cement generally cannot be directly replaced by an equal weight of flyash; rather, a larger quantity of flyash must be used than the amount of cement removed, the extra quantity of flyash being compensated by a reduction in sand. In other words, by redesign of the mixes, the 28-day strengths of the air-entrained flyash and nonflyash concretes could be made about equal, which might also change the final results of the freezing-and-thawing tests.

Report of Committee on Curing of Concrete Pavements

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THIS report is a summary of replies to a questionnaire prepared by the Committee on Curing of Concrete Pavements and sent to each state and to five federal agencies. Information was received on such items as 1) curing methods permitted and extent of their use, 2) test methods, acceptance limits, kinds, rate of application and preferences of membrane-forming compounds, 3) provisions governing the opening of pavements, 4) order of preference of curing methods or materials, and 5) special conditions provided for curing concrete in cold weather.

The response to the questionnaire was excellent. The data indicate that the most-popular methods on the basis of extent of use are membrane-forming compounds, waterproof paper, and wet burlap, followed by earth, hay, or straw. The preference of clear and pigmented membrane compounds is about equally divided. The rate of application of membrane compounds showed considerable variation with about half requiring a rate of not more than 200 sq. ft. per gal. of compound. The test methods and acceptance limits of membrane compounds varied considerably.

There was not much agreement as to preference of curing methods or materials. A substantial difference was found in the provisions governing the opening of pavements both from the standpoint of strength or age of the pavement. There was closer agreement on the requirements for curing of concrete in cold weather.

● THIS committee, which is concerned with the study of all factors relating to the curing of concrete in pavements, was organized in 1928. Since that time a number of committee reports have been submitted. The committee has also sponsored a number of papers presented before the Highway Research Board which have been a valuable contribution to the knowledge in this field. During the war the committee prepared "Curing Concrete Pavements under Wartime Restrictions on Critical Materials," Wartime Road Problems No. 1, July 1942. Since the war this bulletin has been revised as Current Road Problems 1-R, "Curing of Concrete Pavements," (October 1952).

In accordance with the assigned scope of the activities of the committee it has recently made a national survey of curing methods to obtain an indication of current trends in the use of materials and methods. The committee prepared a questionnaire which was sent to each state, the District of Columbia, the Corps of Engineers, the Bureau of Yards and Docks, the Bureau of Reclamation, and the Civil Aeronautics Administration. The response was excellent in that replies were received from all of the 53 to whom the questionnaire was sent.

QUESTIONNAIRE RESULTS

The questionnaire requested information concerning the methods and materials used by the state or agency in the curing of con-

crete pavements and the extent of their use, the testing of membrane-forming materials, provisions governing the opening of the pavement, preferences as to methods or materials, and the conditions provided for the curing of concrete placed in cold weather. Three states advised that they do not construct concrete pavements and were, therefore, not in a position to reply to the questionnaire.

The data obtained from the questionnaire are discussed below. Insofar as practicable the data have been placed in tabular form.

Curing Methods Permitted

The curing methods permitted by the states and agencies are shown in Table 1. If the reply did not indicate that the material was being used or permitted or specifically state that it was not permitted, it is indicated in the column headed as "not stating." It is apparent from this table that the more generally permitted curing methods are wet burlap, cotton mats, membrane-forming compounds, waterproof paper, and initial cure with wet burlap followed by wet earth, straw, or hay.

Extent of Use

The extent to which the various curing methods are used by those permitting their use is shown in Tables 2 and 3. Table 2 includes the methods which do not involve an initial cure with wet burlap. Some did not indicate the extent of use in their replies and are listed in the tables in the column so designated. Although wet burlap and cotton mats are indicated in Table 1 as being rather extensively permitted, the extent of their use, as shown in Table 2, is limited. The material most-extensively used in the group of materials in this table is membrane-forming compound. Twenty four report that it is extensively used in their state or agency, and seven reported that it is sometimes used. Waterproof paper was reported as being extensively used in 11 replies and sometimes used in 12. It is interesting to note that none reported the use of sodium silicate, either with or without initial cure.

