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MICHIGAN
STATE HIGHWAY DEPARTMENT
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THE APPLICATION OF
CHLORIDE SALTS FOR ICE CONTROL TO
CONCRETE PAVEMENTS CONSTRUCTED WITHOUT THE
USE OF AIR-ENTRAINING AGENTS

C. C. Rhodes

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THE APPLICATION OF
CHLORIDE SALTS FOR ICE CONTROL TO CONCRETE PAVEMENTS
CONSTRUCTED WITHOUT THE USE OF AIR-ENTRAINING AGENTS

At the present time it is the policy of the Michigan State Highway Department to permit the application of chloride salts without abrasives to bituminous road surfaces for ice control. The question has arisen as to whether or not such a practice may be safely extended to include concrete pavements of a definite minimum age which have been constructed without the use of air-entraining cements. The advantages to be gained by such a procedure are quite obvious and can be readily appreciated by the highway engineer. It would not only effect a considerable economy of materials, men, and equipment, but would also eliminate troublesome abrasive residues which may clog drains and contribute materially to the deterioration of the pavement by their grinding action under traffic and infiltration into joints and cracks.

With these considerations in mind, the Testing and Research Division was requested by the Maintenance Division and authorized by H. C. Coons, Deputy Commissioner and Chief Engineer of the Department, to make a study of the problem during the past winter in order that conclusive data might be obtained upon which to base future policy in the matter.

In the literature on the subject of scaling caused by the application of chloride salts to concrete pavements, the statement has frequently been made that concrete pavements more than about four years of age are less vulnerable to attack by these salts than those of lesser age (1)*(2)%. Although this statement appears to have been founded upon reliable general

* See bibliography appended to this report.

observation and experience, no definite statistical data have been found which could be used to determine the minimum age at which chlorides could be safely applied to concrete pavements in Michigan in sufficient concentration for ice control without the use of abrasives.

The first problem to be solved, then, was: What is the minimum age of the concrete after which chloride salts may be used for ice control? Other questions naturally arose. What characteristics of the concrete itself, other than age, will influence its resistance to this type of attack? Will chloride salts be as effective in melting ice and packed snow on concrete pavements as they are on bituminous surfaces? What effect will temperature at the time of application have on the comparative efficiency of the two methods (applying chloride salts with and without abrasive) in eliminating traffic hazards?

Some of these questions have been answered for all practical purposes by the results of field studies. Others have been answered in the laboratory. Of the pavements selected for the accelerated test, ranging in age from four to nine years and all in good initial condition, none showed any appreciable scaling at the end of the test except the youngest. Observation of some other pavements whose history is known definitely establishes the fact that age is of no benefit to intrinsically poor concrete; rather the reverse. Rock salt and flake calcium chloride appeared to be about equal in their scaling effect on the younger concretes, while evaporated fine salt of a relatively pure grade had a noticeably less effect than either. Since the use of chloride salts without abrasives necessarily implies bare pavement maintenance and the melting power of the chloride salts diminishes with decreasing temperatures, some difficulty may arise in

completely clearing the pavements from ice when applications of raw salts are made at temperatures below approximately 10 degrees Fahrenheit. In such cases sand-chloride mixtures will probably have to be used.

The several phases of the study mentioned above will be discussed in this report under three general headings, field studies, properties of salt solutions and phase relations, and the age effect. The first part will deal with the results of the work designed to evaluate the age factor and the effect of quality of the concrete on its subsequent resistance to scaling. The second will deal with the properties of salt solutions and phase relations as they affect the problem under consideration. Finally, an attempt will be made to point out some of the factors in the mechanism of the age effect.

FIELD STUDY

The field work was originally set up to include two types of test. The first was to consist of an accelerated freezing and thawing treatment applied under close control by experienced personnel to selected areas four years old on the Michigan Test Road and on other sections of pavement in the vicinity of the test road which had attained ages of 6, 7, 8 and 9 years. The second type of test was to be somewhat different in detail and more comprehensive geographically. In this phase of the field study rock salt, instead of sand-chloride, was to be applied for routine ice control to concrete pavements at approximately fifty designated locations throughout the central part of the state, the work to be done by Department maintenance methods and in cooperation with the various county and district maintenance engineers. All locations selected for the second type of test were on pavements more than four years old and records were to be kept by the County personnel of the dates and times of salt application, amounts used, temperature at time of application and other pertinent data. Since the field work of this test had not progressed far enough to yield noticeable results by the end of the first winter, (1944-1945) only the tests conducted at the Michigan Test Road and vicinity will be discussed at this time.

Description of Tests

The locality chosen to provide sites for the controlled freezing and thawing tests had several important advantages. Winters are rigorous, allowing almost daily cycles of freezing and thawing. Experienced operators who had conducted similar tests on the durability project of the test road were available to carry on the work, and unscaled sections of pavement on

US 10 ranging in age from 6 to 9 years in yearly intervals lay within a few miles of the test road. The following paragraphs describe briefly the materials used, location and construction of test panels, test procedure and data obtained.

Materials: Rock salt and flake calcium chloride conforming to standard specifications of the Department, and a commercial evaporated fine salt were used in the tests.

The calcium chloride was a well-known brand meeting the following requirements as to chemical composition:

Calcium Chloride, CaCl_2 (anhydrous)	77% Min.
Magnesium Chloride, MgCl_2	0.5% Max.
Total alkali chlorides	2.0% Max.
Other impurities	1.0% Max.

Chemical analyses of the rock salt and evaporated fine salt (Table I) show that the evaporated salt was of a high degree of purity, but that the rock salt contained an appreciable amount of calcium sulphate.

