Ice Removal on Highways and Outdoor Storage of Chloride Salts

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This study was undertaken to determine the comparative effectiveness of chloride salts and abrasive-chloride salt mixtures for ice removal, and also to study the storage characteristics of sodium chloride, calcium chloride, and mixtures of these materials. Controlled, field ice-removal tests were run on 15 combinations of materials within three temperature ranges. Data were collected on thickness of ice, actual quantity and location of chemical or abrasive applied, and periodic condition of the ice with regard to amount of ice removed. The outdoor storage characteristics of seven bulk materials and one packaged material under a light polyethylene sheeting were studied. The materials were sampled for moisture, crusting, and caking for a period of ten months.

A mixture of ⅓ $CaCl_2$ and ⅔ NaCl appears to be one of the better economical materials for ice removal, and this mixture was found to store well in bulk for a period in excess of ten months. Straight NaCl was found ineffective in clearing a wheelpath within a 60-min time period as compared with the mixture of ⅓ $CaCl_2$ and ⅔ NaCl. Also, NaCl cannot be stored outdoors in bulk longer than two months without considerable caking. Mixtures of salt, with abrasive were found to be relatively ineffective for removing ice below about 15 F. Further research on similar and additional chemicals should be conducted under well-controlled field conditions.

• THE INCREASED daily use of highways throughout the country has brought on a demand for safer and more efficient roadways for use during every season of the year. One of the largest problems confronting engineers charged with the maintenance of these streets and highways in the northern areas is the efficient removal of accumulated ice and snow.

Years ago, efforts to make roadways safe for motor vehicle travel consisted of the use of mechanical equipment to plow the roadways reasonably free of snow and the use of abrasives to provide some degree of traction on hills and curves. These efforts, however, were confined chiefly to the primary routes. In later years, the use of abrasives became more widespread and it was found that through the use of a mixture of calcium chloride and an abrasive the freezing of the abrasive stockpiles was eliminated. Secondly, it was found the chemical also aided in the embedment of the abrasive material in the ice or compacted snow.

The use of straight calcium chloride and sodium chloride was begun on a limited scale in the late 1920's and early 1930's. Because of an apparent detrimental effect to portland cement concrete pavement containing no entrained air, the use of straight chemicals was not recommended for general use (1) but was recommended where severe conditions existed. In areas where straight chemicals were found necessary it was advisable to plow off the resulting slush to minimize the damage.

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More recently, the use of straight calcium chloride, sodium chloride, and mixtures of these chemicals has gained popularity as compared with the use of abrasives alone or the use of abrasive-chloride mixtures. The primary reason for this popularity, it is believed, is the greater speed with which the straight chemicals provide a cleared wheelpath and roadway. Furthermore, there are indications that the total cost of using chemicals alone, particularly in bulk, may be lower than the cost of using the abrasive-chemical mixtures, which involve handling of much larger quantities of materials.

Few reliable published data are presently available concerning the effectiveness of these materials for actual highway use. Consequently, no recommended application rates based on field tests are available. Application thus far has largely been on a trial and error basis according to the judgment of the individual supervisor in charge of winter maintenance.

This study consisted of two basic parts: ice removal and outdoor storage of chloride salts. The ice removal portion was undertaken to determine the comparative effectiveness of chloride salts and abrasive-chloride salt mixtures in the removal of a controlled amount of ice from pavements under field conditions. The tests were conducted within three temperature ranges and using a controlled amount of vehicular traffic. The outdoor storage portion of the study was undertaken to determine the storage characteristics of sodium chloride, calcium chloride, and mixtures of these chemicals when stored outdoors under polyethylene sheeting. The bulk storage of these materials was of prime concern; however, packaged sodium chloride was included to study the problem of caking in some types of paper bags.

ICE REMOVAL

Test Site

The test site selected for this portion of the study was a short section of unopened Interstate highway. The facility is a four-lane divided portland cement concrete-paved roadway with bituminous-surfaced shoulders. Only one roadway of the divided highway was used for the study, the layout of which is shown in Figure 1.

The test sections were 200 ft in length with a distance of 100 ft between test sections to provide a "track-off" area and to minimize carry-over from one test section to another. An over-all view of the site during a test is shown in Figure 2.

Originally it was planned to run the tests primarily on a bituminous-surfaced roadway; however, difficulties in obtaining a suitable test site prevented this. Only one test was performed on a bituminous pavement, that being in the 1961-62 series of tests on the 10-ft bituminous-surfaced shoulder of the Interstate highway.

Site Preparation

Before each test, the site was cleared of snow using snow plows and power brooms. Next, copper constantan thermocouples, AS & W Wire Gauge No. 25, were installed on the roadway surface to measure the ice temperatures throughout the test periods. Figure 3 shows a typical thermocouple installation with the thermocouple tip about 5 in. from the expansion joint near the black tape.

Two additional thermocouples were used to measure air temperature—one was placed in a 2-in. diameter black tube 12 in. in length; the second was placed in a Florence flask. All thermocouple readings were measured with a Leads and Northrup laboratory potentiometer. For comparison, a mercury thermometer was also used for measuring air temperature. A tabulation of the average ice and air temperatures and cloud cover conditions is given in Table 1.

After installation of the roadway thermocouples, water was applied to the test sections using a trailer-mounted water tank and spray bar distributor. The output of the distributor was calibrated and a reasonable speed of the vehicle determined to apply the necessary quantity of water in several passes to produce an ice thickness approximately $\frac{1}{16}$ in. over a width of about 10 ft. Figure 4 shows the equipment and method used to ice the road. The air temperature at the time of ice formation was generally below 15 F.

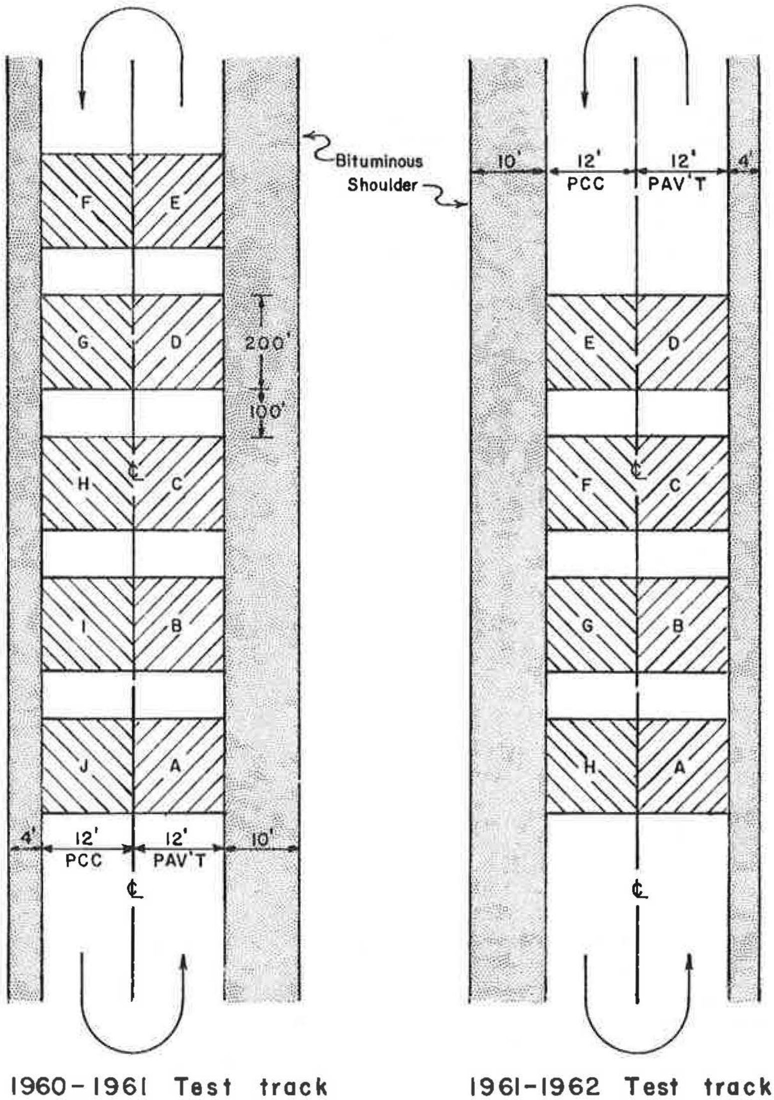

Figure 1. Layout of test sections.

