Some of the states had not put a strength requirement for opening concrete pavement into effect, but were expecting to

Replies to the questionnaire show conclusively that there are variations in type of machine, in size of specimen, and in interpretation of results Replies also show non-uniform practice for casting and curing the specimens With all these variations it is scarcely to be hoped that the modulus of rupture as obtained by one state could be compared with that obtained in some other states The committee considers that this method of field determination of strength of concrete is very valuable, but that the tests and equipment should be sufficiently standardized so that the results may be compared, and will truly represent the factor used in design of the pavement.

CURING CONCRETE PAVEMENTS

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Within the past few years a number of methods for curing concrete pavements, designed to take the place of the conventional water-curing process, have been introduced and actively promoted in this country This has created a somewhat confusing situation, as regards this important feature of the construction process, which should be clarified as soon as possible The all-inclusive claims which are made for each of these special curing agents, together with the more or less conflicting reports as to the results so far secured, have yielded but little definite data upon which the specification writer can depend with any degree of assurance

From a strictly economic point of view, almost all of the proposed methods of curing are preferable to the old style water-curing process, largely because of ease of application and the fact that no attention is required subsequent to application. There is probably no feature of the construction process so difficult to control as curing by means of water, due to the difficulty of maintaining an adequate supply over several days' run of pavement Then, too, adequate supervision of the sprinkling operation is extremely difficult, which makes this feature an endless source of contention between the engineer and the contractor It is evident, therefore, that there is a real field for a method or methods of curing which will be as economical, more easily controlled,

[1] This is a joint report by the committees on Materials and Design

and at the same time just as efficient as the conventional method of applying water All of these proposed methods are more easily controlled, most of them are as cheap or cheaper, and it remains therefore to determine which, if any of them, are as efficient.

It has been demonstrated many times that moisture must either be retained in or added to concrete during the early hardening period if the maximum strength and durability, of which it is capable, is to be attained A continual supply of moisture during this period is necessary, 1st—in order that the chemical changes involved in the hardening process may take place in a normal manner, and 2d—in order to delay the contraction of the concrete which begins just as soon as it is allowed to dry out It has been clearly shown[2] that the ultimate strength of concrete is greatly reduced by omitting or curtailing the curing period Likewise, it has been shown by both laboratory and field tests[3] that concrete can be prevented from contracting for an indefinite period just as long as it is kept moist It is obvious, therefore, that a pavement of this type should be kept wet a sufficient length of time to allow the tensile strength of the concrete to build up to the point where maximum resistance will be offered to the stresses set up within the concrete when it is finally allowed to dry out

In addition to the standard method of actually supplying water to the surface by sprinkling, ponding, etc, there are three general principles involved in the use of the various special curing agents which have been proposed In the first of these the material is applied to the surface of the concrete as soon after the initial hardening as possible in order to provide a seal against the evaporation of moisture Sodium silicate, or water glass and the so-called asphaltic paints, asphaltic emulsions, etc, are examples of materials in this class The second method involves the use of a hygroscopic salt, such as calcium chloride, spread upon the surface of the concrete for the purpose of attracting moisture from the air and thus providing the necessary water for curing purposes The third method is by the use of an admixture which by chemical action tends to produce an earlier hardening than would otherwise occur, and also by its hygroscopic action retains in the concrete moisture which would otherwise evaporate Calcium chloride as well as certain admixtures in which calcium chloride is the active constituent, are examples of such materials

[2] Effect of Curing Condition on the Wear and Strength of Concrete, by Duff A Abrams, Bulletin 2, Structural Materials Research Laboratory, Chicago, Illinois

[3] Expansion and Contraction of Concrete and Concrete Roads, by A T Goldbeck and F H Jackson, U S Dept of Agric Bulletin No 532

Research and experimental activities in connection with the use of these special curing agents have so far been confined largely to studies of the value of calcium chloride, both as a surface curing agent and as an admixture The first experimental work along this line appears to have been done by the Illinois Department of Public Works, Division of Highways, about seven years ago[4] As a result of these tests the State of Illinois adopted, and still uses, the method of curing by means of a surface application of calcium chloride Experience with calcium chloride as a surface curing agent in a number of other States, however, has indicated that its use for this purpose may be associated with surface scaling This effect is in all probability due to the non-uniform application of the salt to the surface of the pavement, resulting in over concentration at certain points It is in fact quite difficult in actual construction to secure an even distribution of the chemical even by means of the special devices which have been placed in use

Reports which have been received from various parts of the country, as well as the results of recent research work carried out by the Bureau of Public Roads at Arlington, Virginia, indicate that the successful use of this material depends to a very large extent upon the temperature and humidity conditions prevailing during the curing period In regions of low relative humidity and high temperatures, reports indicate that calcium chloride may not successfully be used Experiments made at Sacramento, California, in 1924[5] substantiate this conclusion In the Sacramento tests it was entirely probable that the calcium chloride did not function in the desired manner at all, due to the very low relative humidity recorded during the test period