TABLE I
CHEMICAL ANALYSES OF ROCK SALT AND EVAPORATED SALT

	<u>Rock Salt</u>	<u>Evaporated Salt</u>
Moisture, as received, percent	0.62	0.65
Calculated composition (dry basis) percent		
CaSO_4	1.65	0.06
MgCl_2	0.42	0.11
CaCl_2	0.06	0.24
$\text{Fe}_2\text{O}_3, \text{Al}_2\text{O}_3, \text{SiO}_2$	0.69	0.04
NaCl (by difference)	97.18	99.55

Location and Construction of Test Panels: Six test areas were laid out at the locations given in the following table:

TABLE II
LOCATION OF TEST AREAS

<u>Test Area Number</u>	<u>Route</u>	<u>Project</u>	<u>General Location</u>	<u>Station</u>	<u>Built</u>	<u>Age Years</u>
1	M-115	18-20,03	Series 4E Cement No. 1	464+00	10-1940	4
2	M-115	18-20,03	Series 4I Cement No. 2	499+55	10-1940	4
3*	US-10	18-16,09	M-115 to Lake Station	860+00	5-1938	6
4*	US-10	18-16,09	M-115 to Lake Station	893+00	11-1937	7
5	US-10	18-10,06	Clare to Farwell.	71+00	7-1936	8
6	US-10	18-16,01	Farwell to M-115	300+00	6-1935	9

* Project 18-16,09, Stations 830+00 to 862+00 constructed in 1938. Balance constructed in 1937.

Each test area consisted of three sections, one each for tests with rock salt, fine salt, and calcium chloride. These sections were each 2 feet wide, 18 feet long, and dyked at the boundaries by means of 3/4 inch wooden strips cemented and sealed to the pavement surface with tar. Additional dykes were added to each section across the short dimension to facilitate the daily work and create a more uniform layer of water or ice over the surface of the pavement. Figure 1 shows a view of a typical test area after the installation of panels.



Figure 1. Typical installation of test panels.

Test Procedure: The test procedure adopted was essentially the same as that used in the accelerated scaling studies conducted on the Durability Project of the Test Road during the winters of 1940-1941 and 1941-1942. Water was added to each section of the test area to a depth of 1/4 inch and allowed to freeze over night. The following morning commercial rock salt, evaporated fine salt and calcium chloride were applied to their respective panels at the rate of 5 pounds per 36 square feet. After decomposition of the ice, the surface of the pavement was cleared, flushed and again covered with water to a depth of 1/4 inch. This constituted a daily cycle of freezing and thawing. When scaling occurred the amount was determined at each successive cycle by superimposing a grid with cross pieces 12 inches apart on the test panel and estimating the extent of the affected area.

Test Results: Freezing and thawing with the two types of sodium chloride was begun January 23, 1945 and thirty cycles had been completed when the tests were discontinued on March 10, 1945. The calcium chloride tests did not get under way until January 30th, and ran for 26 cycles. At test area No. 1, located on the durability project of the Michigan Test Road (standard construction, brand No. 1 cement), the calcium chloride was applied to concrete of an adjoining series containing Orvus. Complete data of the study are given in Table III.

Discussion of Results

The data obtained from this study throw some light on the subject of age effect and the comparative effect of different types of chloride used, which topics will be discussed in order. There is, however, a third important factor which must be considered in connection with the age effect. This factor is the quality of the original concrete. Although no data of

this kind were obtained in the present field study, all of the test areas being located on unscaled and apparently sound concrete, the subject of the effect of quality on the subsequent scaling of concrete will be touched on here because of its association with the age effect.

TABLE III

SUMMARY OF DATA FROM CONTROLLED FIELD STUDIES

Test Area Number	Age Years	Percent Scale		
		30 cycles Fine Salt	Rock Salt	26 cycles Calcium Chloride
1	4	19	38	0*
2	4	8	13	11
3	6	0	0	0
4	7	0	0	0
5	8	0	0	0
6	9	0	0	0

* This panel placed on concrete containing Orvus.

Effect of Age of the Concrete: From the data in Table III it can be seen at once that no significant scaling occurred on any of the concretes 6 to 9 years of age. This is shown by Figures 2A, B, C and D which illustrate the condition of the rock salt panels at test areas 3, 4, 5 and 6 at the end of 30 cycles of freezing and thawing. Figures 3A and 3B show that concrete containing Orvus is still as resistant to the action of calcium chloride as it was three years ago. Both of the four year old concretes scaled to some degree in this test, the extent of the scale in test area No. 1 being more than double that of No. 2. Both, however, have improved definitely in scale resistance since similar tests were made when they were a little more than a year old. The following data are taken from the results of durability tests on the Michigan Test Road during the winter of 1941-1942:

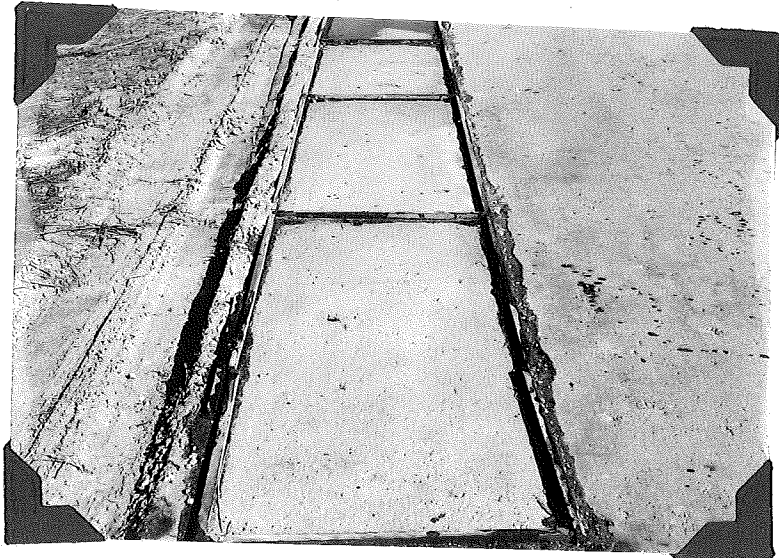


Figure 2A. Rock Salt panel of test area No. 3 after 30 cycles. Concrete 6 years old. No scale.



Figure 2B. Rock Salt panel of test area No. 4 in foreground after 30 cycles. Concrete 7 years old. No scale.