Figure 2. Over-all view of test site.

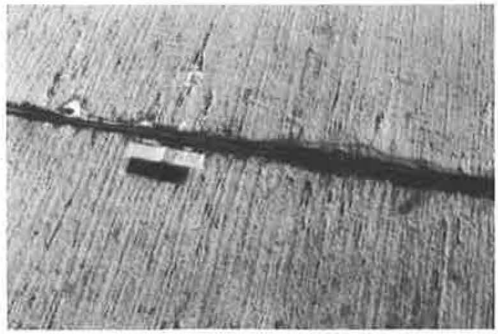

Figure 3. Typical thermocouple installation.

TABLE 1

ICE AND AIR TEMPERATURES

Test No.[a]	Date of Test	Pavement Surface Type[b]	Condition			
			Temperature (°F)			Weather
			Ice	Air	Avg.	
H-1	1-6-61	PCC	32	32	32	Sunny
H-2	1-23-62	Bit.	28	24	26	Variable cloudiness
M-1	1-19-61	PCC	27	12	19.5	Cloudy
M-2	11-11-62	PCC	13	11	12	Cloudy[c]
M-3	2-1-62	PCC	23	12	17.5	Cloudy
M-4	2-7-62	PCC	24	9	16.5	Bright sun
L-1	1-27-61	PCC	15	8	11.5	Partly cloudy
L-2	1-16-62	PCC	12	6	9	Moderate sun
L-3	3-2-62	PCC	15	10	12.5	Slightly sunny

[a]Letter refers to temperature range; number refers to test series.

[b]PCC = portland cement concrete; Bit. = bituminous.

[c]Started snowing during test.

A period of at least 1 hr was provided for the ice to become completely formed before the chemicals and abrasives were applied.

Ice Removal Materials

The ice removal materials selected for comparison in this study were sodium chloride (rock salt and evaporated salt); Type I and Type II calcium chloride flakes; calcium chloride pellets; mixtures of calcium chloride and sodium chloride; a mixture of calcium chloride and sand; and a mixture of sodium chloride and sand. The materials used are identified in Table 2.

The sodium chloride and calcium chloride used in this study met the requirements of AASHO Designation M143-54 and M144-55, respectively. The sand used met the gradation requirements of AASHO Designation M6-51.

Originally, tests were contemplated on a more extensive variety of chemical mixtures. However, after performing three field tests during the winter of 1960-61 and analyzing the results of these; it was decided to eliminate some of the variations in mixtures because the comparative ice removal action between mixtures was not too apparent. At this time it was also decided to include mixtures of chemicals and abrasives in the 1961-62 program of tests because the use of mixtures of these materials is quite common.

Application of Chemicals and Abrasives

In this study the application of chemicals and abrasives was, to a certain extent, a variation of the practices commonly used by maintenance engineers. In the State of Minnesota, straight chemicals are commonly applied in a narrow band along the centerline of two-lane roadways. Abrasives are applied by vehicles straddling the centerline and spreading the material with a disc spinner over both lanes in a single operation; although in some cases, single-lane spreading operations are required and used.

TABLE 2

MATERIALS

Material No.	Sodium Chloride: Rock Salt	Sodium Chloride: Evaporated	Calcium Chloride: Pellets[a]	Calcium Chloride: Flakes Type I[b]	Calcium Chloride: Flakes Type II[c]	Calcium Chloride: Sand
1	1					
2			1			
3				1		
4		1				
5	3/4		1/4			
6	2/3		1/3			
7	3/4			1/4		
8	2/3			1/3		
9			1/2			1/2
10	1/2					1/2
11	1/2		1/2			
12	1/2			1/2		
13					1	
14	1/2				1/2	
15	3/4				1/4	

[a]AASHO M 144-57 concentrated pellet calcium chloride, 94 percent minimum purity.
[b]AASHO M 144-57 regular flake calcium chloride, 77 percent minimum purity.
[c]AASHO M 144-57 concentrated flake calcium chloride, 94 percent minimum purity.

Figure 4. Applying water to ice road.

In this study, chemicals were applied in a narrow band approximately 3 ft out from the centerline using the chemical dribbler shown in Figures 5, 6, and 7.

In Figure 6, the application of evaporated salt is shown to produce a very narrow band of chemical on the roadway, whereas in Figure 7 the mixture of calcium chloride and sodium chloride is shown to scatter considerably. Similar scattering was noted with straight calcium chloride pellets as well as with rock salt. The calcium chloride flakes, however,

Figure 5. Chemical dribbler.

Figure 6. Dribbler applying evaporated salt.

Figure 7. Dribbler applying calcium chloride and sodium chloride mixture.

Figure 8. Disc spinner applying abrasive mixture.

scattered less than the calcium chloride pellets or rock salt but more than the evaporated salt.

Equipment used for applying the abrasive mixtures is shown in Figure 8. This equipment produced the least degree of uniformity of applied materials to the roadway although it is probably one of the more extensively used pieces of winter maintenance equipment.

The width of application of abrasives varied from about 3 ft to 10 ft; however, most applications were between 3 and 8 ft wide.

Traffic

Simulated traffic over the test sections consisted of three vehicles of mixed traffic operating with a 1-min headway between vehicles traveling at 15 to 20 mph. The vehicles were one 3-ton dump truck, one ½-ton pickup truck, and one passenger car. This volume of traffic corresponds approximately to 1,440 vehicles per lane per day. Traffic began immediately after all materials were placed and the conditions of spread recorded. Because the vehicle headway remained constant, the data are analyzed on a time basis rather than on vehicle coverage.

Collection of Test Data

The observed data were collected by two rating teams each consisting of two raters. Observations were made and recorded by the rating teams at 15-min intervals throughout the test period. The observations included such items as width, length, and thickness of ice; actual quantity and location of chemical or abrasive applied; forma-

tion of brine; and condition of the ice with respect to the amount of removal. A typical rating sheet is shown in Figure 9 and the observed and calculated data are given in Tables 3 and 4.

INV. 604
SECTION E

ICING DATA:

Date: 2/1/62 — Air Temp. Beg. 16 °F.
Surf. Condition (Not used) — Air Temp. End 15 °F.
Water Applied 600 Ga
Width of Ice 11½' Ft. — Thick. of Ice 1/16 In
Remarks

SALT APPLICATION DATA:

Date: 2/1/62 — Humidity (Not Determined)
Initial Surf. Cond. (Not Used)

Chemical Used NaCl (Rock Salt) — Salt Application Rate 263 #/lane/mile
Rel. Length of Appl/-Beg. +6 — Width of Application 3½' to 4½'
End +15 — Location of Application 1'-5½' & ½'-4'
Traffic: 1440 vplpd — Remarks

ICE REMOVAL RATING:

Time	Formation of Brine	Condition of Ice: Total	IWT	OWT	Width Affected	Cleared Area	Flaking Off	Tracking Off Section	General Comments
15	G	—	Hc - Sc	Brine Running	5' 1'-6'	15% IWT	—	80'	—
30	D	—	Sc - Cl	✓	✓	1'-5' 90%	—	100'	—
45	✓	—	Cl	✓	✓	1'-5' 100%	—	✓	S. end 3' cl 1'-4'
1:00	✓	—	✓	Some Slush	✓	✓	—	✓	✓
1:15	✓	—	✓	✓	✓	✓	—	✓	✓
1:30									
1:45									
2:00									
2:15									
2:30									
2:45									
3:00									
3:15									
3:30									
3:45									
4:00									

Note:
G = Good
D = Done
Hc = Honeycombed
Sc = Scabby
Cl = Clear

Figure 9. Typical rating sheet.