Of these methods or materials shown in Table 3, which lists those methods involving the use of wet burlap as initial cure, the method reported as being most extensively used was wet burlap followed by earth. Six report this method as being extensively used and three as being sometimes used. Wet burlap followed by straw or hay was reported as extensively used by six and sometimes used by four. It is apparent that there is lack of agreement in the length of time of cure, the time varying from 60 hr. to 20 days after the placement of the earth or straw. Membrane compounds are apparently not being used to any considerable extent with preliminary curing with wet burlap.

TABLE 1
CURING METHODS PERMITTED

Curing Method	Number of States or Agencies		
	Permitting use	Not permitting	Not stating
With No Initial Cure			
1. Wet burlap	20	8	22
2. Cotton mats	39	4	7
3. Water spray	8	14	28
4. Membrane	37	7	6
5. Calcium chloride (surface)	2	25	23
6. Calcium chloride (integral)	11[a]	20	19
7. Sodium silicate	0	26	24
8. Waterproof paper	37	4	9
9. Other	8	2	40
With Initial Cure			
10. Wet burlap followed by			
a. Wet earth, hay or straw	36	5	9
b. Waterproof paper	15	7	28
c. Membrane	13	11	26
d. Calcium chloride	4[b]	15	31
e. Sodium silicate	1	18	31
f. Other	17	6	27

[a] Six indicated that calcium chloride was used during cold weather to accelerate the hydration.
[b] One indicated that calcium chloride was used integrally at low temperatures.

Other than the above there appears to be no extensive use of the methods listed in Table 3.

Types of Membrane Compound Permitted

The committee thought that it might be of interest to obtain information as to the types of membrane compound permitted for use and the preferences in these materials. This information is shown in Table 4.

The use of these types of materials is approximately equally divided between the clear and the pigmented materials with about an equal number permitting either. Only five permit the use of bituminous membrane compounds. One of the five requires

the use of whitewash, another permits the bituminous membrane on concrete base only and another permits its use only in special cases.

Three report a preference for the clear membrane, 12 for the pigmented and 27 indicate no preference.

the same rate of application where power equipment is used but a heavier rate when applied manually. Eight of those reporting require a heavier application than the more commonly used rate of not to exceed 200 sq. ft. per gal. Five report lighter rates of application than 200 sq. ft. per gal. States

TABLE 2
EXTENT OF USE OF CURING METHODS INDICATED (WITHOUT INITIAL CURE)

Curing Method	Extensively Used	Sometimes Used	Rarely Used	Extent of Use Not Stated	
1. Wet burlap for					
72 hr.	0	5	9	1*	* On high early only.
4 days	—	1	—	1	
7 days	—	1	1*	—	* Double layer.
14 days	—	—	—	1*	*21 days for Type IV, 7 days for Type III (Probably structures).
2 Cotton mats for					
72 hr.	0	8	16	2	
4 days	—	3	2	—	
6 days	—	—	1	—	
7 days	—	—	3*	1	* One 7 days or 600 lb. Modulus of Rupture
10 days	—	—	1	—	
14 days	—	1	—	1*	* Same as for "Wet burlap for 14 days".
3. Water Spray for					
72 hr.	0	2	3	—	
10 days	—	—	1	—	
14 days	—	—	—	1*	* Same as for "Wet burlap for 14 days".
4. Membrane-forming compound	24*	7*	3	1	* 3 permit pigmented only.
	1*	—	—	—	* Widening and patching only.
	—	—	—	1*	* One when specifically permitted.
5. Calcium chloride surface application	1	1	—	—	
6. Calcium chloride integral	1*	1	4	5*	* During cold weather as accelerator.
7. Sodium silicate	0	0	0	0	
8. Waterproof paper for					
72 hr.	7	5	11	—	
4 days	2	1	—	—	
6 days	—	1	—	—	
7 days	1	1	1	—	
10 days	—	—	1	—	
14 days	1	—	—	—	
Time not given	—	4	1	—	
9. Other methods					
Ponding or wet earth	—	—	1		
Wet earth, 72 hr.	—	—	1		
Wet straw, 72 hr.	—	—	1		
Ponding	—	—	1		
Jute mats	—	—	2		
Quilted cover—4 to 6 days	1	—	—		
Wet earth or straw	—	—	1		
Wet earth or straw or jute mats	—	1	—		

Rate of Application of Membrane Compounds

Information as to the specified rate of application of the membrane-forming compounds was provided by 42 states and agencies. These data are shown in Table 5.