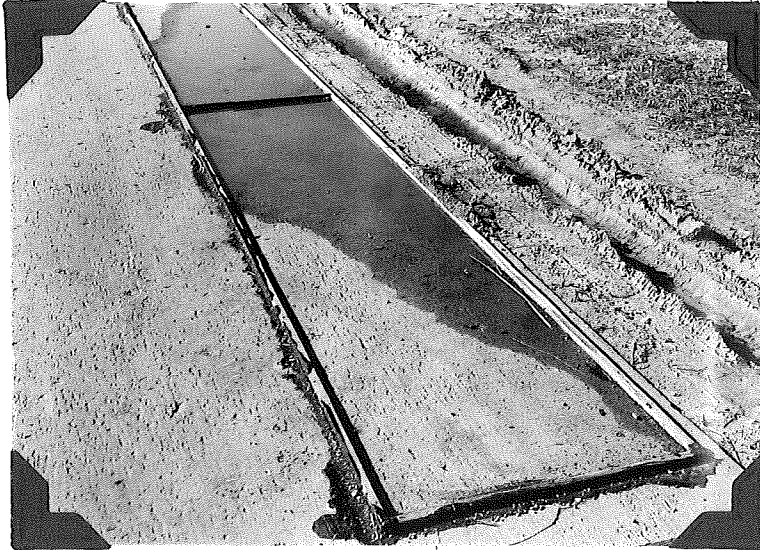


Figure 2C. Rock Salt panel of test area No. 5 after 30 cycles. Concrete 8 years old. No scale.



Figure 2D. Rock Salt panel of test area No. 6 after 30 cycles. Concrete 9 years old. No scale.



Figure 3A. Calcium Chloride panel of test area No. 1 after 26 cycles. Pavement 4 years old containing Orvus. Project 18-20,C3. Station 463+50. No scale.

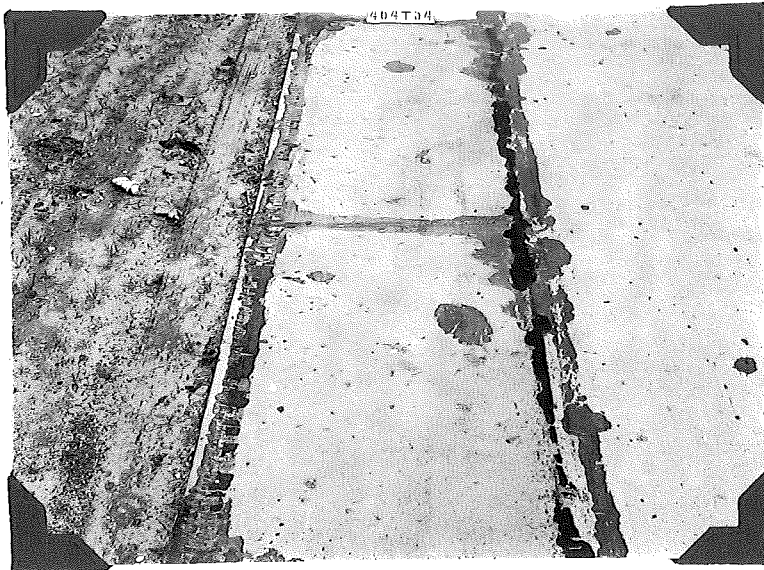


Figure 3B. Calcium Chloride panel No. 12 after 93 cycles. Pavement 1 year old containing Orvus. Project 18-20,C3. Station 464+54. No scale.

<u>Factor Studied</u>	Scaling Studies 1941-1942		
	<u>Panel No.</u>	<u>Cycles</u>	<u>Percent Scale</u>
Standard Construction			
Cement Brand No. 1	11	41	100
Cement Brand No. 2	21	32	100
Cement Brand No. 1	27	9	100
Cement Brand No. 2	16	9	100
Cement Brand No. 2	34	7	100
Cement Brand No. 2	33	9	100

Calcium chloride was used in the tests recorded in the above table. Note that all concretes of standard construction scaled 100 percent in 7 to 41 cycles, with the majority failing completely at less than 10 cycles. At four years of age, concretes of the same materials and construction show a maximum of 38 percent scale at 30 cycles of freezing and thawing. Photographs illustrating the condition of standard concrete in Series 4I of the durability project containing cement brand 2 after tests at ages of 1 and 4 years are shown in Figures 4A and 4B. The conclusions to be drawn from the foregoing data confirm prevailing opinion that there is a progressive beneficial effect of age on the resistance of good concrete to scaling from the action of chloride salts. For these pavements, and under the conditions of this test, the minimum age for practical immunity seems to lie somewhere between 4 and 6 years.

Effect of Type of Chloride Used for Ice Control: Again referring to Table III, it may be seen that, on the two areas where scaling occurred, the action of rock salt was considerably more vigorous than that of the evaporated fine salt. Although it is dangerous to draw final conclusions from the limited data available, the wide difference between the severity of action of the two sodium chloride salts is certainly significant, and

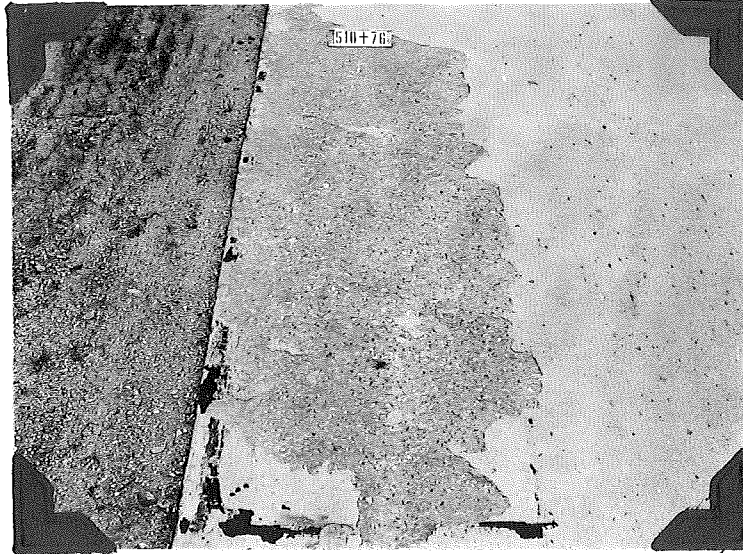


Figure 4A. Calcium chloride panel No. 16 after 9 cycles. Pavement 1 year old containing cement brand No. 2. Project 18-20,C3. Station 510+76. 100 percent scaled.