TABLE 3

OBSERVED AND CALCULATED DATA

Icing Data				Chemical and Abrasive Application						
Test No.[a]	Average Width (ft)	Computed Thickness (in.)	Planned (lb per lane-mile)	Test Section Applied		Measured Width (ft)	Measured Length (ft)		Computed Weight[c]	
				60-61[b]	61-62		Total	On Ice	Lb per Lane-Mile	Lb per Sq Yd
H-1-1	9	0.075	250	A		4.0	208	187	240	0.10
H-2-1	8	0.056	275		E	3.5	157	157	350	0.17
M-1-1	10	0.075	250	A		4.0	190	190	263	0.11
M-2-1	9	0.077	275		E	4.5	215	200	256	0.10
M-3-1	12	0.045	275		E	4.0	209	194	263	0.11
M-4-1	9	0.078	275		E	4.5	137	137	402	0.15
L-1-1	9	0.075	250	A		4.0	170	170	294	0.13
L-2-1	8	0.055	350		E	4.0	139	139	503	0.21
L-3-1	8	0.065	350		E	2.5	242	197	289	0.19
H-1-2	9	0.075	250	D		4.0	235	194	213	0.09
H-2-2	8	0.056	275		A	3.5	198	198	278	0.14
M-1-2	10	0.075	250	D		2.5	223	190	224	0.15
M-2-2	9	0.077	275		A	3.5	204	200	270	0.13
M-3-2	12	0.045	275		A	5.0	202	197	272	0.09
M-4-2	9	0.078	275		A	4.5	175	175	314	0.12
L-1-2	10	0.075	250	D		4.0	240	200	208	0.09
L-2-2	8	0.055	350		A	3.5	235	200	298	0.15
L-3-2	9.5	0.065	350		A	6.0	200	200	350	0.10
H-1-3	9	0.075	250	J		3.0	231	200	217	0.12
H-2-3	8	0.056	275		B	3.0	147	141	374	0.21
M-1-3	10	0.075	250	J		3.0	186	186	269	0.15
M-2-3	9	0.077	275		B	3.5	212	200	259	0.13
M-3-3	12	0.035	275		B	4.0	187	187	294	0.13
M-4-3	9	0.078	275		B	3.0	160	160	344	0.19
L-1-3		0.075	250	J		1.5	202	198	248	0.29
L-2-3	8	0.055	350		B	2.8	162	162	432	0.27
L-3-3	9.5	0.065	350		B	3.5	180	180	389	0.19
H-2-4	8	0.056	275		G	3.0	169	169	325	0.19
M-2-4	9	0.077	275		G	4.0	170	170	324	0.14
M-3-4	12	0.045	275		G	2.5	202	196	136	0.19
M-4-4	9	0.078	275		G	2.5	202	200	272	0.19
L-2-4	8	0.055	350		G	2.5	144	144	486	0.33
L-3-4	9.5	0.065	350		G	2.0	220	200	318	0.27
H-1-5	9	0.075	250	B		6.0	227	180	250	0.06
H-2-6	8	0.056	275		F	3.5	137	137	401	0.20
M-1-5	10	0.075	250	B		4.0	200	200	250	0.16
M-2-6	9	0.077	275		F	4.0	182	182	302	0.16
M-3-6	12	0.045	275		F	4.0	174	174	302	0.13
M-4-6	9	0.078	275		F	6.0	150	150	367	0.14
L-1-5	9	0.075	250	B		4.5	191	191	263	0.10
L-2-6	8	0.055	350		F	4.3	143	143	490	0.19
L-3-6	9.5	0.065	350		F	3.5	210	200	333	0.16
H-1-7	9	0.075	250	G		2.5	226	200	250	0.17
H-2-8	8	0.056	275		C	3.5	139	139	396	0.19
M-1-7	10	0.075	250	G		3.5	189	189	265	0.13
M-2-8	10	0.077	275		C	4.0	196	196	281	0.12
M-3-8	11	0.045	275		C	4.0	181	181	304	0.13
M-4-8	9	0.078	275		C	2.5	137	137	401	0.27
L-1-7	9	0.075	250	G		3.0	191	185	279	0.15
L-2-8	8	0.055	350		C	2.5	140	140	500	0.34
L-3-8	9.5	0.065	350		C	5.0	204	200	344	0.34
H-2-9	8	0.056	275		H	10.0	241	200	157	0.04
M-2-9	9	0.077	275		H	7.0	210	190	261	0.08
M-3-9	11.5	0.045	275		H	9.5	227	200	167	0.04
M-4-9	9.5	0.078	275		H	5.0	215	190	177	0.09
L-2-9	8	0.055	350		H	2.8	195	177	244	0.15
L-3-9	9.5	0.065	350		H	5.5	191	191	249	0.08
H-2-10	8	0.056	275		D	8.0	133	133	323	0.07
M-2-10	10	0.077	275		D	5.0	189	159	228	0.08
M-3-10	10.5	0.045	275		D	3.0	221	200	194	0.11
M-4-10	9	0.078	275		D	5.5	215	200	200	0.06
L-2-10	8	0.055	350		D	2.7	183	183	376	0.24
L-3-10	9.5	0.065	350		D	4.0	210	170	256	0.11
L-1-11	9	0.075	250	C		4.0	207	200	258	0.11
H-1-11	9	0.075	250	C		7.0	231	179	259	0.06
M-1-11	10	0.075	250	C		4.0	210	193	230	0.10
L-1-12	9	0.075	250	I		3.0	200	200	250	0.14
H-1-12	9	0.075	250	I		2.5	255	200	216	0.14
M-1-12	10	0.075	250	I		4.0	206	194	243	0.10
L-1-13	9	0.075	250	E		1.5	193	193	258	0.29
H-1-13	9	0.075	250	E		1.5	224	194	223	0.25
M-1-13	10	0.075	250	E		1.5	206	200	243	0.27
L-1-14	9	0.075	250	H		3.5	200	200	250	0.12
H-1-14	9	0.075	250	H		2.5	231	188	222	0.15
M-1-14	10	0.075	250	H		3.5	153	153	325	0.15
L-1-15	9	0.075	250	F		3.0	208	193	258	0.15
H-1-15	9	0.075	250	F		2.0	246	200	203	0.17
M-1-15	10	0.075	250	F		4.0	196	196	255	0.11

[a] Letter refers to temperature range; first number refers to test series; second number refers to material type (Table 2).

[b] Years 1960 and 1961.

[c] Actually applied to the ice.

TABLE 4

OBSERVED ICE REMOVAL DATA

Test No.[a]	100% Brine Formation (min)	Time Required for Ice Removal in 18-In. Wheelpath (min)					Time (min) for Outer Wheel Track to Have	
		10% (Pitted)	15% (Pocked)	40% (Honeycombed)	55% (Scabby)	80% (Clear)	55% Removal (Scabby)	80% Removal (Clear)
H-1-1	45	15	20		30	30	45	90
H-2-1	30				15	30	75	-[b]
M-1-1	30		10	45	75	-[b]		
M-2-1	-[c]	15	30	-[b]				
M-3-1	30			10	30	30	-[b]	
M-4-1	45		15	45	-[b]			
L-1-1	-[c]	15	50	-[b]				
L-2-1	60		15	40	-[b]			
L-3-1	45			15	45	-[b]		
H-1-2	45				15	30	45	75
H-2-2	30				15	30	-[b]	
M-1-2	30			15	-[b]			
M-2-2	-[c]		15	40	60	-[b]		
M-3-2	30				15	15	-[b]	
M-4-2	45			15	45	-[b]		
L-1-2	-[c]	10	25	45	-[b]			
L-2-2	60			10	30	45		
L-3-2	60		15	30	45	90		
H-1-3	45	15	20	30	30	45	45	90
H-2-3	30				15	30	-[b]	
M-1-3	45			15	-[b]			
M-2-3	30		10	-[b]				
M-3-3	20				15	15	-[b]	
M-4-3	30			15	45	-[b]		
L-1-3	-[c]	15	25	50	-[b]			
L-2-3	60			10	15	45		
L-3-3	30		10	25	60	-[b]		
H-2-4	30				15	15	-[b]	
M-2-4	-[c]	-[b]						
M-3-4	30				15	45		
M-4-4	15				15	60		
L-2-4	30				15	75		
L-3-4	45				15	60		
H-1-5	45				15	30	75	120
H-2-6	30				15	15	-[b]	
M-1-5	45		10	45	120	-[b]		
M-2-6	30					15	-[b]	
M-3-6	30			10	15	30	-[b]	
M-4-6	-[c]		15	40	75	-[b]		
L-1-5	-[c]	15	40	-[b]				
L-2-6	75		15	30	45	-[b]		
L-3-6	45				15	30		
H-1-7	30	15	20	30	45	60	60	75
H-2-8	20				20	30	-[b]	
M-1-7	60		15	50	-[b]			
M-2-8	-[c]	10	20	40	-[b]		-[b]	
M-3-8	30					15		
M-4-8	45			15	30	30	-[b]	
L-1-7	-[c]	15	25	75	90	-[b]		
L-2-8	75			15	30	-[b]		
L-3-8	60		15	45	-[b]			
H-2-9	-[c]		15	-[b]				
M-2-9	-[c]	15	30	-[b]				
M-3-9	45			15	45	-[b]		
M-4-9	-[c]	15	25	75	-[b]			
L-2-9	-[c]	15	30	45	-[b]			
L-3-9	60		30	45	60	90		
H-2-10	30				15	45		
M-2-10	-[c]	15	-[b]					
M-3-10	30				15	45		
M-4-10	-[c]		15	40	-[b]			
L-2-10	-[c]	5	15	60	-[b]			
L-3-10	60	15	60	b				
L-1-11	60	15	30	-[b]				
H-1-11	15	30	-[b]					
M-1-11	45	15	30	60	-[b]			
L-1-12	-[c]	15	45	-[b]				
H-1-12	45	15	-[b]					
M-1-12	30	15		30	-[b]			
L-1-13	45	15	-[b]					
H-1-13	45					30		
M-1-13	30			15	60	-[b]		
L-1-14	45		15	30	45	-[b]		
H-1-14	-[c]	10	30	45	-[b]			
M-1-14	60	15		30	60	-[b]		
L-1-15	-[c]	10	30	-[b]				
H-1-15	60	15	-[b]					
M-1-15	60	15	30	75	-[b]			

