of the curing methods in that series may have been affected by natural curing conditions

Comparison of laboratory and field investigations

In general tests made under controlled laboratory conditions might be expected to afford a basis for comparison of curing methods However, the data studied show in some cases diverging relations between

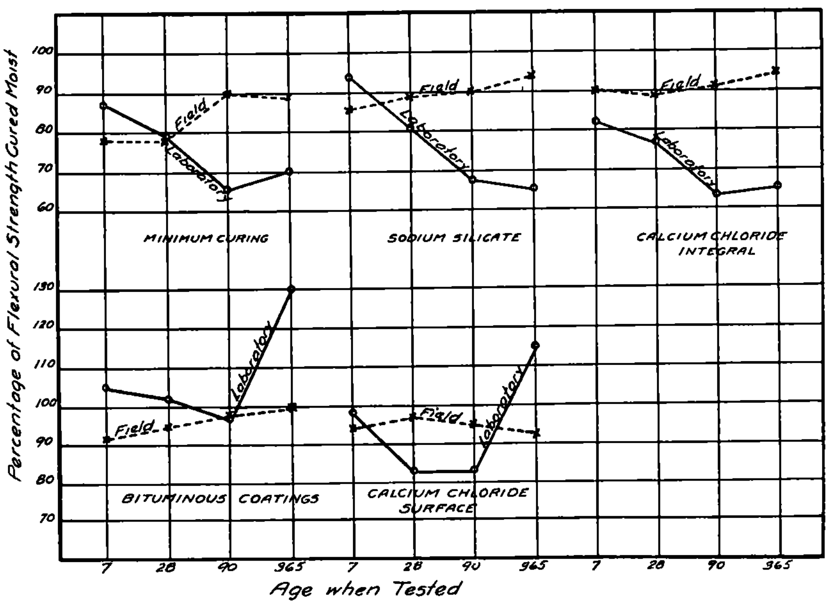

Figure 7. Relation between Field and Laboratory Tests for Different Methods of Curing with Increasing Age

The field tests were made by the Iowa Highway Commission. The basis of comparison was moist earth curing for 9 days. (See notes (s) and (n) Table II) The laboratory tests were made by the Portland Cement Association The Basis of comparison was moist room curing for 13 days (See notes (L), (j) and (k) Table IV)

laboratory and field tests (Figures 5 and 6) the causes for which must be determined before final comparisons can be made

The ratios of the strengths of laboratory specimens cured with integral calcium chloride, sodium silicate and minimum curing to the strengths of corresponding moist cured specimens decreased with increasing age The corresponding ratios for field specimens increased with age The results with calcium chloride surface application were less definite The bituminous methods appeared to maintain approximately the same ratios at all ages, both in the field and laboratory See Figure 7

A possible explanation of these conditions may be found in the hypothesis that in the later ages the laboratory specimen may have reached such a degree of dryness that hydration of cement has practically ceased while in the field there are various sources from which additional water may be drawn Such sources of moisture are rain, high humidity, and subgrade The study of the field test data showed that these natural curing conditions were often present and exerted a beneficial effect

SURVEY OF SURFACE CONDITIONS

The conclusions of the committee concerning the relations between surface scaling and curing methods are based upon the detailed survey of concrete pavements described in the 1929 progress report Of the pavements surveyed 617 miles were cured with wet earth, 1257 miles were cured with Calcium Chloride Surface application, and 169 miles were cured with Calcium Chloride used integrally One hundred samples of scale and 96 pictures of the scaled pavement were obtained

In addition to the visual examination of the pavements, the complete material and construction records from the 405 separate projects surveyed were studied

Scaling is a complex phenomenon and the causes are still a matter of conjecture It has been attributed to the cement, the aggregate, the curing method, excess mixing water, harsh mixes, over finishing and frost action

This report is concerned principally with the effects of Calcium chloride surface application and wet earth methods of curing upon surface scaling

The phenomenon classed as scale in this report is the typical thin layer of surface that flakes off cleanly from underlying sound concrete The thickness varied approximately from 07 to 20 inches, with an average of 15 inches

The thin surface peel, commonly called, "paper scale," is not classed as scale This "paper scale" is always less than 05 inches in thickness and is unnoticeable except when driving at a low rate of speed and with a favorable angle of light reflection from the pavement

Progressive disintegration of concrete is not classed as scale and was not considered in this survey, although a few samples were taken In such cases the depth affected is usually in excess of 25 inches, and the underlying concrete is of poor quality with strong indications of further disintegration

The following facts were disclosed by the survey of 2043 miles of pavement in Wisconsin, Minnesota, Illinois, Missouri and Rhode Island

1 Surface scaling, as defined in the report, under all conditions was relatively very small in amount

2 The scaling observed in this survey was not uniformly distributed over a project but occurred in widely separated areas

3 Of the 1550 miles of comparable pavement built between 1922 and 1927 inclusive that were surveyed 67 per cent of 1124 miles cured with calcium chloride surface application and 74 per cent of the 426 miles cured with earth and water showed less than one (1) square yard of scaling per mile of 18 foot pavement

4 Of the 1550 miles of comparable pavement built between 1922 and 1927 inclusive that were surveyed 22 per cent of the 1124 miles cured with calcium chloride surface application and 22 per cent of the 426 miles cured with earth and water showed more than one (1) and less than 50 square yards of scaling per mile of 18 foot pavement

5 Of the 1550 miles of comparable pavement built between 1922 and 1927 inclusive that were surveyed 11 per cent of the 1124 miles cured with calcium chloride surface application and 4 per cent of the 426 miles cured with earth and water showed more than 50 square yards of scaling per mile of 18 foot pavement While this shows the scaled areas are more extensive on the calcium chloride cured pavements, the total percentage of scaling in either case is very small as only 0 08 per cent of the total area is affected in the case of wet earth curing, and 0 20 per cent in the case of calcium chloride curing

Conclusions

In view of the facts and data given in the foregoing paragraphs the committee concludes that

1 Calcium chloride surface application used as a curing method under normal[2] conditions is not a primary cause of scaling

2 If conditions conducive to scaling are present the scale will probably occur to some extent under either earth and water or calcium chloride surface methods of curing

3 In so far as calcium chloride surface curing is concerned, scaling is not an important factor

Strong indications

The data indicate strongly that

1 Climatic conditions influence the extent of scaling A decrease in the extent of scaling in the various states in direct relation to their geographical location from north to south was noted