Figure 4B. Calcium chloride panel of test area No. 2 after 26 cycles. Pavement 4 years old containing cement brand No. 2. Project 18-20,C3. Station 500+50. 11 percent scaled.

additional field tests should be performed to verify the results of this phase of the study. Photographs in Figures 5A, B, C, and D show the relative effect of the two types of sodium chloride at 30 cycles.

Because of the fact that scaling occurred on only two of the areas, one of which did not receive calcium chloride on a section of standard concrete, we have the data from only one set of panels from which to make a comparison of the effect of calcium chloride and sodium chloride salts. At test area No. 2, where these panels were located, 11 percent of the surface was scaled by calcium chloride compared to 8 and 13 percent by fine salt and rock salt respectively. Since the section treated with calcium chloride was subjected to only 26 cycles of freezing and thawing as against 30 cycles for the sodium chloride panels, it appears that rock salt and calcium chloride were about equal in scaling power, with the fine salt producing noticeably less effect than either. The photograph of the calcium chloride section of test area No. 2 shown in Figure 4B may be referred to for comparison with those of the rock salt and fine salt sections of the same test area given in Figures 5C and 5D.

Effect of Quality of the Concrete: The purpose of this paragraph is to emphasize the fact that initially poor concretes cannot be expected to derive benefit in salt resistance from the aging process. Characteristics of the cement, quality and grading of the aggregates, proportioning and placing of the mix, finishing, and curing all have an influence on permeability to salt solutions and subsequent durability. Figure 6 illustrates the effect of chlorides on a concrete pavement 12 years old carrying inferior aggregates. Even air-entraining agents cannot be expected to protect such aggregates (5) (6). The most essential requirement of a potentially resistant portland cement concrete constructed without air-

entraining agents is a dense, more or less impermeable surface which prohibits the entrance of water and salt solutions. In such a concrete, impermeability of "tightness" will increase with age. Some or all of these considerations may have influenced some authors to modify the statement referred to in the introduction of this report to read "unscaled pavements more than four years old - - - - " (3) (4). There may be pavements, however, which are fundamentally sound, and still show a light surface scale due to laitance formed by excessive manipulation at the time of placing the concrete. Unless the scaling has been progressive, it may be taken for granted that the concrete is sound and its condition can be considered to come within the meaning of the term "unscaled".

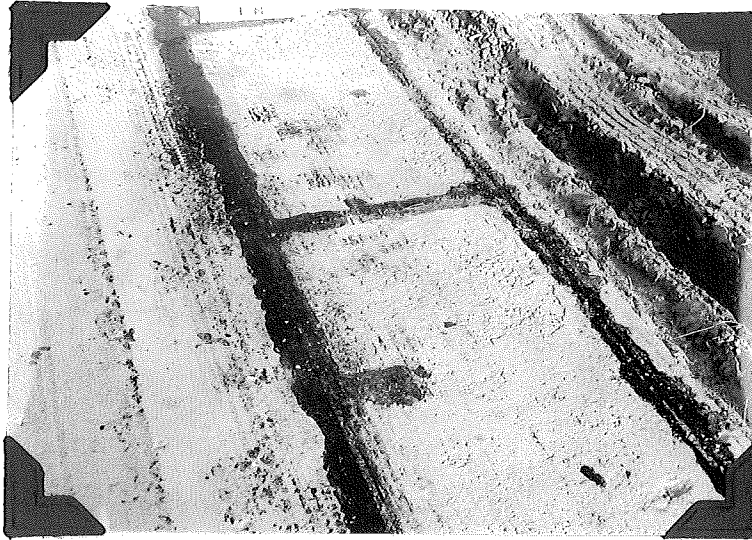


Figure 5A. Fine salt panel of test area No. 1 after 30 cycles. 19 percent scaled.

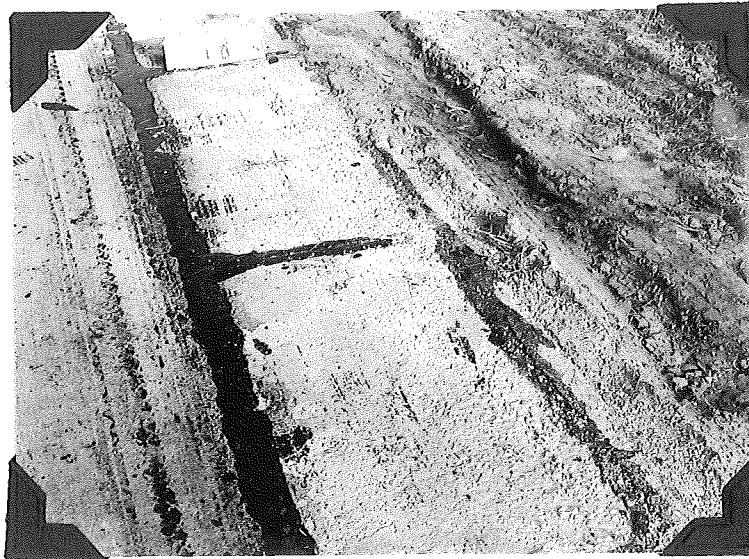


Figure 5B. Rock salt panel of test area No. 1 after 30 cycles. 38 percent scaled.