[a]Letter refers to temperature range; first number refers to test series; second number refers to material type (Table 2).

[b]Condition not achieved within time period of test.

[c]Formation of brine incomplete at end of test.

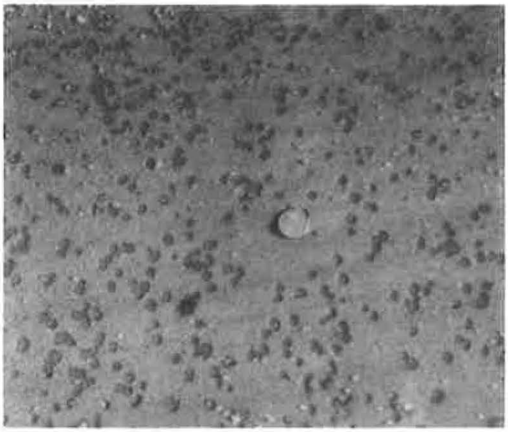

Figure 10. Pocked condition.

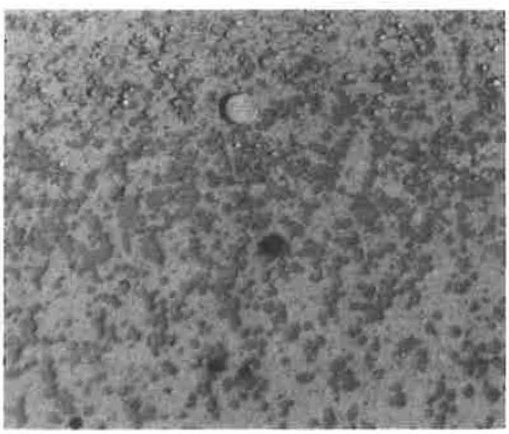

Figure 11. Honeycombed condition.

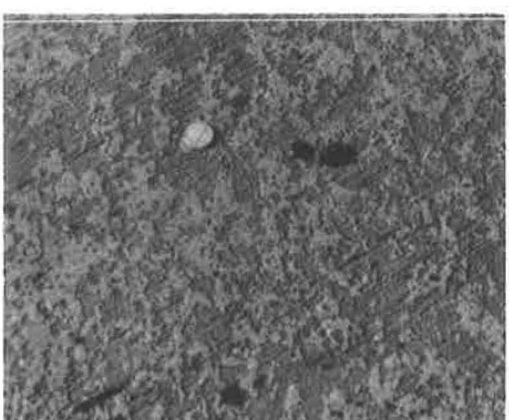

Figure 12. Scabby condition.

Figure 9 and Table 4 show that certain arbitrary standards were established to record the degree of ice removal. The first of these standards was called "pitted." This condition existed when only the ice immediately under the particles of chemical became melted. The second condition was called "pocked" (Fig. 10). In this case, the initial pits have enlarged and bare pavement is beginning to show through.

As melting continues, the holes begin to interconnect as shown in Figure 11 and the third condition, "honeycombed", is achieved. Approximately 40 percent of the ice has melted when the condition "honeycombed" exists.

The fourth condition was called "scabby" (Fig. 12). In this condition only separate fragments of the ice remain on the roadway and approximately 55 percent of the ice has melted. Beyond the "scabby" condition, a "clear" condition was usually achieved where at least 80 percent of the ice had melted and a definite, clear wheelpath was provided.

Temperature Ranges

For the purpose of this report only three temperature ranges are considered; in each case, the temperature of the air is the controlling factor. The low temperature range (0 to 10 F), medium (10 to 20 F), and high (20 to 32 F) are referred to as L, M, and H, respectively. As an example, L-3 would indicate the third test series in the lowest temperature range. It was observed that the ice temperature as measured by the thermocouple was generally significantly higher than the air temperature.

Analysis of Data

Because this portion of the study had so many uncontrolled variables (such as temperature, wind, and humidity), the results are not repeatable. Therefore, the graph plots presented are considered trends based on mean values of the observed and calculated data.

Figure 13 shows a plot of the volume of ice melted by sodium chloride (rock salt) in cubic feet per lane-mile vs time in minutes (vehicle headway remaining constant) for three conditions of average ice and air temperature.

As indicated by the curves, sodium

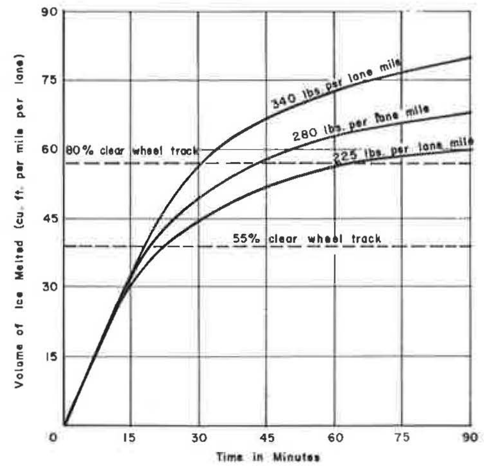

Figure 13. Rate of ice removal for NaCl (rock salt).

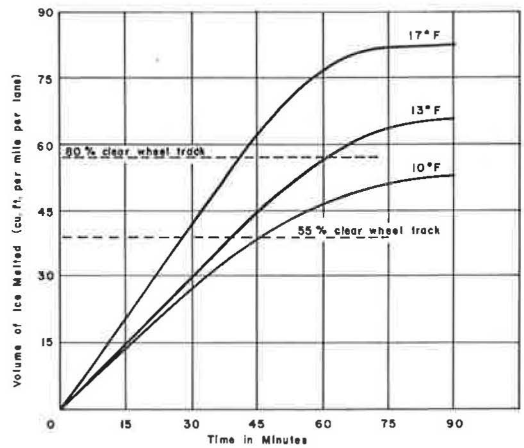

Figure 14. Rate of ice removal by calcium chloride with temperature adjustment.

chloride, with its relatively high eutectic point of -6 F, appears to melt ice at a rate highly dependent on the average of the ice and air temperature. From the observed data, an equation was developed to give a reasonable estimate of the volume of ice that can be melted at a terminal period of 90 min and within a temperature range of 10 to 20 F:

$$V = \frac{R^{1/2}\, T^{1.5}\, k}{I} \qquad (1)$$

in which

V = volume of ice melted (cubic feet per lane-mile);
R = rate of applied salt (pounds per lane-mile);
T = average of air and ice temperature (^{0}F);
I = thickness of ice (inches); and
k = constant with a value of 32×10^{-4}.