A specified rate of application of not to exceed 200 sq. ft. per gal. was reported by 23 states and agencies. One state also requires

permitting bituminous materials require a heavier rate of application.

Testing of Membrane Curing Compounds

Of the states and agencies, 42 supplied information relative to the methods of test employed and the specification limits governing their acceptance of membrane-forming curing compounds.

Five states and agencies specify AASHO M 148 "Nonbituminous Liquid Compounds for Curing Concrete" as their standard. On the basis of the replies to the questionnaire, the above five require the efficiency index to be not less than 90.

TABLE 3
EXTENT OF USE OF CURING METHODS INDICATED (WITH INITIAL WET BURLAP)

Curing Method	Extensively Used	Sometimes Used	Rarely Used	Extent of Use Not Stated	Preliminary wet burlap
10 (a) Wet burlap followed by earth					
60 hr.	—	—	1	—	12 hr.
72 hr.	2	1	4	1	6 to 24 hr.
96 hr.	—	—	1	—	6 hr.
100 hr.	—	—	1	—	20 hr.
108 hr.	—	—	1	—	12 hr.
5 days	—	—	2	—	12 to 24 hr.
6 days	—	1	4	—	6 to 24 hr.
148 to 150 hr.	—	—	2	—	18 to 20 hr.
7 days	1	—	1	—	8 to 24 hr.
8 days	1	—	—	—	overnite
9 to 9½ days	—	—	2	—	12 to 24 hr.
20 days	1	—	—	—	24 hr.
Not stated	—	1	1	—	12 to 24 hr.
500 lb. Modulus of Rupture	1	—	—	—	24 hr.
Wet burlap followed by straw or hay					
72 hr.	—	2	2	1	6 to 24 hr.
100 hr.	—	—	1	—	20 hr.
108 hr.	—	—	1	—	12 hr.
4 days	1	—	1	—	overnite
5 days	1	—	1	—	12 hr.—until hard
6 days	1	1	4	—	6 to 24 hr.
148 to 150 hr.	—	—	2	—	18 to 20 hr.
7 days	1	—	1	—	8 to 24 hr.
8 days	1	—	—	—	overnite to 24 hr.
9 days	—	—	1	—	18 hr.
Not stated	—	1	1	—	12 to 24 hr.
500 lb. Modulus of Rupture	1	—	—	—	24 hr.
8 to 12 days	—	—	1	—	
10 (b) Wet burlap followed by waterproof paper					
48 hr.	1	1	—	—	24 hr.
52 hr.	—	—	1	—	20 hr.
64 hr.	—	—	1	—	8 hr.
68 hr.	—	1	—	—	4 hr.
72 hr.	—	1	1[a]	1	6 to 24 hr.
4 days	—	1	—	—	overnite
6 days	—	—	3[b]	—	6 to 24 hr.
150 hr.	—	1	—	—	18 hr.
7 days	—	—	1[c]	—	8 to 12 hr.
8 days	—	—	1	—	18 hr.
10 (c) Wet burlap followed by membrane-forming compounds[d]	3	4	6	—	
10 (d) Wet burlap followed by calcium chloride[e]	1[g]	—	1[f]	2[h]	
10 (e) Wet burlap followed by sodium silicate	0	0	0	0	
10 (f) Wet burlap followed by other methods as indicated					
Ponding 3 to 6 days	—	—	10	1	
Cotton Mats 2 to 5 days	—	1	5	1	
Jute Mats 2 to 4 days	—	1	2	—	
12 hr. burlap—108 hr. sawdust	—	—	1	—	
12 hr. burlap—72 hr. second layer	—	—	1	—	
96 hr. double layer wet burlap	—	—	1	—	

[a] Preliminary burlap only if hairchecking develops.
[b] Preliminary burlap only if hairchecking develops, in case of one state.
[c] Probably structures.
[d] The specified initial curing with wet burlap ranged from "a few hours" to 24 hr. 2 states require initial curing with wet burlap only in case hairchecking develops.
[e] The specified initial curing with wet burlap was 24 hr. in 3 cases and overnight in the 4th.
[f] Surface application or admixture.
[g] Admixture.
[h] In one case surface application except at low temperature when it is added integrally.