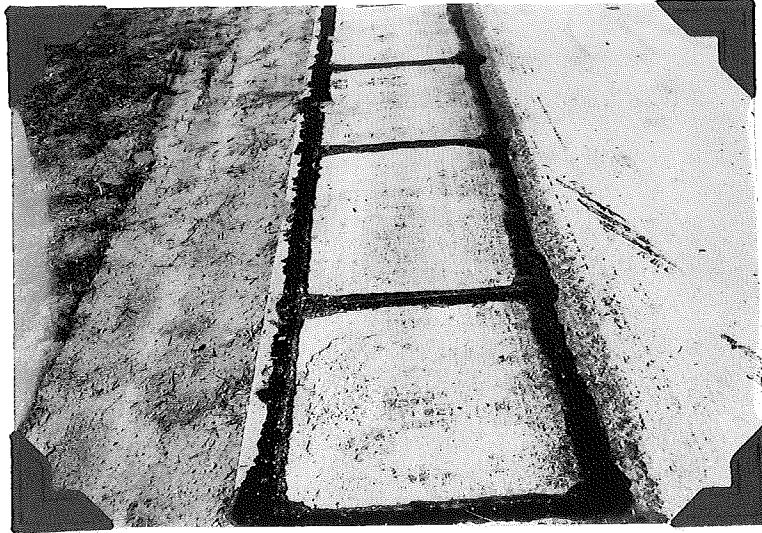


Figure 5C. Fine salt panel of test area No. 2 after 30 cycles. 8 percent scaled.

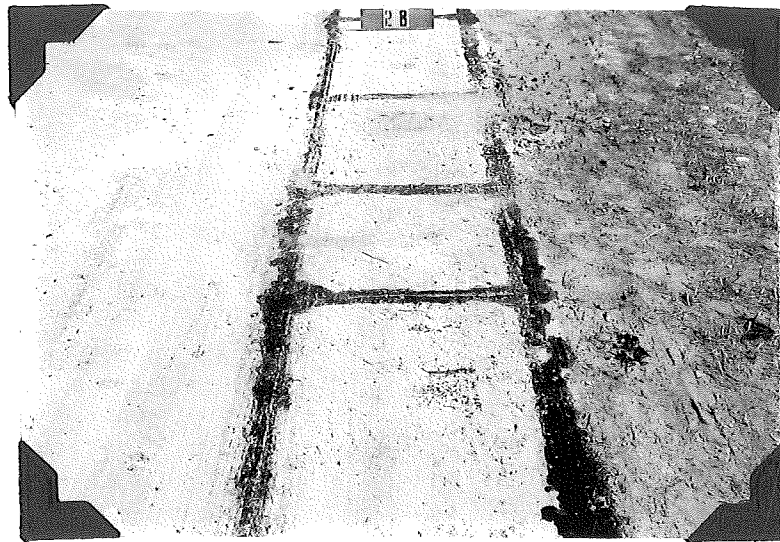


Figure 5D. Rock salt panel of test area No. 2 after 30 cycles. 13 percent scaled.

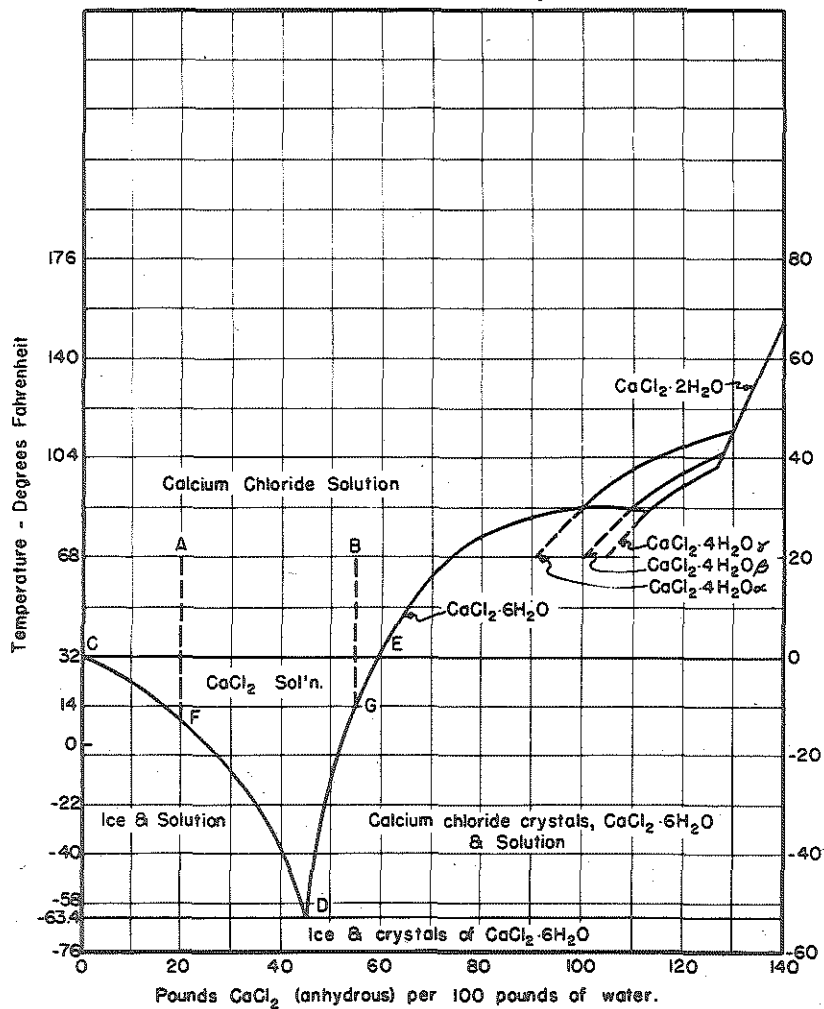


Figure 6. Photograph showing the effect of chloride salts on concrete containing inferior aggregates.