[2] There are indications that undue concentrations of the calcium chloride, too early application, and contact with soil during the early curing period may produce deleterious conditions These factors will receive further study by the committee

2 The percentage of scaling increases as the silt content of the fine aggregate increases when the final finishing operations and general construction methods are similar

3 Too much and too late finishing are contributory causes of scaling that are independent of the laitance removal operation and materials used

4 The extent of scaling was greater where hand finishing was employed than where mechanical finishers were used

Methods of procedure

The projects to be surveyed were mostly selected at random In the States of Minnesota and Rhode Island practically all of the projects were surveyed in which the curing was done by means of calcium chloride surface application In the states of Wisconsin and Missouri, the projects surveyed were arbitrarily selected from study of the construction reports of all projects on the basis of curing method, location and year of construction In the state of Illinois on account of the large mileage available, equal mileage of pavements in certain classifications having a possible bearing on the extent of scaling were selected at random

The field party consisted of at least two persons, one of whom acted as an observer and driver and the other as an observer and recorder The observational data on each project were obtained while traversing the pavement at a speed of from 10 to 15 miles per hour The scaled places were located by odometer readings, reckoned from the start of each project The area of scale at each place was determined by estimation This method was used because the actual measurement of the areas, due to their unsymmetrical shapes, would have been laborious and slow, and the results by estimation were thought to be sufficiently accurate

The relation of the scale in respect to pavement surface, location and other special construction features was noted

Frequent stops were made to obtain samples of the scale, to photograph the scaled areas and to check the estimation of areas

As the process of analyzing and interpreting the data progressed, further detailed information on mixer operation and weather conditions prevailing during the construction periods, especially on the badly scaled projects, became necessary in order to clarify the tentative inferences previously drawn This latter information was obtained by correspondence

Discussion of data

Variation of extent of scaling in different States

Figure 8 gives a graphical view of the extent of scaling by States for calcium chloride and wet earth curing Attention is called to the absence of scaling on the Rhode Island projects The major difference in

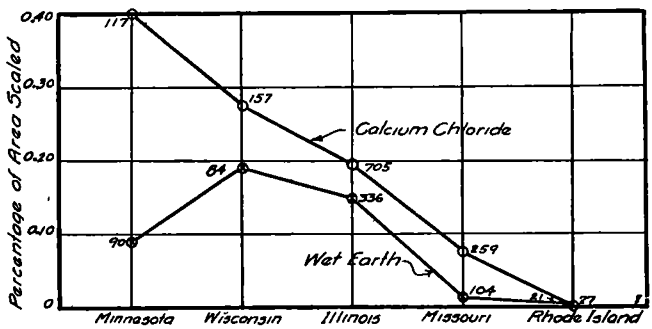

Figure 8. Amount of Scaling on Pavements Cured with Wet Earth and Calcium Chloride Surface Applications, in the Various States Covered by the Surface Condition Survey. The numbers show the mileage examined

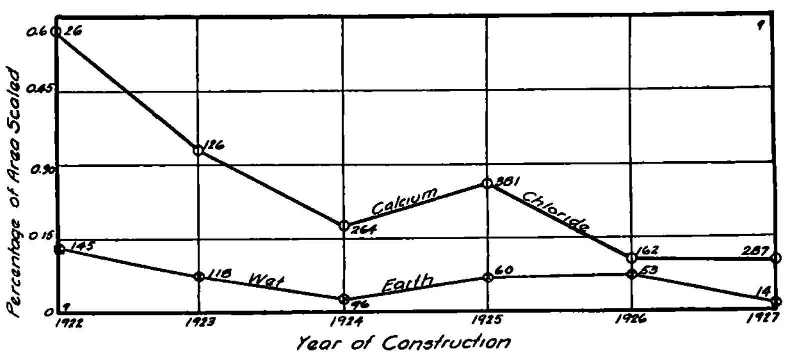

Figure 9. Relative Amounts of Scaling on Pavements Cured with Wet Earth and Calcium Chloride Surface Application by Year of Construction. The numbers show the mileage examined

finishing operations as practiced in this State from those in the other States surveyed was the brooming of the surface

The decrease noted in the amount of scaling in middle western states in the approximate order of their geographical location from north to south suggests the possibility of effects of climatic conditions on scaling

Variation of extent of scaling in different years of construction

In Figure 9 is shown the relation of the area of scale in percentage and the year of construction for all projects surveyed that were cured with wet earth and calcium chloride surface application This comparison starts in 1922 when calcium chloride was first used

Further analysis of data by comparison of arbitrary scaling units

Although expressing the extent of scaling by percentage of total area, furnishes a suitable index of the general action of the respective curing methods, it does not give an entirely true picture of conditions, because several of the projects have no surface defects, regardless of the curing method, while parts of other projects show considerable scaling This led to the selection of arbitrary limits in defining the extent of scaling

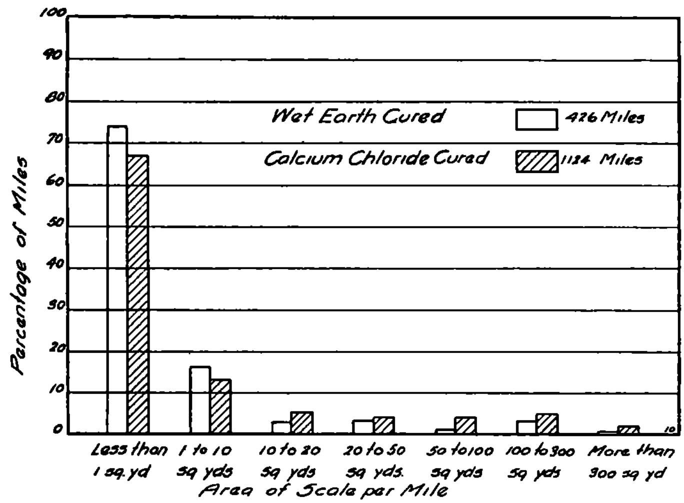

Figure 10. Relative Amounts of Scaling on Individual Miles of Pavement Cured with Wet Earth and Calcium Chloride Surface Application

All of the individual miles, in the order in which they were surveyed were classified into the following scaling units, (a) less than 1 square yard of scale per mile, (b) more than 1 square yard and less than 10 square yards, (c) more than 10 square yards and less than 20 square yards, (d) more than 20 square yards and less than 50 square yards, (e) more than 50 square yards and less than 100 square yards, (f) more than 100 square yards and less than 300 square yards, and (g) more than 300 square yards The basis on which all computations were made, was a mile of pavement 18 feet wide This arrangement makes each square yard of scale equal approximately to 0 01 per cent by area In Figure 10 is shown the relation of these various arbitrary scaling units based on individual miles to the total mileage involved for wet earth and calcium chloride curing methods An analysis of these diagrams shows that the percentage of total mileage having less than 10 square yards of scale per mile was practically the same for both methods of curing