Research data supporting the use of calcium chloride as a curing agent in the form of an admixture are very meager Its use seems to have been justified as the result of experience in actual construction rather than research or experimental work Here again the value of the material as a curing agent appears to depend a great deal upon atmospheric conditions For instance, certain of the Southern States which have attempted to use calcium chloride integrally have experienced difficulty due to rapid hardening during hot weather On the other hand, many of the Northern States, such as Pennsylvania, Con-

[4] Calcium Chloride in Concrete Highway Construction, Engineering News Record, March 9, 1922, by B H Piepmier and H F Clemmer

[5] Studies of Curing Concrete in a Semi-Arid Climate, by H F Gonnerman and C L McKesson, Bulletin 15, Structural Materials Research Laboratory, Chicago, Illinois

necticut, etc, have successfully used the integral method The Highway Departments of both of these States have carried out considerable experimental work along this line, the results of which have not as yet been published It is understood, however, that the data which have been so far secured indicate that under the average temperature and humidity conditions prevailing in these regions, concrete of satisfactory quality is obtained by the use of this curing method

As regards strictly the curing effect of a calcium chloride admixture there seems to be practically no experimental data to support the claim that the salt retains its hygroscopic properties after the concrete has hardened and thus prevents too rapid drying out. Such claims appear to be based largely upon theory, supported by observation on certain pavements where the amount of cracking and checking appears to have been decreased, due to the use of the admixture

The effect of calcium chloride in accelerating the early hardening of concrete appears also to depend upon the composition of the Portland cement with which it is used Experimental work conducted under the auspices of the Committee on Materials, American Association of State Highway officials, shows that there is quite a range in the relative increase in early strength dependent upon this factor alone In general, however, it may be said that the strength of the concrete within the first 48 or 72 hours is increased, and this may account for the decreased amount of initial transverse cracking which is sometimes noted

The use of surface treatments for the purpose of sealing moisture within the concrete has been tried out to a certain extent in the field Experimental work on silicate of soda by the Bureau of Public Roads, both at Arlington and in cooperation with the States of Maryland and Virginia, when complete, should prove of interest in determining the value of this type of curing under average temperature and humidity conditions

NECESSITY FOR EARLY CURING

Practical experience, as well as the results of all available research data, point to the importance of maintaining the concrete in a moist conditions during the first 24 hours In fact, adequate curing during this period is relatively of much greater importance than any subsequent treatment, especially under severe drying conditions, due to the low tensile strength of the concrete Wet burlap applied just as soon as possible seems to be the most effective method yet devised for providing this early protection The tests by the Bureau of Public Roads on

the experimental work being conducted at Arlington which are summarized above show that under severe drying conditions checking may be controlled by the prompt application of saturated burlap to the finished surface of the pavement

The so-called asphaltic paints and asphaltic emulsions which are painted or sprayed upon the surface of the concrete as soon after finishing as possible have been used to a certain extent in California as well as in the East Practically no research data regarding this type of curing agent, however, is available at this time Carefully controlled experiments, made under varying conditions of temperature and humidity, are needed in order to determine under what conditions such surface seal coats are effective

DIGEST OF PUBLISHED RESEARCH DATA

A brief description of a few of the more important tests which have been made, together with the conclusions drawn, follows:

Studies of Curing Concrete in Semi-Arid Climate, Harrison F Gonnerman and C L McKesson (See Bulletin 15, Lewis Institute, Chicago Tests conducted at Sacramento during the summer of 1924 as a cooperative research by the California Highway Commission and the Structural Materials Research Laboratory Because of the low humidity and high mean temperature at Sacramento the site was considered ideal for securing information on curing under extreme conditions

The experiments were carried out on 7 by 10 by 38-inch plain concrete beams made and cured out of doors by the following methods (after removal of forms at 16 to 24 hours)

(1) Covering with 2 inches of earth, wet for 3, 7, 14, 16 and 88 days
(2) Air curing, no surface treatment
(3) Covering with asphaltic paper
(4) Flake calcium chloride, 1½, 2, 2½, 3, and 5 lbs per sq yd applied over the surface
(5) Sodium silicate (41° Baume), applied undiluted, 1 to 1½ and 1 to 3 solutions

Tests were made for transverse and compression strength and surface hardness, from which the following conclusions were drawn

(1) A curing method is efficient which maintains the moisture content of the concrete during the early stages of hydration about equal to the original mixing water Wet earth curing gave the best results of the methods used Curing methods which permitted high evaporation losses gave concrete of low strength
(2) The tests showed that concrete cured under earth wet for 7 or 14 days was only slightly stronger than when cured under earth wet for 3 days In view of this and of the small rate of increase in strength after the fourteenth day, it may be concluded that with temperatures no lower than prevailed in these tests (70° F) concrete pavement cured by covering with wet burlap for 16 to 24 hours and then with earth kept wet 7 days, may safely be opened to traffic in 14 days