This specification requires that the efficiency index of the curing compound when tested in accordance with ASTM Designation C 156 be not less than 90 unless otherwise specified.

Fifteen states advise that they employ ASTM Designation C 156 as their test procedure. One of these states specifies an efficiency index of 90. Eleven specify a mini-

mum percentage of retained water ranging from 80 percent at 6 days to 98 percent at 1 day and 96 percent at 3 days. Two states report their maximum permitted loss in terms of grams per square inch. This value at 3 days ranges from 0.15 to 0.25. One state did not report the permissible loss.

TABLE 4
TYPES OF MEMBRANE COMPOUND PERMITTED

	Number of States or Agencies
Clear only	15
Pigmented only	14
Either clear or pigmented	13
Bituminous	5
Preference	
Clear	3
Pigmented	12
No preference indicated	27

Note: One state specifies clear for structures and pigmented for pavements. One state specifies clear for application after 20 hr. burlap or pigmented without preliminary burlap.

TABLE 5
RATE OF APPLICATION OF MEMBRANE COMPOUNDS

Sq. ft. per gal. (max.)	No. of States or Agencies
250	1
225	1
200	23
180	1
150	3
144	1
135	1
100 (in 2 coats)	1
150 (in 2 coats)	1
225 (hand sprayer)	1
300 (power sprayer)	
225–265 (clear)	1
135–180 (cut-back asphalt)	
90–120 (asp. emul.)	
150 (manual)	1
200 (power)	
64 (asp. emul)	1
90 (cut-back asphalt)	
225–270 (clear)	
153 (pet. dist.)	
Manufacturer's recommendation	2
Visible	1
Not stating	2

Nine states report that they use ASTM Designation C 156 modified. Of these one state requires a minimum efficiency index of 90 and another of 95. Five states specify a minimum percentage of retained moisture ranging from 90 to 95 at 3 days. One of these five states specifies permissible losses at 1, 3, 7, 10, and 14 days. Two states specify the permissible loss in terms of grams per square inch. The first limits it to 0.075 g. at 24 hr., 0.15 g. at 72 hr. and 0.30 at 7 days. The second specifies 0.075 g. at 24 hr. and 0.15 g. at 72 hr.

Two states specify a minimum moisture retention of 85 percent at 7 days. The test method is not stated but it is probably ASTM Desig. C 156 or Desig. C 156 modified.

On the basis of the replies received and available specifications, 26 of those testing membrane-curing compounds base the loss in moisture on that in the specimen at the time of application, five on the original moisture and one on the moisture in the specimen ½ hr. after application.

Of three states apparently not specifying minimum moisture retention, one has a chemical analysis requirement, another specifies drying time and color, and the third specifies limits for viscosity, distillation, specific gravity, ductility, total solids and film qualities. Four states and agencies have their own test procedures for moisture loss. One state does not name its test procedure, one accepts a certificate from the manufacturer and two have no specifications.

A number of the states and agencies list a number of requirements other than that of water retention and it is presumed that in most cases the specifications would include requirements in addition to that of water retention.

Preference of Curing Methods or Materials

Information was also requested of the states or agencies concerning their order of preference of the several curing methods. Data on this question, shown in Table 6 was supplied by 43 organizations. It may be noted that there is no preponderance of preference for any one method.

Provisions Governing Opening of Pavement

Inasmuch as the proper time of opening of the pavement is intimately related to the rate of curing of the concrete, it was thought desirable to obtain information concerning the requirements of the states or agencies; 48 replies were obtained to this question, and the data are shown in Table 7.

Fourteen report that they use the one-third-point type of loading, ten the center-type loading, and six cantilever loading. One state reports cantilever with hinged lever arm, one reports one-third point in the laboratory and center loading in the field,

and a third reports it uses cantilever or center point.