The small exponent of R indicates that the rate of rock salt application is of small concern in the rate of ice removal. On the other hand, the large exponent for T indicates that in the case of rock salt, the amount of melt is primarily dependent on the average of ice and air temperatures. The equation also shows that as the ice thickness increases the total amount of melt decreases.

Calcium chloride pellets and flakes have an eutectic point of -58.5 F. Therefore, they do not appear to be as dependent on temperature as sodium chloride for their ice removal rate. Figure 14 is a plot of the volumes of ice melted by calcium chloride pellets at three application rates and with the curves adjusted for temperature differences. The curves show that the amount of thawing is primarily dependent on the amount of calcium chloride applied.

An end-point equation showing this relationship for volume of ice melted with $CaCl_2$ was derived:

$$V = \frac{R^2\, T\, k}{I^{0.8}} \qquad (2)$$

in which

V = volume of ice melted (cublic feet per lane-mile);

R = rate of application of chloride (pounds per lane-mile);
T = average of air and ice temperature (^{0}F);
I = thickness of ice (inches);
k = constant with a value of 6.15×10^{-6}.

In Eq. 2 the rate of ice removal varies as the square of the rate of application of calcium chloride. Therefore, it appears that the more chemical applied, the faster the ice will melt.

The relative rates of ice removal by calcium chloride and sodium chloride are shown in Figures 15, 16, and 17. The comparison at 17 F shows that initially the $CaCl_2$ is more effective but as the action progresses the rate of melting decreases whereas that of the rock salt remains more nearly constant up to about 1 hr and eventually overtakes the rate of the calcium chloride. As shown in Figure 16, the rate of ice removal by rock salt at lower temperatures does not approach that of the $CaCl_2$ pellets. From Figures 16 and 17 it may be concluded that sodium chloride is relatively ineffective below 10 F in clearing a wheelpath within a reasonable period of time.

Figures 18 and 19 are plots of the comparative ice removal rates of calcium chloride (pellets), sodium chloride (rock salt), and a ⅓ calcium chloride (pellet) to ⅔ sodium chloride (rock salt) mixture at 17 and 10 F, respectively. The plots show that the chemical mixture removes ice at a rate closely resembling that of straight calcium chloride while still retaining most of the economical advantage of sodium chloride.

The comparative ice removal rates of sodium chloride (evaporated salt) and the ⅓ $CaCl_2$ to ⅔ NaCl mixture at 17 and 10 F are shown in Figures 20 and 21, respectively. The plots show that initially the rate of ice removal by the evaporated salt is somewhat greater than the pellet-rock salt mixture; however, the evaporated salt is overtaken by the mixture within 30 to 40 min.

Figures 22 and 23 are plots of the comparative ice removal rates of abrasive-chloride mixtures and a ⅓ $CaCl_2$ to ⅔ NaCl mixture. As indicated by the curves the abrasive-chloride mixtures are relatively ineffective for ice removal from pavements particularly at the lower temperatures.

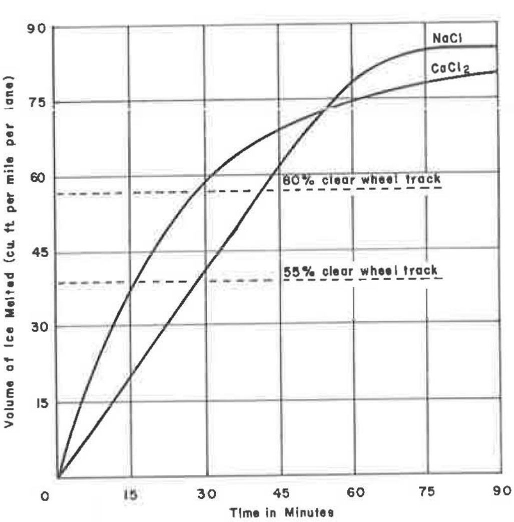

Figure 15. Rate of ice removal by $CaCl_2$ pellets and rock salt at 17 F.

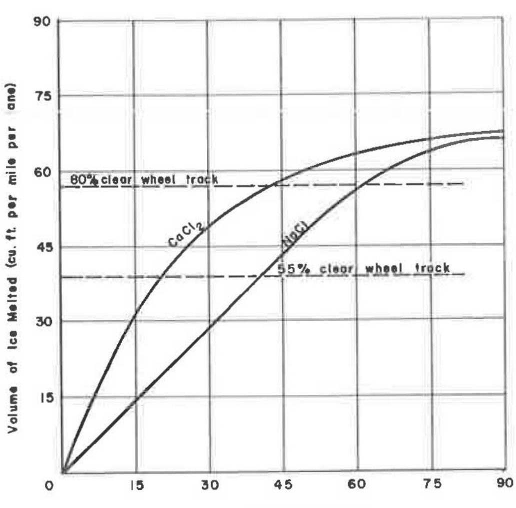

Figure 16. Rate of ice removal by $CaCl_2$ pellets and rock salt at 13 F.

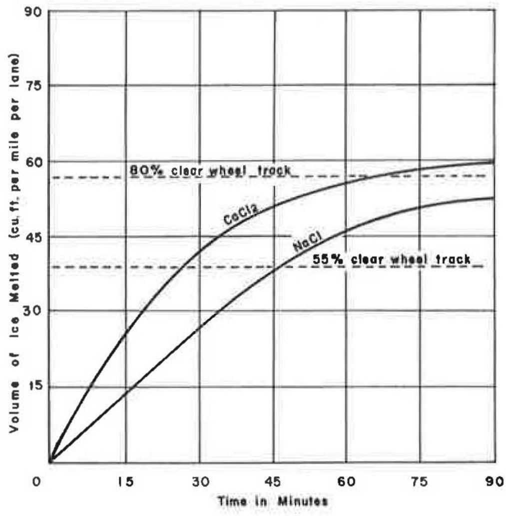

Figure 17. Rate of ice removal by $CaCl_2$ pellets and rock salt at 10 F.

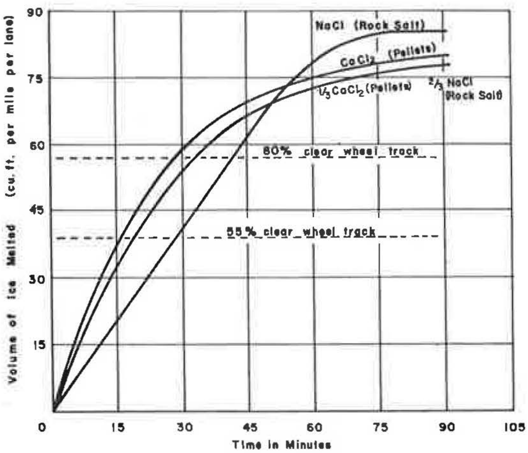

Figure 18. Rate of ice removal by $CaCl_2$ (pellets), NaCl (rock salt), and 1/3 $CaCl_2$ to 2/3 NaCl at 17 F.

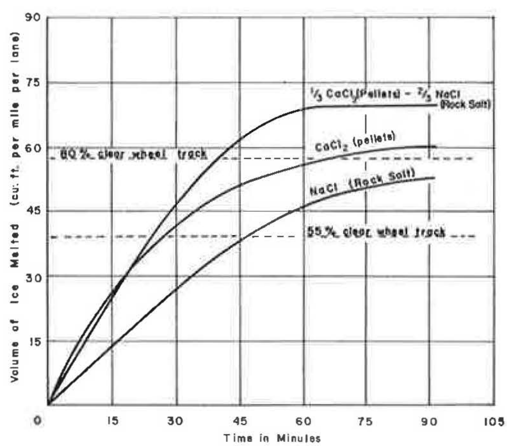

Figure 19. Rate of ice removal by $CaCl_2$ (pellets), NaCl (rock salt), and 1/3 $CaCl_2$ to 2/3 NaCl at 10 F.

