DE-ICING CHEMICALS AND ABRASIVES: STATE OF THE ART

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•THIS PAPER establishes the state of the art of de-icing chemicals and abrasives for winter road maintenance. The paper was prepared to facilitate the application of research results.

With a comprehensive knowledge of the relevant properties of de-icing chemicals and abrasives, the practitioner whose responsibility is to maintain roads in a safe and ridable condition at all times at the lowest possible cost can optimize operations to achieve objectives by considering the prevailing environmental conditions and the availability of funds, materials, equipment, and labor.

The purpose of de-icing chemicals and abrasives for winter road maintenance is (a) to ensure that the roadway is safe, i.e., to eliminate slippery and hazardous driving conditions, and (b) to allow an acceptable flow of uninterrupted traffic during periods of inclement weather. Figure 1 shows the increase in the coefficient of sliding friction as ice is being melted by the action of sodium chloride and calcium chloride (120). Table 1 gives the decrease in stopping distance of an automobile by sanding the pavement surface and by completely melting the ice or snow (wet surface) (136). In each example the relation is valid for the conditions that prevailed during the tests.

The suitability of the various types of chemicals and abrasives is given in Table 2. Essentially, the abrasive will provide immediate traction and increase skid resistance, whereas chemicals will principally act to control snow and ice conditions by (a) preventing the formation of ice films, (b) weakening the bond between the snow and the road surface, (c) melting the fresh snow as it falls, and (d) melting compacted snow that remains after plowing.

PROPERTIES OF DE-ICING CHEMICALS

A chemical suitable for snow and ice control on roads must (a) lower the freezing point of water to normal winter temperatures; (b) melt the snow or ice within a reasonable time interval; (c) penetrate snow and ice layers and break the bond with the pavement; (d) have a nonlubricating effect on the road surface when spread on a dry pavement or when in solution; (e) be available in bulk quantities at low cost; (f) be easy to store, handle, and spread; (g) not be toxic to people, animals, and plants; and (h) have a minimum damaging influence on metallic structures, pavements, and clothing (22, 26, 27, 56).

Of the several chemicals and mixtures that have been tried (26, 40, 43, 82), calcium chloride, sodium chloride, and their mixtures offer, within certain limitations, the best combinations of useful physical properties and reasonable cost. Other more expensive chemicals have also been found suitable for use on special conditions. For example, a mixture of 75 percent Formamide and 25 percent tripotassium phosphate has been proposed for use on runways to reduce stress corrosion of aircrafts (40). A composite de-icing agent of urea and calcium formate has been suggested to reduce the rate of corrosion of highway structures (43).

Sodium Chloride

Sodium chloride is supplied as rock salt, evaporated salt from mines, and solar salt by evaporation of seawater (56). The characteristics of sodium chloride are described in the standard specifications of ASTM D 632 (94). The properties of sodium chloride are given in Table 3 (56). Sodium chloride with a moisture content of less

Figure 1. Effect of de-icing salts on improvement of coefficient of sliding friction with time.

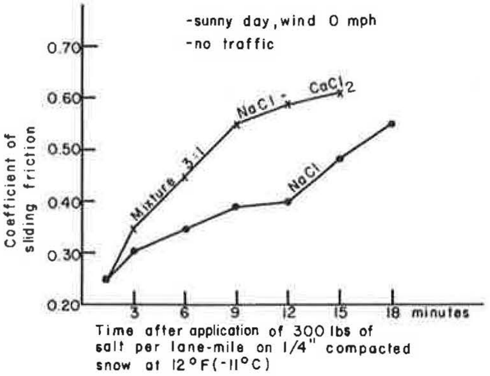


Table 1. Effect of salting and sanding on vehicle stopping distance.

Pavement Condition	Percentage of Road Having Icy Condition	Stopping Distance Feet	Stopping Distance Meters
Icy (at 30 F or -1 C)	100	478	143
Sanded (at 30 F or -1 C)	38	183	55
Bare, wet	14	66	20

Table 2. Suitability of chemicals and abrasives.