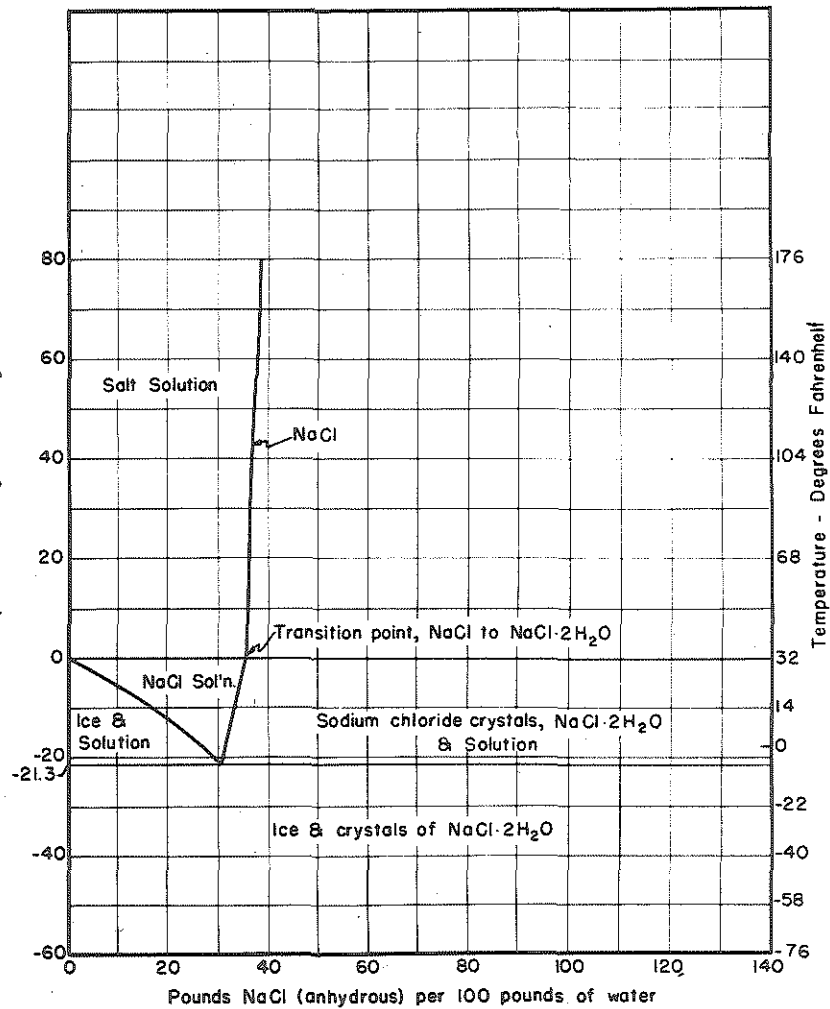
PROPERTIES OF SALT SOLUTIONS AND PHASE RELATIONS

In addition to the field tests described in the preceding paragraphs supplementary studies were undertaken in the laboratory to obtain further information of value bearing on the subject, and to aid in the interpretation of the field data. This part of the work should properly include a brief review of some of the properties of calcium and sodium chloride solutions and phase relations of the system salt-water-ice, because of their important bearing on the whole subject of melting snow and ice by the addition of chloride salts.

In order to fix in mind some of the fundamental principles involved in the action of salts on ice and snow, attention is called to the equilibrium diagrams presented in Figure 7. These diagrams give all of the conditions of equilibrium, exclusive of the vapor phase, which exist in the two systems CaCl_2 -water-ice and NaCl -water-ice at normal atmospheric pressure, and are of considerable practical value in the study of salt action on ice or snow. Both of the diagrams were prepared from solubility and freezing point data of the pure salts (7), but may be applied without appreciable error to the materials used in this investigation. For the purpose of the present discussion, attention will be confined to the portions of the two diagrams which lie below the normal freezing point of pure water (32°F).



CALCIUM CHLORIDE



SODIUM CHLORIDE

EQUILIBRIUM DIAGRAMS FOR SALT SOLUTIONS AT ATMOSPHERIC PRESSURE

Referring to the first diagram in Figure 7, CD represents the freezing point curve of aqueous solutions of calcium chloride and DE the solubility curve of calcium chloride in water at temperatures below 32°F. Interpreting the curves, this means that at concentrations of calcium chloride of less than 45 pounds of the salt to 100 pounds of water, only ice can exist in contact with the solution at temperatures from 32°F. down to the eutectic point D at - 63.4°F, and that at greater concentrations than this, calcium chloride hexahydrate is the only possible solid phase in the same temperature range. Two examples will illustrate. First, suppose we start with a solution of 20 pounds of calcium chloride in 100 pounds of water at 68°F. (point A on the diagram) and then cool it gradually. No solid phase will form from the solution until the freezing point curve CD is reached at point F, corresponding to a temperature of about 6°F. At this point solid ice begins to form which automatically increases the concentration of salt by removal of some of the solvent from the liquid phase, and, on further cooling, ice continues to form at temperatures and concentrations of salt solution represented by the curve CD until the eutectic point D is reached where the whole solidifies into a mass of ice and calcium chloride crystals. Below the point D no liquid phase can exist.

Now suppose we take a solution containing 55 pounds of calcium chloride, instead of 20 pounds, per 100 pounds of water and cool in the same manner. Here no solid phase will leave the solution until point G (14°F.) on the solubility curve DE is reached. At this point solid crystals of the hexahydrate of calcium chloride, $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, begin to form and, on further cooling, more of the salt continues to crystallize from the solution due to its decreased solubility at lower temperatures. Calcium chloride crystals constitute the only solid phase in contact with the

solution, and, on still further cooling, continue to form at temperatures and concentrations of the salt solution given by the curve DE until the eutectic point D is again reached. Below this point the whole solidifies into a mixture of ice and salt crystals as before. From these examples, it may be seen that only at the single point D, corresponding to a concentration of about 45 pounds of chloride (anhydrous) to 100 pounds of water at a temperature of -63.4°F . is it possible for both solid phases to exist simultaneously in contact with the solution.