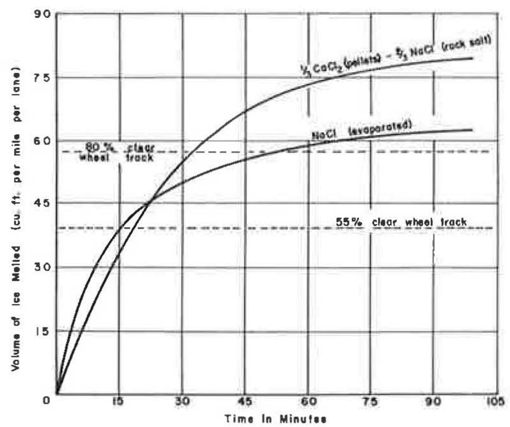

Figure 20. Rate of ice removal by NaCl (evaporated) and 1/3 $CaCl_2$ (pellets) to 2/3 NaCl (rock salt) at 17 F.

Ice Removal Conclusions

On the basis of the limited test data for this study, the following general conclusions are indicated:

1. The amount of melt by sodium chloride (rock salt) is primarily dependent on the average of the ice and air temperatures.
2. The amount of melt by calcium chloride within a given temperature range is proportionate to the amount of chemical applied.
3. The rate of ice removal for both calcium chloride and sodium chloride is similar above 15 F.
4. Below 15 F, calcium chloride was found to be more effective than sodium chloride.

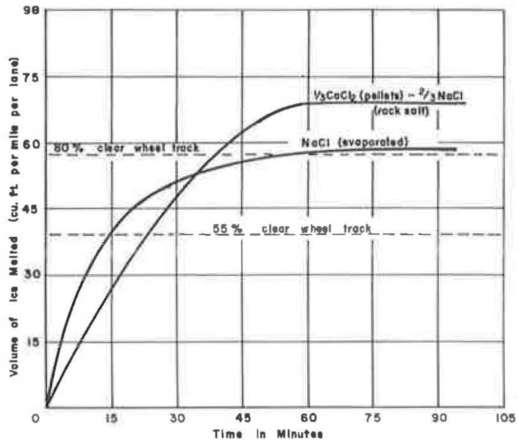

Figure 21. Rate of ice removal by NaCl (evaporated) and ⅓ $CaCl_2$ (pellets) to ⅔ NaCl (rock salt) at 10 F.

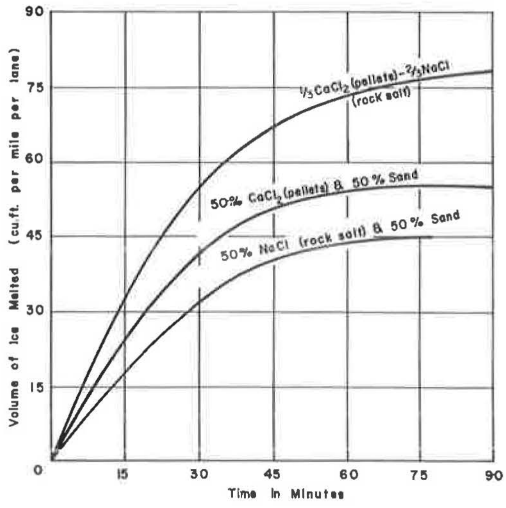

Figure 22. Rate of ice removal by abrasive-chloride mixtures and $CaCl_2$-NaCl mixture at 17 F.

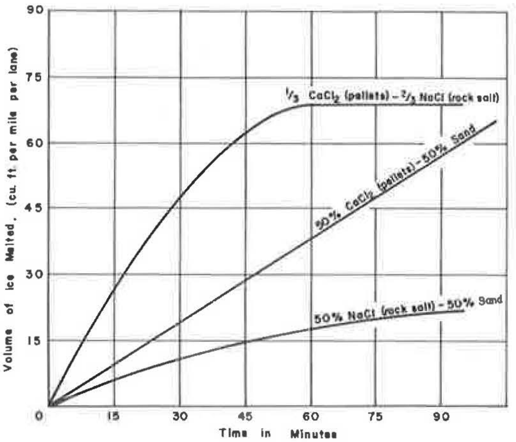

Figure 23. Rate of ice removal by abrasive-chloride mixtures and $CaCl_2$-NaCl mixture at 10 F.

5. Below 10 F, sodium chloride was found to be relatively ineffective in clearing a wheelpath within a reasonable time period of 60 min.

6. The rate of application of sodium chloride should be varied inversely with the temperature.

7. The rate at which both calcium chloride and sodium chloride removes ice is inversely proportional to the ice thickness.

8. Calcium chloride pellets were found to remove ice more rapidly than either calcium chloride flakes or rock salt.

9. A ⅓ $CaCl_2$ to ⅔ NaCl mixture was found to be the only one that provided clear wheelpaths with any consistency. The mixture removed ice at a rate closely resembling that of straight calcium chloride.

10. Sodium chloride (evaporated salt) was found to have a high rate of ice removal in the first 20 min after application, but fell off rapidly after that time.

11. Mixtures of sodium chloride with abrasive and calcium chloride with abrasive were found to be relatively ineffective for ice removal from pavements particularly at temperatures below about 15 F.

OUTDOOR STORAGE OF CHLORIDE SALTS

The primary concern of this portion of the study was the determination of the storage characteristics of bulk sodium chloride, calcium chloride, and mixtures of the two. The decision to include packaged material in the study was based on the problem of salt caking in some types of paper bags. Packaged calcium chloride was

not included in the study because no problem was evident in this respect.

Test Site

The test site selected for this portion of the study was within the storage grounds of a highway maintenance depot. The tests were conducted on a bituminous-surfaced storage base 10 ft wide and 60 ft long. The base had a slope in only one direction of ½ in. per ft across the 10-ft width. The site and materials under test were protected from accidential disturbance by a 4-ft high wood slat snow fence. An over-all view of the test site is shown in Figure 24.

Figure 24. Test site for outdoor storage of chloride salt.

Test Materials

The bulk materials included in the tests are given in Table 5. It was assumed the sodium chloride (rock salt) had a purity of 100 percent and the weights of calcium chloride were computed based on their purity as advertised by the manufacturer.

Where mixtures were included they were prepared by hand using square-nosed shovels to blend the materials.

The packaged material consisted of 40 bags of sodium chloride (rock salt) in several types of paper bags:

Figure 25. General arrangement of packaged NaCl.

1. U—untreated paper bags with three layers of untreated paper (15 bags).
2. B—bituminous-treated bags with three layers of paper, two of which were treated with bituminous (10 bags).
3. Bo—bituminous-treated bags similar to B except they were in previous storage for about nine months (5 bags).
4. P—plastic cemented bags having three layers of paper, two of which were glued together with a plastic cement (10 bags).

The packaged material was placed on planks in five stacks of eight bags per stack. Because there were five stacks, an arrangement was worked out so that no more than two similar bags would be represented in each layer. The arrangement of stacking is shown in Figure 25.

All materials included in the study were placed in test between November 7 and 10, 1960, except test material G (100 percent sodium chloride with a sand cover) which was placed May 3, 1961.

Protective Covering Material

The protective covering material used in this study was a nominal 5-mil white polyethylene sheeting similar to that used for curing concrete. It was anchored with sand-filled burlap bags placed at the base of each storage pile. No polyethylene sheeting material was used to cover test material G because this test was introduced to study the effectiveness of a light sand cover.

TABLE 5

POUNDS OF BULK MATERIALS USED

Identification	Sodium-Chloride Rock Salt (lb)	Calcium Chloride (lb)	
		Type I Flakes	Pellets
A	1,000		
B		1,282	
C			1,053
D	750		263
E	500		526
F	500	641	
G	1,000[a]		

[a]Covered with a 4-in. layer of sand instead of polyethylene sheeting.

Collection of Data

Observations of the bulk test materials were made once a month and those for the packaged material once every two months. Observations included moisture determinations, amounts of caking and crusting, and determination on whether each material was free flowing.

Duplicate moisture samples of the bulk materials were taken about midway between the base and apex of each conical storage pile. They were taken either at a depth of 2 to 3 in. below the surface or one sample was taken at the surface and the other about 5 to 6 in. into the pile. The moisture determinations for the bulk materials are given in Table 6; the figures given are averages of the separate tests.