TABLE VII

Surface Survey Summary Table—Wet Earth Curing

States	Total number of miles surveyed	Year of construction	Percentage of number of miles surveyed having total areas of scale within the limits shown: Less than 1 square yard	1 to 10 square yards	10 to 20 square yards	20 to 50 square yards	50 to 100 square yards	100 to 300 square yards	300 square yards (plus)
Illinois	27 4	1919	60	30	6	4	0	0	0
Minnesota and Illinois	75 1	1920	45	35	4	9	4	3	0
Illinois	28 1	1921	11	21	8	10	14	26	10
Illinois, Minnesota, Wisconsin and Missouri	112 9	1922	53	26	6	8	1	6	0
Illinois, Minnesota, Wisconsin and Missouri	104 2	1923	72	18	3	4	1	2	0
Illinois, Minnesota, Wisconsin and Missouri	96 2	1924	91	8	0	0	0	1	0
Illinois, Minnesota, Wisconsin and Missouri	47 8	1925	73	17	2	2	2	4	0
Minnesota, Missouri and Wisconsin	53 2	1926	85	9	2	0	2	2	0
Illinois, Missouri and Wisconsin	11 7	1927	100	0	0	0	0	0	0
Total 1919 to 1927	556		66	19	5	4	1	4	1
Total 1922 to 1927	426		74	16	3	3	1	3	0

TABLE VIII

Surface Survey Summary Table—Calcium Chloride Surface

States	Total number of miles surveyed	Year of construction	Percentage of number of miles surveyed having total areas of scale within the limits shown: Less than 1 to 10 square yards	1 to 10 square yards	10 to 20 square yards	20 to 50 square yards	50 to 100 square yards	100 to 300 square yards	300 square yards (plus)
Illinois	20 0	1922	40	15	10	5	10	10	10
Illinois and Missouri	118 0	1923	54	19	7	3	7	7	3
Illinois, Missouri, Wisconsin and Minnesota	253 0	1924	70	11	6	6	3	3	1
Illinois, Missouri, Wisconsin and Minnesota	309 0	1925	66	14	2	8	1	7	2
Illinois, Missouri, Wisconsin, Minnesota and Rhode Island	162 0	1926	72	13	6	2	4	3	0
Illinois, Missouri, Wisconsin and Rhode Island	262 0	1927	70	15	5	2	4	3	1
Total—1922–1927	1,124 0		67	13	5	4	4	5	2

and that the percentage of total mileage showing areas of scaling greater than 10 square yards per mile was greater for the calcium chloride than for the wet earth curing method The difference between these curing methods in percentage is rather small, but the variations are on the extensively scaled areas, which greatly affect the percentage by area

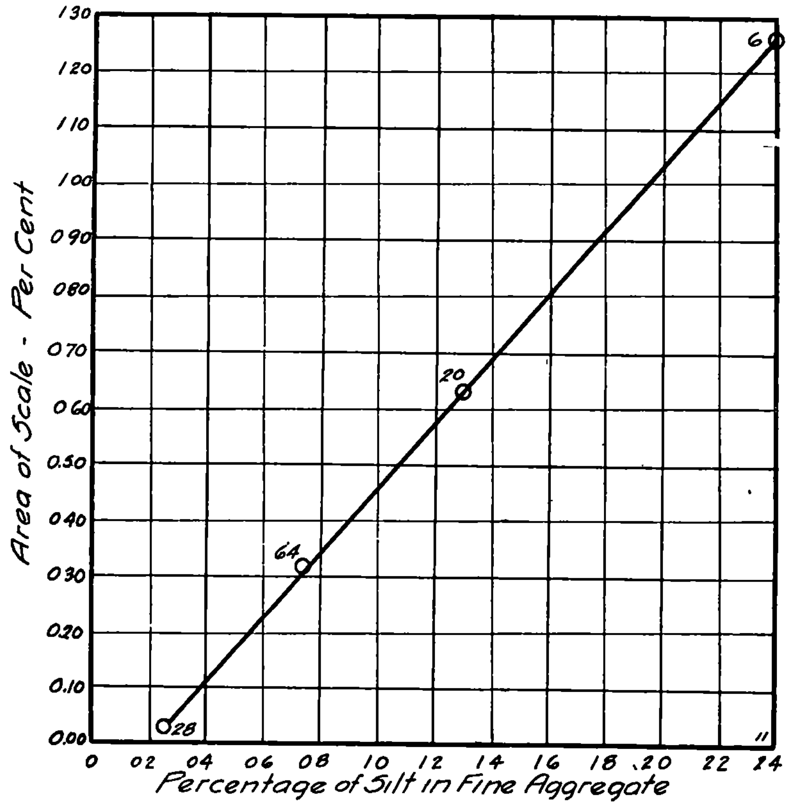

Figure 11 Relation of Scaling to Silt Content of Fine Aggregates as Reported from 4 Projects in Minnesota

The numbers are the lengths of the projects in miles

Tables VII and VIII contain summaries of the arbitrary scaling units classified into yearly averages, for wet earth and calcium chloride curing methods respectively.

Effect of silt content of fine aggregate on scaling

A more detailed treatment of this phase of the problem would be possible if the elutriation tests results were available on all the projects and if the procedure of final finishing of the concrete continued the same in all the States However, the data from one State are complete and extensive enough to show the general relationship, when the final finishing manipulations are fairly constant Figure 11 gives a graphical interpretation of these data This figure shows that the percentage of scaling increased with the silt content when the final finishing operations and general construction methods were similar There were other projects which showed periodic scaling and on which sands of widely different silt contents were used, but the incomplete construction records as to their use, makes a correlation impossible Due to these incomplete construction records there were other elements of this scaling problem that could not be analyzed

VOLUME CHANGES AS AFFECTED BY CURING METHODS

The following facts were disclosed by measurement of volume and temperature changes made by the Iowa, Wisconsin and Missouri Highway Departments and the U S Bureau of Public Roads

1 Bituminous coatings as used caused greater volume changes than the other curing methods studied under similar conditions (wet earth, calcium chloride surface, calcium chloride integral and sodium silicate), both as regards the total volume changes and the magnitude of the daily variations in volume