Five report a strength requirement only and ten report an age requirement only. It is probably true that in most cases where

TABLE 6
CURING METHODS OR MATERIALS IN ORDER OF PREFERENCE

Method	Number of States or Agencies		
	1st choice	2nd choice	3rd choice
Cotton mats	7	6	3
Burlap followed by wet earth	6	2	—
Waterproofed paper	5	5	3
Membrane	4	6	3
White pigmented membrane	2	1	2
Wet curing	7	—	—
Hay or straw	2	—	2
Wet burlap	2	1	—
Quilted covers	1	—	—
Burlap and $CaCl_2$ admixture	1	—	—
Water ponding	1	—	—
Burlap and hay or straw	2	—	—
Wet burlap or cotton and flooding	1	—	—
Wet earth	1	2	1
Burlap followed by cotton or mats	1	—	—
Mat and paper, 5 days	—	1	—
Burlap and paper	—	1	1
Preliminary wet and surface $CaCl_2$	—	1	—
Preliminary wet and integral $CaCl_2$	—	—	1
Surface $CaCl_2$	—	—	1
Double burlap	—	1	—

TABLE 7
PROVISIONS GOVERNING OPENING OF PAVEMENT

	Number of States or Agencies		Number of States or Agencies
Strength	38	Age	43
Modulus of rupture (min.)		Age in days (min.)	
450	1	5	1
500	9	7	12
540	1	9	1
550	10	10	8
575	1	12	2
600	7	14	15
650	3	20	1
		21	2
Compressive strength (min.)		30	1
2,500	2		
3,000	3		
3,300	1		
3,500	1		

both requirements are given that the state or agency exercises its option of using only one of the requirements whichever it deems appropriate.

Two states specify modulus of rupture or compressive strength. An agency reports "specified strength, except 450 for light loads."

Again it is noted that there is no general agreement as to the minimum age or strength required before the pavement may be opened. Permissible age ranges from 5 days to 30 days, modulus of rupture from 450 to 650 psi. and compressive strength from 2,500 to 3,500 psi.

Information was also requested as to where specimens were cured and tested and also as to methods of curing. Test specimens are cured and tested in the field by 33 agencies and states. Three report that the specimens are tested in the laboratory; one reports that they are sometimes so tested. Two report laboratory curing. Nineteen report curing of the specimens under conditions comparable to the pavement, eight with moist earth, sand or straw and five immersed in water after preliminary curing. One state reported the curing of cylinders for 365 days in the field in addition to the usual 7- and 28-day tests.

Curing of Concrete in Cold Weather

The curing of concrete under adverse conditions probably poses the most-serious problem to the engineer concerned. It was thought that information on this phase of concreting operations would be of interest.

Four questions were asked relative to the special conditions provided for curing concrete in cold weather. There was greater unanimity expressed on this phase of concrete curing than on any other.

For those states confronted with the problem of freezing weather it was almost a unanimous requirement that the subgrade be not frozen.

The second question in this group was concerned with the minimum temperature at which the placing of concrete is permitted. Four advise that they permit placing at a minimum temperature of 35 F. and rising, whereas seven simply state 35 F. Ten permit placing at 40 F. and one each at 36 F., 38 F., 45 F. and 60 F. Three require a minimum of 40 F. and rising temperature. Eleven permit placing to start at 35 F. and rising but forbid pouring when the temperature is 40 F. and falling. One specifies 40 F. and rising temperature and 45 F. and falling, another 40 F. and 50 F. respectively. One state specifies that operations may start when the temperature of concrete delivered to subgrade is 40 F. or above and the air temperature remains above 38 F. Another requires for mean air

temperatures of 50 F. to 35 F. a minimum mix temperature of 60 F. plus 1 percent chloride or 50 F. plus 2 percent chloride; for mean air temperatures 35 F. to 20 F. a minimum mix temperature of 60 F., plus 1½ percent chloride, and for mean air temperature below 20 F. a minimum mix temperature of 65 F. and 2 percent chloride. Another requires a temperature above 35 F. and rising, if 40 F. and falling, written permission requiring an enclosure to maintain a minimum air temperature of 50 F. for not less than 5 days. Another specifies 50 F. without admixtures or 38 F. with integral calcium chloride. Another requires that concrete shall not be less than 40 F. when placed and air in contact with the concrete shall not be less than 40 F. for 5 days. The construction covered by the latter requirements is presumably that of structures. One agency specifies no minimum temperature but requires that concreting be stopped at 2 p.m. so as to permit setting of the concrete before the temperature begins to drop. It also requires the use of integral calcium chloride at low temperatures. Seven states report provisions for the use of integral calcium chloride as an accelerating agent during cold weather. Three states list no minimum temperature requirements but other corrective measures are taken to prevent freezing. It is probably true in most, if not all, specifications that the contractor is responsible for protection against freezing.