Material	Main Purpose	Suitability for Use	Principal Advantages	Principal Disadvantages
Sodium chloride	Melt snow and ice	Very effective above 25 F; effective between 15 and 25 F; marginal between 10 and 15 F; not effective below 10 F	Provides immediate traction; salt particles bore, penetrate, and undercut ice layer; freezes dry on pavement surfaces; low cost	Low rate of solution; useless at very low temperatures
Calcium chloride	Melt snow and ice	Normally used below 10 F; effective to -20 F; marginal between -20 and -30 F; not effective below -30 F	High rate of solution; liberates heat when going into solution; effective at low temperatures	Higher cost; melting action takes place at ice surface; pavement remains wet
Mixtures of $CaCl_2$ and NaCl	Melt snow and ice	In cold weather (to 0 F) when snow and ice must be melted in a short time	High rate of solution; effective at low temperature; more stable on the road	Higher cost; pavement wet longer than with NaCl
Mixtures of abrasives and salt	Increase sliding friction immediately	In very cold weather when salt is not effective or where clean plowing is impossible if immediate protection is necessary	Free flowing material; no freezing of stockpiles; abrasives more stable on road; quick anchoring of abrasive to road; skid resistance improved immediately	Creates spring clean-up problems; does not remove ice or snow, causing slipperiness; may damage vehicles traveling at high speeds
Abrasives	Increase sliding friction immediately		Skid resistance immediately improved	As above; easily brushed off road by tires

Table 3. Properties of sodium chloride and calcium chloride.

Property	Sodium Chloride	Calcium Chloride
Eutectic temperature	-6 F (-21 C)	-59 F (-50.6 C)
Rate of solution (rate of ice melting)	Lower	Considerably higher
Ice melting capability given unlimited time	More down to 10 F (-12 F)	Less
Moisture attraction for solution	Will not attract moisture	Will attract moisture
Heat of solution	Takes on heat when going into solution	Liberates heat when going into solution
Characteristics of the salt in solution	Recrystallizes	Remains in solution
Cost	Lower	Two to three times that of NaCl

than 2 percent can be considered as being dry (36). There is never a problem when the moisture content is less than 1 percent (78).

Sodium chloride is generally used at temperatures above 10 F (-12 C); at lower temperatures, the amount of salt that would be required becomes prohibitively large.

Because of its weight and relatively slow rate of solution, the individual coarse particle of sodium chloride will bore and penetrate the ice surface and eventually weaken the bond between the road surface and the layer of ice. This will allow the traffic or plow to break up the compacted snow or ice crust and cast it to the side of the road (22).

Calcium Chloride

Calcium chloride is supplied in the form of flakes or pellets. Flakes contain 77 to 80 percent $CaCl_2$ by weight, the remaining being mainly water or crystallization. Pellets contain approximately 95 percent $CaCl_2$ by weight (56). Specifications covering calcium chloride for snow and ice control on roads are given in ASTM D 98. The properties of calcium chloride are also given in Table 3.

Stored calcium chloride must be protected from moisture and the weather. The use of calcium chloride is generally limited to temperatures above -30 F (-34 C).

The cost of calcium chloride is two to three times that of sodium chloride. However, due to its rapid rate of solution, less $CaCl_2$ is wasted during frequent plowing operations (42).

Sodium Chloride and Calcium Chloride Mixtures

The two chemicals complement each other advantageously. Calcium chloride attracts moisture and dissolves when exposed, thus speeding up its melting action. Sodium chloride does not absorb moisture but takes on heat as it dissolves. When calcium chloride and sodium chloride are combined, the deliquescent calcium chloride supplies the triggering action to provide rapid melting action at all temperatures. Its speed of action produces a brine that sets off and sustains the melting action of sodium chloride over a longer period for prolonged protection (38, 62).

Experiences of road maintenance organizations have shown (Fig. 2) that with decreasing temperatures the relative proportions of $CaCl_2$ and NaCl in mixture should tend toward a ratio of 1:1 in lieu of 1:3 (56, 62, 78). At the end of a storm and at temperatures in the mid-20s, the pavement can be cleaned in 15 to 20 min after spreading of chemical mixture (18).