In recent tests in Missouri and Iowa volume changes of bituminous coated concrete slabs were considerably reduced by covering the bituminous coatings as soon as possible with light colored material such as white-wash, portland cement, or limestone dust

2 The total and daily variations in volume changes in the pavement slabs cured with bituminous coatings were affected by climatic conditions, especially intensity of sunlight, and by time of exposure

The following facts were disclosed by crack surveys of pavements in Kansas, Wisconsin, Iowa, Missouri, California and Texas

1 Projects surveyed in Iowa, Missouri and Texas, where no transverse joints except those caused by temporary suspension of the work were used, showed the average length of uncracked slabs on pavements cured with bituminous coatings to be approximately 50 per cent of that of pavements cured with wet earth

2 Projects surveyed in California where no transverse joints except those caused by temporary suspension of the work were used showed uncracked slab lengths on pavements cured with bituminous coatings as great or greater than those on pavements cured with wet earth On most of these projects and on a project on Long Island where no intermediate cracks between joints 78 5 feet apart were found up to one year, fine sand subgrades are a distinctive characteristic of the localities

3 Projects in Kansas and Wisconsin, on which transverse joints were used showed that the characteristics of the aggregates had a consider-

able effect on the length of slab that could be laid without subsequent intermediate cracking between joints

For slabs cured with wet earth, observations up to about one year showed that the installation of transverse joints at 30 to 50 feet intervals eliminated intermediate cracking in the slabs For slabs cured with bituminous coatings and having a similar joint spacing, the number of slabs with no intermediate cracks in the various projects varied from 60 to 100 per cent, depending upon the characteristics of the aggregates used

Conclusions

In view of the facts given in the foregoing paragraphs the committee concludes that

1 The volume changes occurring with the use of wet earth, calcium chloride surface treatment and sodium silicate as curing agents were not great enough to make this factor a matter of importance in deciding upon their use

2 It may be expected that the use of bituminous coatings for curing will result in a greater tendency toward shrinkage cracks than will the use of wet earth However, when shrinkage cracks are prevented by means of properly spaced transverse and longitudinal joints, this tendency need not be considered a factor of major importance in considering the use of bituminous coatings as curing agents

Strong indications

The committee is of the opinion that the available data indicate very strongly that under the following conditions shrinkage cracks need not be considered a factor of major importance in considering the use of bituminous coatings as curing agents

(a) When the character of the subgrade is such that the frictional resistance to movement of the slab is very low

(b) When the surface is covered as soon as possible with light colored material such as portland cement, limestone dust, or whitewash

Discussion of data

Measurement of volume and temperature changes

Tests by The Iowa Highway Commission One slab each for six methods of curing, were built at Ames, August 29 and 30, 1929, for the purpose of determining the effect of different methods of curing upon volume changes in concrete slabs subjected as nearly as possible to conditions encountered by actual pavements These slabs were six inches in thickness, two feet wide and eighty feet long Instruments for measuring the change in length of the slabs were installed on permanent reference monuments at each and of the slab

Observations on the changes of lengths of each of these slabs are being made daily, except Sunday This report includes the movements up to June 5, 1930

Figure 12 summarizes these data for the first ten months of their existence The average maximum shrinkage, for each of the five curing methods is given at four week intervals The mean air temperatures for these periods are also given It will be noted from this figure that all of the curing methods show some shrinkage, but that the shrinkage of the bituminous cured slabs was considerably greater than the others The smallness of the variation during the first three months between

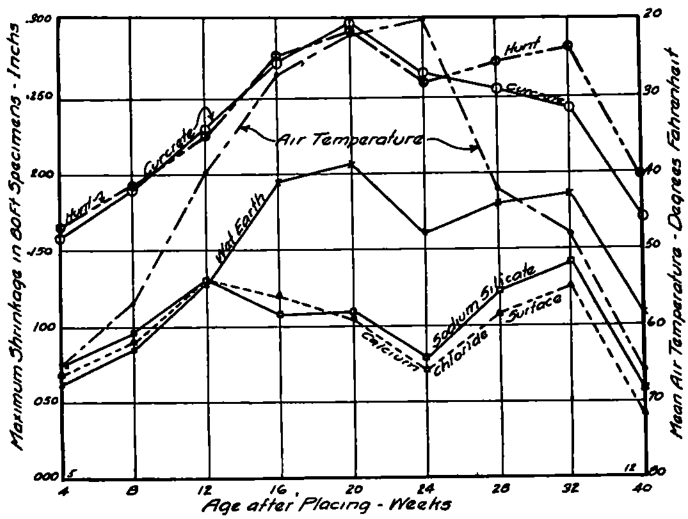

Figure 12 Maximum Shrinkage Observed in Slabs 80 Feet Long Cured by Different Methods, at Intervals up to 40 Weeks after Construction, with Corresponding Air Temperatures

Data furnished by the Iowa Highway Commission

wet earth, sodium silicate and calcium chloride surface application methods of curing is of interest

Tests by the Wisconsin Highway Commission The Wisconsin Highway Commission, during the month of August 1929, conducted an experimental study on the curing of approximately 6400 feet of highway The road slab is the standard Wisconsin section 9 inches thick at the edges, 6½ inches at the center, and 20 feet wide with no reinforcement The center joint was formed as a longitudinal plane of weakness by the Flexplane machine, and ½ inch square tiebars were placed across the center joint on 2-foot centers

In order that a direct comparison might be made between earth curing and other curing agents, 2 x 4 inch timbers were placed on the longitudinal joint filler while it was still hot, thus separating the halves of the road slab Earth cover was placed on one half, while the experimental curing agents were used on the other half

Air temperature and humidity records as well as temperatures of the concrete at various depths were taken continuously during the test period. The temperatures in the slab were obtained by placing thermometers in the temperature wells imbedded in the pavement These wells consisted of glass test tubes filled with water to a depth of about one inch with a cover of Kerosene on the water to prevent its evaporation