(3) Curing with a surface application of flaked calcium chloride, 2½ lbs per sq yd, gave strength ratios of from 88% at 7 days to 83% at 90 days, with less, and with 3 and 5 lbs there was a slightly further reduction in strength

When the calcium chloride was washed off after 3 hours, the strengths were reduced perceptibly, washing off calcium chloride after one day gave essentially the same strengths as when left on the surface

Surface hardness for calcium chloride beams was considerably less than for beams cured with wet earth or with asphaltic paper

(4) For beams molded and cured in concrete forms, using calcium chloride, 2½ lbs per sq yd, the strength ratios ranged from 100% at 14 days to 89% at 90 days

(5) Both air curing and sodium silicate curing showed low strength and surface hardness The strength ratios for these methods ranged from about 77% at 7 days to 74% at 90 days

(6) Two percent calcium chloride used as admixture increased the flexural strength about 4% at 3 days for air and calcium chloride curing and gave no increase for wet earth curing

Extensive tests with calcium chloride as a curing agent were made in Illinois during the year 1921, by H F Clemmer and Fred Burggraf, of the Illinois Highway Department

The results obtained with various curing treatments were based on transverse strength and, when compared with the strength obtained from specimens cured with 2 inches of wet earth for 14 days and tested at the end of 28 days, were as follows

96 5%—No treatment
101 5%—2 inches wet dirt, 3 days
100 5%—2 inches wet dirt, 7 days
100 0%—2 inches wet dirt, 14 days
112 5%—1 lb per sq yd Calcium chloride dry
103 5%—1 lb per sq yd Calcium chloride—1 in dirt
117 0%—3 lb per sq yd Calcium chloride dry
107 5%—3 lb per sq yd Calcium chloride—1 in dirt
105 5%—½ to ⅔ gal per sq yd asphalt

The results secured from this investigation were also such that the Illinois Division of Highways was satisfied that calcium chloride could be incorporated in concrete to advantage during cold weather construction

There is nothing in the report of these tests to show the weather conditions under which they were made Naturally the question as to uniformity of conditions for the different tests arises, however, in view of the high strength results obtained on the beams treated with calcium chloride, as well as on those without any treatment, the inference is that the curing conditions were, in general, not severe for these tests

Since July, 1926, the Bureau of Public Roads has been conducting an investigation at Arlington Experiment Farm, Virginia, on the curing of concrete

A series of concrete slabs of size 6 by 24 inches by 200 feet were built and given a wide range of curing treatments Control specimens for compression, tension, modulus of rupture, and loss of moisture, were made in conjunction with and treated similarly to the corresponding experimental slabs These specimens have all been tested but the slabs are still under observation until a later time when further strength tests will be made on portions of the different slabs

Uniformly severe curing conditions prevailed during these tests The relative humidity was lower during the early period of curing than it would generally be on construction work for any long period in localities other than in the South and West

A preliminary report has been made on these tests in which the following conclusions are given

(1) The greatest loss in moisture occurred during the first 24 hours after placing
(2) The loss in moisture on the dry subgrade without curing was approximately 4½ times that obtained on a wet subgrade and curing with wet burlap during the first 24 hours after placing
(3) The loss in moisture from 30-pound concrete pan specimens with evaporation limited to the surface was largest during the first 3 or 4 hours after placing
(4) Rapid early moisture loss caused local shrinkage cracking of the concrete
(5) Wet burlap largely prevented early shrinkage cracking
(6) It was found that the ordinary average variations in the humidity caused almost as much difference in the curing as was obtained with the various treatments

The results obtained from different curing experiments agree in general Such apparent disagreements as appear are largely explained by the differences in weather conditions under which the tests were made The results of tests made under severe curing conditions show the great importance of proper curing, while others made under high humidity conditions give results very little different from those without treatment Obviously, curing treatments are more important in some parts of the country than in others However, most sections of the country have a portion of the year during which the weather conditions are comparatively severe for curing

A review of all the existing research and experimental data on this subject emphasizes a point which has only recently been recognized, which is that the necessity and effectiveness of any curing treatment subsequent to the initial burlap covering depends almost entirely upon atmospheric conditions However, inasmuch as in almost all sections of the country weather conditions unfavorable to curing are to be expected at certain seasons of the year, it is necessary to provide for additional curing in the construction specifications

NECESSITY FOR FURTHER RESEARCH

At the present time it does not seem that sufficient research and experimental work has been done to determine definitely which, if any, of the special curing agents so far proposed are as effective as the common water-curing method.

Further curing studies should be made to determine

(1) The effect of various treatments for different periods of curing under a wide range of humidity and temperature conditions
(2) The suitability of the various treatments for different conditions of humidity and temperature

(3) The relation between the condition of the concrete in control specimens as shown by their strength and the actual strength condition of the pavement

(4) The effect of various curing treatments on the surface characteristics of the concrete

(5) The effect of various curing treatments on the expansive properties of the concrete

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