Single moisture samples were taken of the bagged material by cutting a small opening near the center of the bag, as shown in Figure 26, removing about 300 g of salt and then taping the opening closed.

Each bag of sodium chloride was sampled at least twice during the test period and almost one-half were sampled three times or more. The moisture data and date of moisture test are given in Table 7.

Some slight caking was found to exist in only a few of the bags of rock salt within the 10-month storage period. However, the cake was easily broken by hand and no difficulty would have been experienced in using the material.

On the other hand, considerable caking and crusting did occur in some of the bulk storage piles which would create difficulty in their use. The observations of crusting and caking are summarized in Table 8 along with the average moisture content of each material.

Analysis of Data

As shown by the data, 100 percent sodium-chloride rock salt (test material A) crusted within a two-month storage period; it was completely caked within ten months although the moisture content remained quite low (0.6 to 0.9 percent).

The 100 percent calcium chloride, Type I flakes, (test material B) developed a base crust of 1 to 1½ in. within a two-month storage period while no surface crusting was evident even though the moisture content was quite high (11.9 percent). At ten months, a slight outer surface crust developed which was easily broken. The chemical remained free flowing in spite of the fact that the moisture content almost doubled in an eight-month period. It is believed the base crust formation in this and other stockpiles in the test, as shown in Figures 27 and 28, is related to the amount of surface water on the storage base that is available to the stockpile. This points up the need for a well-constructed, free-draining storage base.

TABLE 6
MOISTURE DATA FOR BULK MATERIALS

Test Material	Average Moisture (percent of dry weight)											
	12-6-60	1-3-61	2-3-61	3-1-61	4-7-61	5-3-61	6-1-61	7-6-61	8-7-61	9-6-61	10-4-61	12-7-61
A	0.8	0.5	0.7	0.9	0.6	0.2	0.9	2.2	1.1	0.9	2.5	-
B	11.7	11.9	11.1	11.8	10.3	11.9	15.6	16.0	16.9	22.8	23.6	-
C	0.6	0.4	0.4	0.6	0.1	0.4	0.8	0.8	0.6	1.3	1.7	-
D	0.6	0.6	0.5	1.1	0.6	0.4	0.6	1.1	1.3	1.5	5.8	-
E	0.4	0.5	0.3	0.5	0.3	0.4	0.4	0.9	0.6	1.7	6.4	-
F	6.7	8.0	6.7	7.2	6.2	8.3	10.7	14.2	12.8	14.5	21.5	-
G	-	-	-	-	-	0.2	0.5	2.6	0.6	0.5	1.0	1.0

Figure 26. Method of taking moisture sample from packaged NaCl.

Figure 27. Base crust formation in rock salt.

Figure 28. Base crust formation in calcium chloride.

The 100 percent calcium chloride pellets (test material C) developed a base crust of ½ to 1½ in. within a two-month storage period but no surface crusting occurred. At ten months, no increase in base crust was noted although a crust varying from 0 to ½ in. developed on the surface. The moisture content remained low (1.3 percent) and the chemical was free flowing.

Mixtures of sodium chloride and calcium chloride all developed a base crust of 0 to 1½ in. within a two-month storage period with no surface crusting at all. At ten months the base crust varied from 1 to 2 in. with only slight surface crusting. All chemical mixtures remained in a free flowing condition condition throughout the test period. The moisture contents remained below 2 percent except in test material F (50 percent sodium chloride and 50 percent calcium chloride flakes) which had a gradual increase to 15 percent at the end of ten months. In all cases of the mixtures, after a short period of storage only particles of rock salt were left on the surface. These particles then fused together to form this light crust.

Sodium chloride with a 4-in. sand cover, (test material G) developed into a fairly hard cake with a two-month period and at the end of seven months became very hard on the surface. The material was not free flowing and this method of storage cannot be considered desirable.

Packaged rock salt stored well. The moisture content generally remained under 1 percent during the ten-month storage period with no detrimental amount of hardening or caking occurring. Only in a few cases where the moisture content approached or exceeded 1 percent was any caking noticed and in these cases the cake was easily

TABLE 7

MOISTURE DATA FOR PACKAGED NaCl

Bag Position[a]	Moisture (percent of dry weight)					
	2-3-61	4-7-61	6-2-61	8-7-61	10-4-61	11-8-61
1 NB		0.2				0.4
1 EB			0.3			0.3
1 SU			0.9			0.4
1 WU		0.4				0.5
1 CP		0.1				0.4
2 NP			0.4			0.2
2 EP			0.5			0.3
2 SB			0.6			0.2
2 WU			0.4			0.4
2 CU		0.3				0.4
3 NU			0.5			0.6
3 EU			0.5			0.2
3 SP			0.5			0.3
3 WB			0.3			0.2
3 CB		0.3				0.2
4 NBo			0.4			0.1
4 EB			0.3			0.2
4 SU			0.4			0.1
4 WP			0.3			0.3
4 CP		0.1		0.2		0.2
5 NP	0.3			0.1		0.2
5 EBo	0.3			0.3		0.2
5 SB	0.3			0.2		0.2
5 WU	0.4			0.1		0.4
5 CU	0.4			0.4		0.3
6 NU	0.6					0.6
6 EU			0.4			0.4
6 SP		0.2		0.3		0.3
6 WB			0.3			0.3
6 CB	0.3			0.1		0.2
7 NBo		0.1			0.3	0.3
7 EB		0.1			0.1	0.5
7 SU		0.6			0.2	0.4
7 WU			0.3		0.4	0.4
7 CP	0.3			0.1	0.2	0.3
8 NP	0.4			0.3	0.3	0.5
8 EBo	0.3			0.4	0.1	0.2
8 SB	0.4			0.2	0.3	0.2
8 WU	0.4			0.6	0.6	0.8
8 CU		0.4			0.9	1.2

[a]Number indicates layer within stack; first letter refers to compass position of stack (north, east, south, west, or center); second letter refers to type of paper bag as identified in text.

TABLE 8

SUMMARY OF BULK STORAGE PILE CONDITIONS

Test Material	After Two Months Storage: Physical Condition	After Two Months Storage: Moisture (avg %)	After Ten[a] Months Storage: Physical Condition	After Ten[a] Months Storage: Moisture (avg %)
A	2- to 3-in. hard base crust; slight crust on outer surface, easily broken	0.6	Entire pile caked in solid mass; broken only with some difficulty	0.9
B	1- to 1½-in. base crust; no surface crust, free flowing	11.9	Slight outer surface crust, easily broken and free flowing beneath	22.8
C	½- to 1½-in. base crust; no surface crust, free flowing	0.4	1- to 1½-in. base crust; 0- to ½-in. surface crust, free flowing beneath	1.3
D	0- to 1-in. base crust; no outer surface crust, free flowing	0.6	1-in. base crust; slight crusting at outer surface, free flowing beneath	1.5
E	1-in. base crust; no surface crust, free flowing	0.5	1-in. base crust; slight crusting in outer surface, free flowing beneath	1.7
F	1- to 1½-in. base crust; no outer surface crust, free flowing	8.0	2-in. base crust; no crusting at outer surface, free flowing	15.0
G	Fairly hard cake developing especially on outside, softer within	2.6	2- to 3-in. very hard surface crust; inner portion caked but not too hard	1.0

[a]All except test material G which was seven months.

broken by hand. A marked difference in moisture is noted between the types of paper bags. The moisture of the salt in the unlined bags was as much as double that in the treated bags. The polyethylene sheeting used in this study as a cover over the bags provided a very effective moisture barrier. In fact, the barrier was so effective that it prevented the natural escape of moisture during dry periods. The moisture then collected on the outside of the bags as shown in Figure 29 and, in some cases, deteriorated the bags to the point of breaking.

Figure 29. Collection of moisture on bags.

Outdoor Storage Conclusions

1. Calcium chloride (pellets or

flakes), and mixtures of sodium chloride with at least 25 percent calcium chloride, can be stored outdoors in bulk with a light polyethylene sheet cover for at least ten months without appreciable hardening.