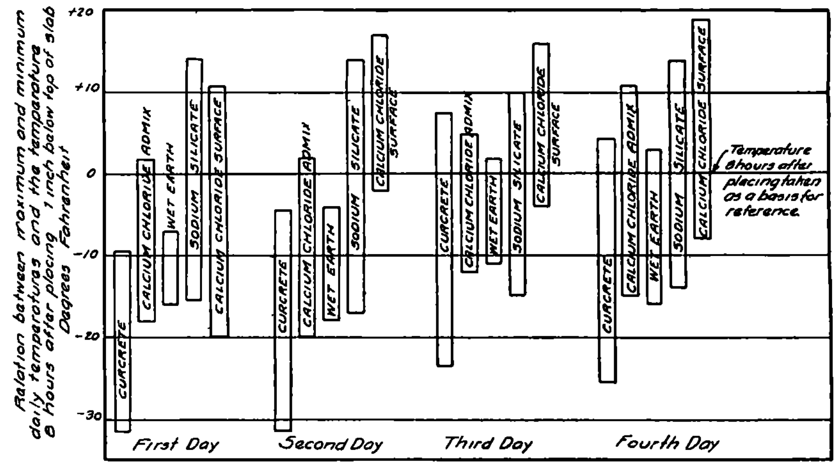

Figure 13. Daily Ranges in Temperatures at a Point 1 Inch Below the Upper Surface of Slabs Cured by Various Methods

The maximum and minimum variation each day for 4 days from the temperature at 8 hours after placing, which was assumed as the time of set are shown. Temperatures higher than that at time of set place the concrete in compression or cause swelling, and temperatures lower place the concrete in tension or cause shrinkage. The stresses or volume changes at any time are proportional to the difference between the temperature at that time and temperature at time of set

On each section temperatures were read hourly for the first 48 hours and at three hour intervals for the next three days

Figure 13 (from the Wisconsin data) shows the daily range in temperature of the concrete one inch below the surface with respect to the temperature at the time of set

Study of temperature gradients offers a probable explanation of the greater shrinkage in bituminous cured concrete

The data from the Iowa Highway Commission disclosed the rather surprising fact, that in spite of the added absorption of heat due to the black surface, the slabs coated with bituminous material had greater shrinkage than did the others. The general results of the crack surveys corroborated this disclosure

A study of the temperature records from the Wisconsin experiments indicated a probable explanation of this action

1 The evidence indicates that, the relatively large shrinkage of concrete cured with bituminous coatings as compared with other curing methods as shown by volume measurements and cracks in pavements, was due to the larger volume occupied by the concrete at the time of hardening and the consequently greater opportunity for shrinkage on return to normal conditions The greater volume apparently was due to the greater absorption of heat through the black surface, to the heat of hydration and to the retention of a large part of the mixing water Under such circumstances the return to normal temperature and mois-

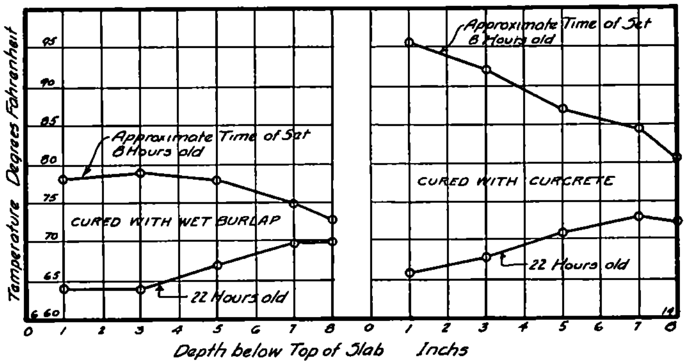

Figure 14. The Ranges in Temperature at Various Depths in Slabs during the First Day after Placing, in the Two Halves of a Concrete Pavement

One side cured with wet burlap—the other with curcrete. The stress is proportional to the drop in temperature between the time of set and the later age. Data furnished by the Wisconsin Highway Commission.

ture conditions must therefore set up tensile stresses that are difficult for the concrete to resist during its early life

2 The favorable results noted with respect to volume changes and cracking shown by concrete cured with sodium silicate, calcium chloride surface application and wet earth, which were protected for the first 24 hours with wet burlap, appeared to be due to the relatively small volume occupied by the concrete at the time of hardening, and to the fact that these lighter colored surfaces give up their internal heat more slowly during the hours of darkness than do the black surfaces The result of these two effects would mean lower tensile stresses The relatively smaller volume occupied by concrete cured with these methods may be accounted for by the fact that the cooling effect of evaporation from the wet burlap covering reduced the absorption of heat by the concrete

Figure 14 shows the relative magnitude of the temperature ranges during the first 24 hours in pavements cured with wet burlap and curcrete From this figure we note that the temperature of the curcrete cured pavement at a depth of one inch from the top, decreased from 95 5 degrees at 8 hours after placing to 66 degrees at 22 hours after placing This is a total decrease of 29 5 degrees (Fahrenheit) at the one inch depth

For the wet burlap cured pavement we note a maximum change of only 14 degrees at the one inch depth between 8 and 22 hours after placing

The shrinkage to be expected for curcrete curing between 8 and 22 hours after placing was therefore greater than that of wet burlap curing

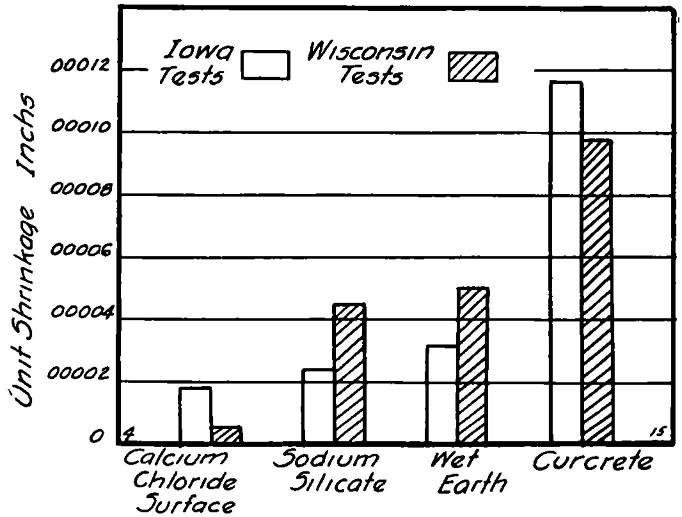

Figure 15 Average Maximum Shrinkage During First 96 Hours after Placing The Iowa data were determined by direct measurement The Wisconsin data were computed from temperature measurements

during the period in which the tensile strength of the concrete was very low

The reason for using the temperatures at 8 hours for a base is that 8 hours was the approximate time of final set, at which time the volume was established

From the above discussion it should not be concluded that ample protection during the first 24 hours of the life of the concrete or a delay of that length of time in applying the bituminous coating will produce a pavement that will not crack The tensile strength for several days may be low enough also to be exceeded by deformation stresses (resistance to movement) induced by temperature and moisture changes of normal magnitude But the first 24 hours is undoubtedly a critical period during which precautions to minimize the effects of shrinkage stresses should be taken