The two preceding examples serve to present a general picture of the equilibrium conditions encountered in the use of calcium chloride for ice control. Of more particular significance from our standpoint, however, is the reverse process, which takes place when salt is used to melt ice. In other words, what happens if, instead of starting with a given calcium chloride solution and cooling to below 32°F ., we now take a definite amount of calcium chloride, say 10 pounds, and add it to an excess of ice at a given temperature, say 0°F ? If the temperature is kept constant, it may be seen at once from the freezing point curve CD of the diagram that this quantity of calcium chloride will melt sufficient ice to produce a solution in equilibrium with ice at the given temperature. The amount of ice melted by the 10 pounds of chloride is perfectly definite at this temperature and may be computed directly from the curve. At 0°F . a solution of calcium chloride in equilibrium with an excess of ice contains about 25 pounds of the salt per 100 pounds of water. By a simple calculation we find that the 10 pounds of chloride will melt approximately 40 pounds of ice, or 1 pound to 4. The diagram for sodium chloride may be interpreted in a similar way, and it will be found that 1 pound of salt will melt about 3.7 pounds of ice under the same conditions. These

figures agree with the experimental results published by the Committee on Highway Maintenance of the Highway Research Board (8). The element of time is also a factor in the melting process since the addition of salt to ice produces a "freezing mixture" which spontaneously lowers the temperature of the system below that of its surroundings, resulting in a temporary decrease in melting power.

Comparing the two diagrams of Figure 7, it is immediately evident that sodium chloride has no melting power below its eutectic point (about $-6.5^{\circ}\text{F}.$) while calcium chloride continues to melt ice at much lower temperatures. On the other hand, sodium chloride has greater melting power in the region just below the freezing point of water, the margin of superiority decreasing at lower temperatures, and becomes approximately equal to calcium chloride in its ability to melt ice at about $10^{\circ}\text{F}.$ Below this point calcium chloride has the greater melting power. Published data referred to in the preceding paragraph on the melting efficiencies of the two salts are reproduced here as Table IV for convenience.

TABLE IV

COMPARISON OF MELTING CAPACITIES OF CALCIUM AND SODIUM CHLORIDE

<u>Temperature</u> <u>Deg. F</u>	<u>Pounds of Ice Melted Per Pound of Chemical</u>	
	<u>77-80 Percent Flake</u> <u>Calcium Chloride</u>	<u>Pure Sodium Chloride</u>
- 30°F.	2.9	-
- 20	3.2	-
- 10	3.5	-
- 6.5	3.7	3.2
0	4.0	3.7
5	4.4	4.1
10	4.8	4.9
15	5.5	6.3
20	6.8	8.6
25	10.4	14.4
30	31.1	46.3

THE AGE EFFECT

The statement was made earlier in this report that the most essential requirement of a durable portland cement concrete constructed without air-entraining agents is a dense, more or less impermeable surface which prohibits the entrance of water and salt solutions. A natural corollary, then, would state that any factor which tends to produce this kind of surface would improve durability. Herein lies the key to the explanation of the effect of age on the salt resistance of concrete pavements. The two most important processes which tend to increase the impermeability and which progress with age are the gradual closure of capillaries and small voids through the continued hydration of cement compounds, and the formation of an impermeable calcium carbonate skin by atmospheric carbonation of calcium hydroxide on the surface.

Effect of Hydration of Cement Compounds.

Normal concretes of good quality consistently decrease in permeability with age. It is known that hydration of cement particles continues for years after the concrete is placed, which process is accompanied by an increase in strength and slight lengthening of dimensions. The additional hydrated material produced increases the impermeability of the mass, for it occupies a greater volume than the unhydrated material from which it was formed. Porous aggregates, deficient grading of aggregates, poor curing and all the other defects which produce an intrinsically poor concrete will, of course, vitiate the beneficial effect of this process.

Effect of Surface Carbonation

While the gradual closing of the pores with age is taking place in concrete due to continued hydration, another process is going on which

progressively seals the surface against the entry of harmful solutions. This process is the carbonation of calcium compounds in the cement by atmospheric carbon dioxide. It seems to be well established that this reaction increases both the strength and impermeability of concrete (15) (16). In Figure 8 is shown a photomicrograph of the top portion of a concrete specimen prepared from a core 4 years old after immersion of the specimen for 40 days in a 30 percent calcium chloride solution. At the edge of the section corresponding to the road surface a slight discoloration was noticed. The picture shows this discoloration, as well as the absence of cracks in this area. The large piece of aggregate has separated from the cement gel along its entire lower edge, but the crack does not continue along the aggregate boundary nearest the road surface. This example seems to indicate a definite strengthening of the surface layer by carbonation.

Although Gonnerman (2) in his tests on the salt resistance of concrete was not able to produce any beneficial effect by laboratory carbonation of concrete specimens, it is apparent that the necessary condition for successful carbonation of concrete was overlooked. Bessey (16) has shown that carbonation proceeds very slowly in cement products saturated with water, due probably to the slow rate of diffusion of the gas through the water, in which it is only sparingly soluble, and to the formation of a skin of calcium carbonate on the wet surface which the carbon dioxide cannot penetrate. As the water content is reduced by exposure to air at successively lower humidities the absorption of carbon dioxide becomes increasingly rapid. This no doubt explains why Gonnerman, who used saturated solutions of carbon dioxide, was unable to secure the desired effect.