2. Sodium chloride (rock salt) can be stored outside up to two months in bulk when covered with a light polyethylene sheeting. Bulk storage of sodium chloride beyond three months appears to be unsatisfactory.

3. Packaged sodium chloride (100-lb bags) may be stored outdoors with a light polyethylene sheet cover for at least ten months with no appreciable hardening.

RECOMMENDATIONS

Ice Removal

Table 9 gives a recommended range of application rate for eight ice removal materials. These rates are based on an ice thickness of about 1/16 in. and on clearing a wheelpath 1½ to 3 ft in width. However, additional material may be required for complete removal of ice from the roadway.

Because the application rates recommended are based on a limited number of tests, they may require modification after being used by the maintenance crews for a suitable period of time. Suggested modifications are therefore invited.

Outdoor Storage of Chloride Salts

Bulk sodium chloride intended for outdoor storage longer than two months should be mixed with at least 25 percent calcium chloride—preferably pellets. A mixture of ⅓ calcium chloride (pellets) to ⅔ sodium chloride (rock salt) appears to be the best all-round mixture when considering storage, ice removal action, and economy.

When bagged chloride salts are stored outdoors under polyethylene sheeting, provisisons should be made for ventilation to eliminate the collection of moisture on the paper bags.

Further Research

Additional testing of the more promising materials to be conducted under field conditions is recommended. It is suggested that the roadway be iced in a manner similar to that used in this study. However, more thought should be given to the

TABLE 9

RECOMMENDED APPLICATION RATES OF CHEMICALS AND CHEMICAL-ABRASIVES FOR ICE REMOVAL

Ice Removal Material	Suggested Width of Spread (ft)	Application Rates (lb per lane-mile[a]) for 1/16-In. Ice		
		Below 10 F	10-20 F	20-32 F
$CaCl_2$ (pellets)	2-4	300-375	250-300	(175-250)[b]
$CaCl_2$ (flakes)	2-4	350-450	275-350	(200-275)[b]
NaCl (rock salt)	3-4	(400-550)[c]	250-400	200-250
NaCl (evaporated)	3	(325-500)[c]	200-325	150-200
⅓ $CaCl_2$ (pellets) - ⅔ NaCl (rock salt)	2-4	300-475	250-300	175-250
⅓ $CaCl_2$ (flakes) - ⅔ NaCl (rock salt)	2-4	350-500	275-350	200-275
50% $CaCl_2$ (pellets) - 50% sand	4	(excess of 500)[c]	(300-500)[c]	200-300
50% NaCl (rock salt) - 50% sand	4	(excess of 600)[c]	(325-600)[c]	225-325

[a]Quantities given doubled for 2-lane roadways.
[b]Not recommended because greasy condition often results; quantities given are suggested if no other material is available.
[c]Not recommended because of low rate of ice removal; quantities given are suggested if no other material is available.

elimination or greater control of some of the variables. For example, the chemicals and chemical mixtures might be applied at a better controlled rate using a fertilizer spreader; also, a better method for evaluating the amount of ice removal might be found.

Other governmental bodies and agencies are encouraged to conduct field tests similar to Minnesota's to validate or disprove the results and conclusions presented herein.

REFERENCE

1. Tiney, B.C., "Treatment of Icy Pavements." HRB Proc., 11:364-366, pt. I, (1931).

Discussion

ALAN K. JEYDEL, Technical Director, Salt Institute, Chicago, Illinois—The Minnesota report is commendable for attempting to simulate actual road ice conditions while providing for measurements of temperature, ice thickness, and rates of application of the various chemicals and mixtures.

Some of the conclusions and recommendations drawn from the data do not seem justified and are at variance with test data. For instance, on the basis of the test data the efficacy of salt at temperatures down to 10 F is at least equal to the mixture. The report cites mixtures for economy, storage, and effectiveness over straight chemicals. It is questionable whether there are data to support these broad claimed advantages.

As for economy, there are no cost figures shown to verify statements made and it is difficult to see how the sodium-calcium chloride mixture can be more economical either on a cost per ton or cost-performance basis under most conditions. The mixture introduces the more expensive calcium chloride, and it introduces the costs of labor, equipment, and space for mixing operations. Furthermore, the mixture means maintaining a double inventory of chemicals, and mixtures presuppose expensive storage space and shelter costs.

As to effective de-icing, the report states that the melting rate for either straight rock salt or calcium chloride is similar above 15 F. Inasmuch as nearly all ice storms occur at higher temperatures, straight salt is better on a cost-performance basis.

At 10 F, evaporated salt was shown to be more effective than calcium chloride. Also, it is approximately one-half the price of calcium chloride.

The main weakness of the report, however, is the paucity of data. In fact, there are not sufficient data to reach satisfactory conclusions from a statistical point of view.

The curves drawn in this report reportedly show a relationship between the volume of ice melted in a given length of time for salt, calcium chloride, and salt-calcium chloride mixtures. An examination of the data used to derive these curves indicates that insufficient data were collected in the experimental portion of this work to justify the curves presented. For example, in the M test series for calcium chloride pellets, no single series of tests had more than three points that could be plotted. Test M-1-2 had only one point, tests M-3-2 and M-4-2 only two points. Because an infinite number of curves can be fitted to these data, the curves presented do not seem justified.

It is understood that some correlation of the various test conditions was attempted by assuming linear interpolation within the variables such as ice thickness, temperature and salt application. No justification is presented to substantiate that such a linear relationship exists.

The function for V (Eq. 1) could not have been developed from the data presented. The small body of data could not indicate such a function.

In closing, it should be emphasized that this report covers only the removal of ice after it is formed by the use of chemicals and chemical mixtures. Good maintenance

practices indicate that chemicals be applied not after the ice is formed but during the storm to prevent just such an ice build-up.

The logical explanation for the effectiveness at lower temperatures of evaporated salt over rock salt is the absence of fines in the rock salt. It would seem desirable to suggest to the Minnesota Highway Department that they consider testing a rock salt with fines rather than recommend the use of a salt containing ⅓ calcium chloride.

The results of storage tests showing that rock salt could not be stored outdoors longer than two months should be re-evaluated in view of the fact that there are at least two anti-caking agents in use (prussian blue and yellow prussiate of soda) that are effective in keeping rock salt from caking indefinitely.

B. F. HIMMELMAN, Closure—The paper presented was prepared as a progress report covering the results of a limited number of ice removal tests run on artificially prepared ice. The study was by no means considered as a fully comprehensive test with all variables controlled or covering all possible chemical application rates. It is recognized that much more work need be undertaken to expand and verify the conclusions and recommendations indicated and this is so stated in the report.

The test data do not show that the efficacy of salt at temperatures down to 10 F to be at least equal to the mixture as stated by Mr. Jeydel. In five series of tests where the ice and air temperatures ranged from 12 to 24 F and 6 to 12 F, respectively, rock salt produced a "clear" wheelpath in only one series, whereas the mixture of ⅓ calcium chloride and ⅔ sodium chloride pellets produced a "clear" wheelpath in three of the five test series.

With reference to economy, no statement is made that a mixture is more economical than the single chemical. Location of source of supply is too great a factor when considering economy of either one or both of the chemicals as compared to a mixture of the two. The reference in the report to economy of a chemical mixture is obviously in comparison to an abrasive-chloride mixture.

Practically all ice storms admittedly occur when the temperature is at or near the freezing point; however, Mr. Jeydel assumes the temperature never drops below 15 F before the ice has dissipated. In Minnesota, the temperature quite often plunges rapidly from above freezing and it is this phenomenon that often produces the ice storm.

The curves shown in the report for the relationship between volume of the ice melted vs time for all materials tested are not direct plots of the data from any one single series of tests. They are trends based on the mean of the observed and calculated data of all the tests for one material within the temperature ranges indicated. This method of approach was necessary because of the many uncontrolled variables such as wind, temperature, and humidity present at one series of tests which were different in another series even though the temperature may have been within a very narrow range. Jeydel's examination of the data presented for the M series of tests must have been somewhat hurried because the M-1-2 series had three points (0, 15, and > 120 min); M-3-2 had two points (0 and 15 min); and M-4-2 had four points (0, 15, 45, and >75 min). Only one good curve for each of these series can be drawn through these data.