Comparison of Wisconsin and Iowa data on volume changes

In order to determine the correctness of the theoretical deformation analysis of the Wisconsin data, a comparison was made with some direct deformation measurements made by Iowa on 80-foot concrete specimens cured with similar methods These data are plotted in comparison with the Wisconsin data on Figure 15 These diagrams although of slightly different magnitudes, show similar relations between the different curing method involved

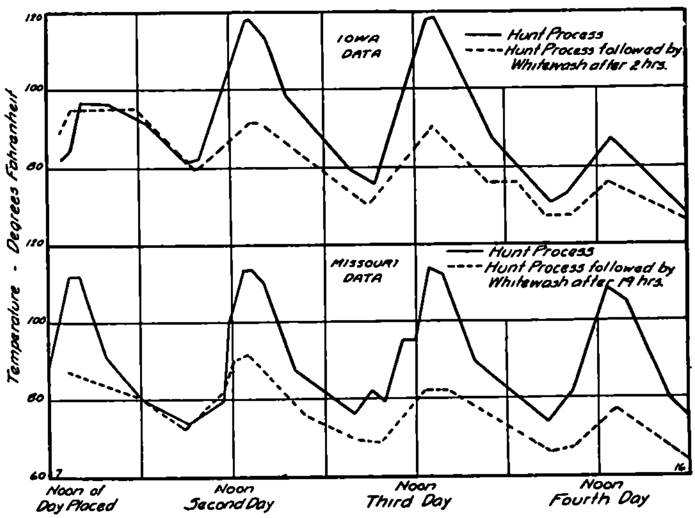

Figure 16. The Effect of a Coat of White Wash Applied over a Hunt Process Treatment, upon the Temperatures of the Top Surface of Concrete Slabs

Hunt Process material was applied when the concrete was one hour old for Iowa tests and when the concrete was two hours old for Missouri tests.

The volume changes in the Wisconsin investigation were computed from the temperatures and do not include the effects of loss or gain in moisture, whereas the volume changes recorded in Iowa included the changes due both to temperature and moisture variations

Effect upon volume change by covering bituminous coating with white-wash

Radiation and absorption

It has been found experimentally that surfaces which radiate heat rapidly when hot, absorb heat rapidly when cold There is a close proportionality between radiation and absorption That is, good absorbers of heat (when cold) are good radiators of heat (when hot). A lamp black surface is about the best radiating surface, while a light colored surface is a poor one

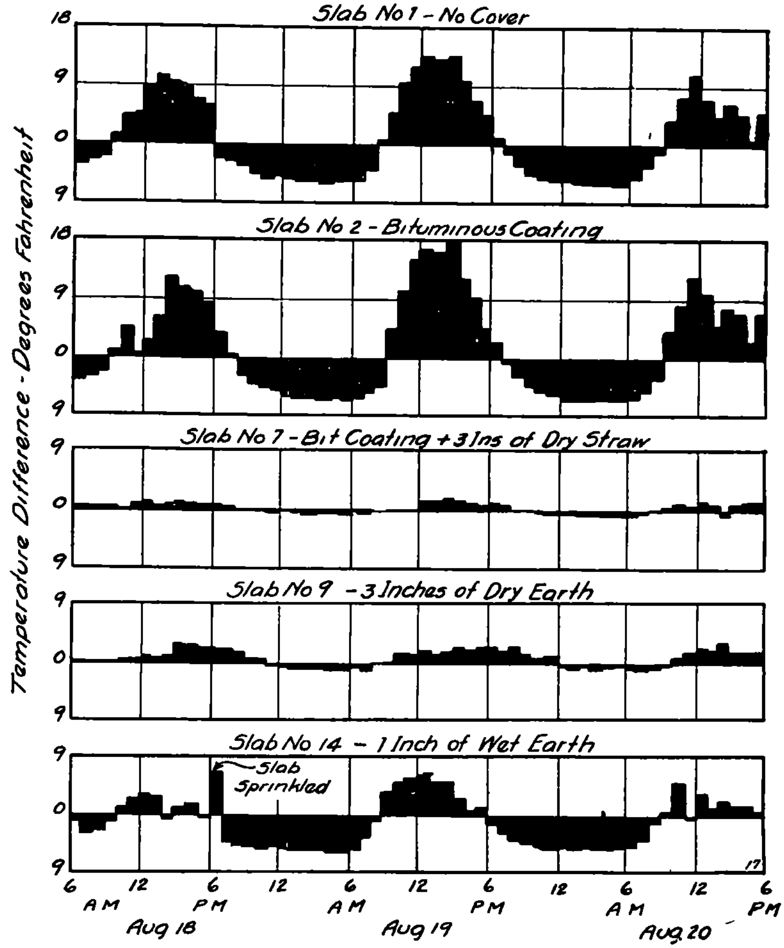

Figure 17. The Effect of Surface Covers upon the Differences in Temperature between the Two Surfaces of an 8 Inch Concrete Slab about One Week Old

Data furnished by the U. S. Bureau of Public Roads

The above facts account for the greater temperature fluctuations in the bituminous cured concretes The use of white-wash or light colored powders as an added covering to the bituminous coatings is based upon the theory that heat absorption will be decreased by reason of reflection from the white surface.

Figure 16 shows graphically the difference in temperature in the top surface of slabs cured with Hunt process and with Hunt process covered with white-wash These curves are indicative of the amount of radiant heat absorbed by the pavement Similar results were obtained by the Bureau of Public Roads by protecting the freshly placed bituminous coating from the sun by a 3 inch layer of dry straw These are shown in Figure 17 from unpublished data released by the U S Bureau of Public Roads

ADDITIONAL INFORMATION NEEDED

The need for further information on the following points is apparent from study of the available data

1 Conditions which obviate the tendency of pavements cured with bituminous coatings toward more frequent shrinkage cracks than in the case of those cured with wet earth

2 Effects of subgrade characteristics upon volume changes and curing processes in general

3 The effects upon volume change and shrinkage cracks of covering the bituminous coating with white-wash or light colored powder

4 The effects of temperature upon warping of concrete slabs and the effects of different degrees of warping upon pavement condition

5 Effects of aggregate characteristics upon volume changes and shrinkage cracks

6 Effects of crack or joint spacing upon durability of pavement and upon maintenance costs

DISCUSSION

ON

CURING OF CONCRETE PAVEMENTS

MR H S MATTIMORE, *Pennsylvania Department of Highways* Results of so-called non-curing experiments in the field and laboratory may be difficult to obtain This is especially so under field conditions, in that it is practically impossible to secure the non-curing in the field under the normal conditions obtained throughout the United States.