The third question in this group requested information concerning the minimum and maximum temperatures of the concrete at the time of placing. Fourteen states do not specify the temperature of the concrete at time of placement. Three states provided no information on this question. The most commonly accepted minimum temperature was 60 F., with 17 states specifying such temperature. Twelve of the 17 specify a range of 60 to 100 F. Three states specify 60 F.+, two 60 to 90 F., one 45 F.+, three 40 F.+, one 70 to 90 F., two 50 to 100 F., one 65 to 100 F., one 65 F.+, two 65 to 85 F., one 75 to 100 F., two 50 F.+, one 40 to 60 F. and one 70 to 80 F.

The last question concerned with the curing of concrete in cold weather requested information as to the measures taken to protect the concrete in cold weather and for what period. Eighteen specify the use of loose, dry hay or straw to protect the concrete from freezing. The thickness specified ranges from 6 to 12 in. and the period of protection from 5 to 10 days, or in some cases, "till cured." In some cases it is specified that calcium chloride be added integrally to the concrete. Twelve other states permit the use of grass or other suitable material in addition to hay or straw. In these states, where the thickness was indicated, it ranged from 6 to 9 in. and for periods of 3 to 10 days with one state specifying a modulus of rupture requirement for the end point and another stating "till cured." One state requires 12 in. of hay or straw on top of paper blankets for 7 days. A few of the above require that at early ages the pavement be housed in with canvas and heated, if necessary, to maintain a specified minimum temperature. For structures, where referred to, it appears to be a common requirement to house in and provide heat if necessary to maintain the required minimum temperatures. One state requires that during freezing temperatures the concrete at time of placement shall have a temperature of 50 to 100 F., maintained for 3 days, with maintenance above 32 F. for 2 days more. Another requires that if the air temperature drops below 40 F. during the 24 hr. following the placing of the concrete, additional protection shall be provided and the concrete maintained at a temperature of not less than 50 F. for the first 96 hr. by approved heating devices, with straw or other approved covering for at least 3 days additional. Another specifies that if concrete is placed when the temperature is 40 F. and falling, approved enclosure must be provided and temperature of 50 F. maintained for not less than 5 days. Another state requires protection with straw, hay, grass, or other suitable material, or lanterns under canvas, or fires along the side to maintain concrete temperatures at a minimum of 60 F. for not less than 72 hr. One agency provides that after the first frost and until the mean temperature falls below 40 F. for more than one day the concrete shall be protected against freezing for not less than 48 hr., and whenever the mean daily temperature falls below 40 F. for more than 1 day, the concrete shall be maintained at a temperature not lower than 50 F. for at least 72 hr. after it has been placed. Also, concrete cured by membrane curing shall be protected against freezing an

additional 72 hr. and, if cured by water, an additional 11 days immediately following the 72 hr. of protection at 50 F. The above provisions of the latter agency probably apply to structures. One state calls for the addition of calcium chloride to the mixing water or the heating of the aggregate and water with curing of 72 hr. as usual. One agency provides that the air shall be kept at 40 to 50 F. for 5 days, above freezing for the rest of the curing period and never more than 25 deg. difference in temperature between air and concrete. This also appears to apply to structures. Three southern states have no cold weather requirements, and four states did not answer the question.

Current Research on Curing

On the basis of the response to a question in the questionnaire it appears that only a limited amount of research on the problem is being conducted at the present time. Further, not much information is available in the nature of unpublished reports from the states and agencies reporting.

SUMMARY

In most items with which the questionnaire was concerned there appears to be substantial lack of agreement. This is particularly noted with reference to materials permitted, extent of use, length of cure, types of membrane materials, rate of application of membrane compounds, their method of testing and acceptance limits, preference of curing methods, and provisions governing the opening of the pavement. Undoubtedly this reflects climatic conditions, magnitude of loads, experience with various curing methods, and other factors. In view of this diversity of opinion on the items of the questionnaire, it would appear that much of the subject of curing is still controversial. This thought, however, does not appear to be reflected in research designed to resolve some of these differences of opinion.