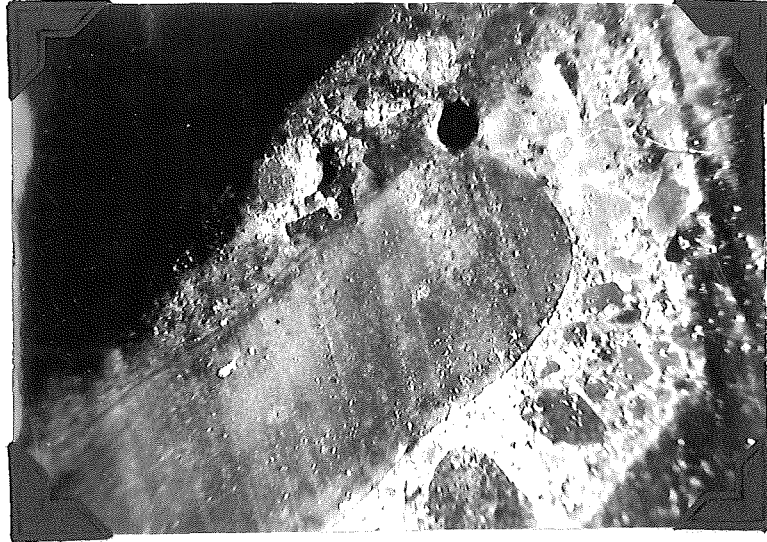


Figure 8. Photomicrograph of a concrete specimen after 40 days' immersion in 30 percent CaCl_2 solution, showing effect of carbonated surface layer. Note absence of cracks at the edge of the specimen. Magnification 40X.

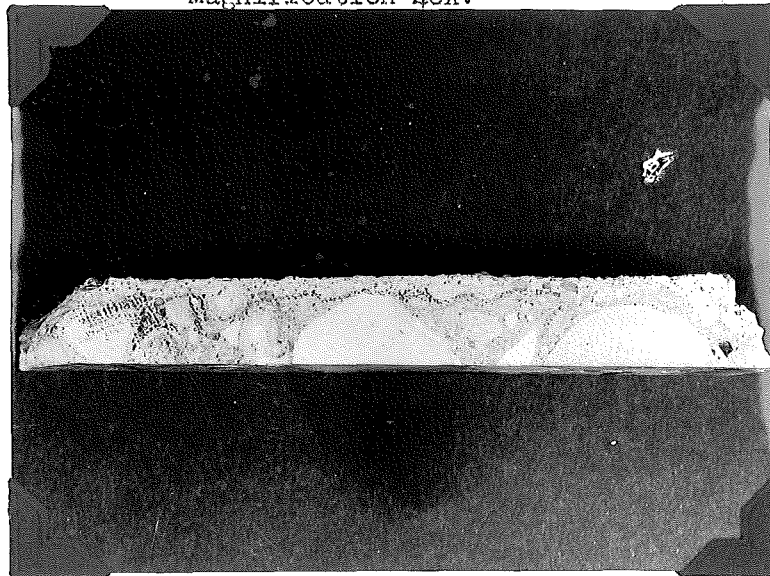


Figure 9. Carbonated layer on the top surface of concrete pavement core 4 years old. This layer is visible as a lighter colored band across the top of the specimen. Photograph about natural size.

Previous experiments in our laboratory, in which carbonation was accomplished by exposure to an atmosphere of carbon dioxide gas indicated definitely beneficial results from the treatment.

It was thought at first that there might be some relation between the depth of carbonation and the age of the concrete. Samples of concrete were taken from several pavements of different ages and specimens prepared for examination by cutting vertical sections about $1/4$ inch thick through the top surface, which were then ground on the faces and stained with phenolphthalein. The carbonated surface was immediately visible as a colorless band in contrast to the brightly colored red of the concrete below, which still contained considerable amounts of basic calcium compounds. This carbonated layer may be seen in the specimen illustrated in Figure 9. Recent determinations of the distribution of calcium hydroxide near the surfaces of concrete cores indicate that partial conversion extends below the colorless margin but the reaction has not progressed sufficiently to neutralize all of the calcium hydroxide present.

The depth to which the carbonation extends in any particular concrete pavement probably depends upon a number of characteristics which are related to its permeability. From the examination of pavements in this manner no correlation was found between age and depth of visible carbonated layer. It should be kept in mind, however, that the permeability of this carbonate skin is not necessarily related to its thickness. The depth of apparent carbonation in samples studied ranged on an average between $1/64$ and $1/16$ of an inch.

Several other factors usually incident with age, but not involved in chemical or physical changes in the concrete itself, may contribute to increasing immunity of pavements with time. Among these may be mentioned the protective effect of crank case oil drippings, silting of external pores in the concrete, and possibly a sealing action due to traffic.

SUMMARY

The combined results of the field and laboratory studies may be summarized as follows:

1. Aging of normal concrete of good quality is beneficial in increasing its resistance to the action of chloride salts used for ice control.
2. For the pavements tested in this investigation, and under the conditions of this test, some scaling occurred on pavements 4 years old, but none was observed on pavements 6 to 9 years of age. The scaling on the pavement 4 years old was less than when similar tests were conducted on the same pavement at the age of one year.
3. Concrete of poor quality does not improve in salt resistance with age.
4. The age effect is considered to be due primarily to the gradual continuation of the hydration process in the cement, and to the formation of a strong, impermeable carbonate skin through the reaction of lime compounds in the set cement with atmospheric carbon dioxide. Other external factors, such as the deposition of oil films from crankcase drippings incident with age and associated with traffic conditions, may contribute somewhat to the improved salt resistance of pavements with time.
5. Where scaling occurred on the test sections of the 4 year old concrete, rock salt and calcium chloride were about equal in severity of action with evaporated fine salt producing a noticeably less effect than either.

6. Calcium chloride has greater ice melting capacity than sodium chloride below 10°F., above this point the reverse is true.
7. The use of raw chloride salts will probably not be as effective on concrete pavements as on the darker bituminous surfaces due to the higher temperatures attained at the surface of the latter from the absorption of radiant heat.
8. Under most circumstances chloride salts can be used without abrasives for bare pavement maintenance, provided they are used in sufficient amounts during the period of moderate temperatures which usually prevail during and immediately after a snow storm. If, however, application is delayed until the temperature falls again to a point below about 10°F., it may be difficult or even impossible to melt the ice sufficiently to eliminate traffic hazards by this method. In such cases the use of abrasives with salt would probably have to be resorted to in order to prevent skidding.

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Although the field studies utilizing routine ice control methods have not progressed far enough to yield noticeable results at present, the author wishes to express his thanks also to the Maintenance Division and all of the District and County Engineers taking part in this phase of the work for their full and unfailing cooperation at all times.

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