The humidity of the atmosphere has considerable influence on any type of curing other than the surface seal In our research we used an admixture of calcium chloride as a curing agent, and we found that laboratory humidity varied between 25 and 45 per cent The average outdoor humidity was considerable in excess of this, so from this standpoint it is doubtful if the so-called non-curing under laboratory and field conditions are comparable.

One notable point in the report was the amount of scaling observed in Minnesota where calcium chloride surface curing was used This is especially notable on the slides

Mr Burggraf The large difference in the extent of scaling between wet earth and calcium chloride surface application methods of curing in the Minnesota Scale Survey, is probably due to the non-comparable conditions both as to the time and methods of construction All of the calcium chloride surface cured pavements (117 miles) were placed in 1924, 1925 and 1926, whereas for the same period there were only 35 miles of wet earth cured pavement placed

There are also two very badly scaled projects (approximately half of scaled area) included in the calcium chloride total which had unusual construction conditions One was constructed from a central mixing plant and the other used an unwashed local sand Scaling was noted on the latter project before its completion and a washed sand was used on the remainder of the section, which is practically free from scale

Mr H F Clemmer, *Engineer of Tests and Materials, District of Columbia* I wish to express my appreciation for the very splendid study and report which this Special Committee on Curing has presented It has done much to clarify the question of proper curing and has been of particular help in formulating programs of research

It is however of interest to refer to the following·

The Committee states that the amount of original mixing water retained in the concrete is a factor on which it may be found possible to base a specification for curing For best curing it is only necessary that sufficient moisture be present in the concrete for continued hydration of the cement at the maximum rate Any amount in excess of this reduces the possible density of the concrete As has been thoroughly demonstrated the concrete having greatest strength, other factors being equal, is that using the least amount of water for mixing An ideal curing condition would consist in the retention of only enough moisture to properly start hydration and the subsequent furnishing of such moisture as might be needed for the continued hydration of the cement. Therefore a method of curing which would insure the presence of sufficient moisture for proper hydration might be far more effective than one which would retain a much larger percentage of the original mixing water

In the conclusions regarding the effect of volume changes the Committee states that if transverse and longitudinal joints are properly spaced the tendency towards shrinkage, which is increased by the use of some methods of curing, is not of major importance It does not refer to the increase of the coefficient of expansion and contraction caused by greater temperature variations

Engineers who design concrete pavements are giving considerable thought to the advisability of taking into account the amount of stress caused by the movement of the pavement slab over the subgrade Tests have shown that the coefficient of friction between the subgrade and the slab increases with the amount of movement It is therefore of importance to reduce the coefficient of expansion and contraction to a minimum That this is of particular importance if expansion joints become ineffective and the concrete is confined is very evident It would seem therefore that any factor which tends to reduce the coefficient of expansion and contraction to a minimum and yet does not affect the quality of the concrete is most important

Mr H Hershey Miller, *Pennsylvania Department of Highways* Professor Lang, the committee and especially Mr Burggraf are to be congratulated on the thorough manner in which they have approached this problem of curing concrete

The comprehensive outline "For Suggested Curing Investigations" if followed by investigators would result in findings that would go far toward clarifying our existing knowledge of different curing methods

The effect of different curing methods on the resulting pavement after service is a feature that should be studied on a comparative basis, too often we submit as evidence isolated cases or individual projects and base our conclusions on meager data where other factors may have been an influence

The committee has avoided this pit fall and has examined hundreds of miles of pavements in various states before offering conclusions

The Pennsylvania Department of Highways has used the Calcium Chloride admixture method of curing concrete for ten years, the last six as an alternate to wet earth or straw This method of curing has grown in popularity until at the present time more than 95 per cent of our concrete roads are cured in this manner

From strength tests, examination of road surfaces, crack surveys, drilled cores, examination of reinforcing, we are convinced that under our conditions this method is a satisfactory alternate method of curing and gives us the advantage of higher early strength with a resulting advantage of earlier opening of pavements to traffic

The following discussion is submitted with the thought that it may call attention to existing data and stimulate further investigations on this important subject

General A system of supplying, retaining or attracting moisture that will insure sufficient water to cure concrete adequately is a problem that confronts the engineer charged with concrete construction

The usual means for supplying this moisture is by sprinkling, ponding, wet sand, earth or straw augmented by placing wet burlap as soon as possible after final finish

These methods while effective are open to criticism in that it is almost impossible to obtain a continuous uninterrupted supply of moisture during the total curing period This is especially true in a concrete road slab since a portion of the work is generally at some distance from the mixing operation and constant supervision of the curing is often not practicable

Curing increases strength and durability No part of the process of making good concrete is more important than thorough curing Unfortunately it is the one operation most frequently neglected Proper curing of concrete has long been recognized as one of the most important steps in producing strength and durability, yet curing one of the cheapest items, paying the greatest dividends, is often entirely omitted or improperly done

Abrams (1) states "It appears that proper curing is by all odds the cheapest method of getting full value from the cement used," and again (2) "Use the smallest quantity of mixing water that will produce workable concrete then allow the concrete to have as much water as possible during the period of curing "

Green (3) "Careful curing of concrete test specimens is an important item when uniform results are desired "

New curing methods The need for a method of curing concrete pavements without the use of water has long been recognized by Engineers and methods have been advocated that would retain or attract moisture The Calcium Chloride methods (surface and integral) are based on the affinity of that salt for moisture The theory being that it will not only attract moisture but will aid in retaining a part of the water used for mixing, during curing The surface curing methods such as sodium silicate, tar and asphalt applications are based on the theory that sufficient excess water is present in the concrete incident to mixing to cure properly provided this excess water is retained in the concrete by sealing the surface

Discussion on Curing methods In the following abstracts an attempt has been made to review some of the more important curing experiments The numbers refer to the references listed at the end of this discussion

The experiments by Clemmer and Burggraf (4) indicate calcium chloride surface application to be a satisfactory curing method They state, however, that calcium chloride should not be placed until the concrete has hardened, in order that the surface will not be affected Their experiments include asphalt application which also proved effective The strength obtained with sodium silicate was about 90 per cent of that obtained with wet earth

Experiments by Harsch (5) indicate that the flexural strengths of concrete cured with surface application of calcium chloride, water gas tar and coal gas tar were very much less than those cured with wet sand Compression results, however, show the calcium chloride surface cured concrete to have 93 to 110 per cent of the strength of plain concrete

Committee C-9 (6) Nine cooperating agencies show that the addition of calcium chloride to the mixing water accelerates the hardening of concrete at the early ages and with little or no retrogression up to 1 year with a 2 per cent solution and a slight gain with 4 per cent

Mattimore (7) using an admixture of 4 per cent of calcium chloride shows a gain in strength up to and including 1 year

Gonnerman and McKesson (8) show that wet earth is more effective as a curing agent in semi-arid climates than, calcium chloride, asphalt paper or sodium silicate They conclude "deliquescence of calcium chloride takes place very slowly when relative humidity is less than 40 or temperature is in excess of 90°F" This would indicate that calcium chloride curing is not effective in semi-arid or arid climates or when average temperatures are more than 90°F

Abrams (9) in a series of experiments with calcium chloride used as an admixture and several commercial preparations (essentially calcium chloride solutions) found increased strengths up to and including 3 years

Pennsylvania Department of Highways (10) found that calcium chloride admixture proves efficient as a curing agent when used outdoors but indoors with low humidity and high temperatures the strengths of specimens are less than those of wet burlap cured specimens.

Stewart (11) made an investigation covering the effect of temperature with and without addition of 2 per cent solution of calcium chloride and found increased strength when the solution was used

Crum (12) shows no retrogression in flexural strength of concrete containing 2 per cent solution of calcium chloride up to 180 days and a gain in compressive strength

Jackson (13) gives results of an investigation covering use of sodium silicate and calcium chloride and concludes that both appear to act as effective curing agents

Runner (14) compares air, earth, sodium silicate, curcrete and calcium chloride surface curing The methods all show some merit Air cured specimens seem best in compression and about equal to the others in modulus of rupture This might be explained by the fact that dry concrete usually shows an excess of 25 per cent over wet specimens, in compressive strength

Pennsylvania Department of Highways (15) comparing calcium chloride admixture, tar and sodium silicate on laboratory cured specimens shows sodium silicate and calcium chloride higher in transverse and compressive strength and tar lower than wet straw cured specimens In field experiments sodium silicate was lower than calcium chloride

New Jersey (16) comparing Curcrete, Hunt process, calcium chloride surface, calcium chloride admixture and sodium silicate shows strength in excess of damp straw for all methods except sodium silicate which was slightly less

Lang and Burggraf (17) review 36 curing investigations and outline a plan for a comprehensive curing experiment The laboratory cured specimens show lower strengths in general than field specimens which leads one to believe that when concrete is allowed to cure under low humidity and high temperature sufficient moisture is not retained or attracted to insure proper curing

Conclusions It appears from a comparison of the data reviewed that several of the methods outlined have merit as curing mediums In these tests *no curing* ranges in strength from 75 to 100 per cent of earth cured, with the different alternate methods falling somewhere within or above this range

In these experiments an attempt was made to provide adequate moisture to specimens cured with earth, straw, etc , while in practice on road slabs much of the pavement is not properly cured

Curcrete From results of tests this method seems to offer possibilities as an alternate curing method Care must be used when this method is employed on subgrades that readily absorb water or sufficient moisture will not be retained to give adequate curing (19) The black surface will absorb more heat than surfaces not so treated This heat will cause expansion that may result in excess cracking Conclusions drawn from limited data

Hunt process and asphalt These methods are similar to *Curcrete* method and the same tentative conclusions may be drawn

Sodium silicate This method seems to have some merit The sodium silicate should not be applied until the concrete has thoroughly hardened to guard against reaction with concrete Concrete should be protected with wet burlap until the surface has hardened for best results

Calcium Chloride (surface method) This method has proved satisfactory as an alternate curing method provided the relative humidity is expected to exceed 50 with normal temperatures Its use should not be advocated in arid or semi-arid regions or under high temperatures It should not be applied until concrete has hardened to guard against warping or scaling Green concrete should be protected with set burlap until ready for the application of calcium chloride

Calcium chloride admixture This method has proved satisfactory as an alternate curing method provided the relative humidity is expected to exceed 50 with normal temperatures Its use should not be advocated in arid or semi-arid regions or under high temperatures Laboratory investigations generally show lower strengths then wet curing which substantiates the theory that unless sufficient moisture is present in the atmosphere this method will not prove as efficient as wet curing

The use of calcium chloride as an admixture has the added advantage of acceleration which tends to strengthen the concrete at the earlier periods This should result in a reduction of curing time The concrete should be protected for the first 24 hours with saturated burlap

Other methods The data on other methods of curing are limited and no conclusions are given

Summary It would appear from the material presented that several of the alternate methods of curing have been successful Probably more mileage has been cured with calcium chloride surface and admixture than any other method except wet curing Both these methods have their limitations and should be used only under the best conditions of field control The various bituminous methods require careful control in order to obtain best results Sodium silicate generally shows lower strength than either bituminous or calcium chloride curing This method has been used extensively by one State Highway Department with satisfactory results

It is the writer's opinion that if any of the alternate curing methods are used it would add to their efficiency by insisting on *wet* curing for a period of 24 to 72 hours, dependent on atmospheric conditions With the usual wet curing encountered on road construction the alternate methods would at least be as efficient and would offer a possible solution to a vexing problem

SUMMARY OF CURING EXPERIMENTS

Ages below 7 days not included

Curing	Reference														Average
	4	5	6a	7	8	9b	10	11c	13	14	15	16	17	*	
	Ratio of strength to that of wet cured concrete—in percentage														
Wet Curing	100	100	100	100	100	100	100	100	100	100	100	100	100	0	100
No Curing	93	82			75					108d			78	24	82
Curcrete										98		101	96	11	98
Hunt												107	94	6	100
Asphalt	106												94	6	100
Sodium Silicate	88				75				99	88	110	96	84	31	91
$CaCl_2$ Surface	107	81			92					95		106	97	22	96
$CaCl_2$ Admixture			105	119	·	116	99	108	103		115	103	90	45	105
$MgCl_2$-$CaCl_2$ Surface	93													1	93
Cal						115								1	
Vitriflux						110								1	
Low Chlorine Cal						109								1	
Tar		59									92			2	76
Asphalt Paper					87									1	87

(a) Not included in averages (b) Not included in averages (c) Includes tests on concrete at 70°F (d) Not included in averages

* Indicates number of projects on which results for a given method of curing are based

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