A satisfactory mixing operation can be achieved by feeding both salts to a conveyor belt and adjusting the hopper gates to obtain the desired proportion (56). The cost of mixing varies between 10 and 30 percent of the materials cost (79).

ABRASIVES

Abrasives are natural sand, manufactured sand, crushed slag, or cinder. Abrasives are generally used to obtain an immediate increase in the skid resistance of a thick mat of snow or ice or both. Abrasives are especially useful at very low temperatures when de-icing chemicals are not active (5, 7). The desirable characteristics of abrasives are as follows (20):

Characteristic	Benefit
Great resistance to compression, crushing, impact, and grinding	Resists degradation under the action of traffic; avoids blowaway; can be recovered in spring
Angular shape	Provides greater stability; prevents its being blown away
Darkish color	Absorbs heat to melt itself into the surface of ice
Uniform grain size	Provides uniform spreading pattern; is less likely to damage equipment

The maximum aggregate size is generally limited to ½ in. because of risk of damage to vehicles and injury to pedestrians (5). Fine particles passing the No. 50 sieve should be eliminated because they contribute almost nothing to the increase in skid resistance (61).

To obtain a good skid resistance requires a high rate of application of abrasives. Spreading rates varying from 2 to 4 tons per mile on a two-lane highway have proved to be effective. Spreading rates below 1 ton per mile were not effective (20).

Abrasives Treated With De-Icing Chemicals

Experience has shown that, on heavily traveled highways, untreated abrasives will be whipped off the road and that even moderate winds will sweep the material from the surface (6). Schneider found that the initial slippery condition could be reestablished after only 10 to 15 passes of an automobile traveling at a high speed (20).

The treatment of an abrasive with about $\frac{1}{30}$ of its weight of salt (i.e., 50 to 100 lb of salt per ton of abrasive) will prevent the abrasive particles from forming frozen lumps and will help the particles penetrate and anchor themselves to the surface of the hard snow or ice. Treatment will stop the abrasive from being swept off by wind or traffic. It will also facilitate loading from stockpiles and improve the uniformity of distribution by mechanical spreaders (2). The methods of preparation and storage of treated abrasives are described elsewhere (2, 6, 24, 56).

Mixtures of Abrasive and De-Icing Chemicals

Several organizations have been known to use mixtures of either calcium or sodium chloride with abrasives to decrease the slipperiness of the road and to melt the snow as the temperature rises. Experience has shown that, to be effective, the mixtures should be prepared with coarse-graded rather than fine-graded salt. Coarse salt particles will penetrate individually into the snow and ice layer without carrying with them an appreciable quantity of sand, thus leaving the latter on the surface to fight slipperiness (17). If the salt particles are too fine, the salt will soften the snow and ice surface, thus allowing the abrasive to penetrate the ice layer under the action of traffic and to lose its antiskid effect.

As shown in Figure 3, the melting of snow and ice will be delayed by using a mixture of salt and sand (17, 31). Some authors recommend the use at low temperatures of coarse salt alone, which will initially serve as an abrasive and later activate melting when the temperature increases. This will eliminate the cleaning of streets and catch basins in the spring (56).

In a study by the New York State Thruway Authority, it was found that a satisfactory mixture for almost all storm conditions was two parts mixed chemicals (1:3 calcium chloride to sodium chloride by weight) and one part abrasives. This mixture was found to be nearly as effective in melting action as the chemicals alone and in addition provides abrasives for skid protection (18).

FACTORS INFLUENCING THE MELTING RATE OF SNOW AND ICE

Physical Characteristics of Snow and Ice

The rate of removal of solid ice and snow is greatly influenced by their physical characteristics, particularly density, thickness, and uniformity of the ice or snow layer.

As shown in Figure 4 (38), the density of snow depends mainly on the air temperature during the snowstorm. The snow that a plow fails to remove varies in nature from day to day depending on the weather, kind of precipitation, and traffic density (120).

The thickness of ice may vary from a scarcely visible film formed by the precipitation of supercooled fog to a thick layer of ice resulting from the freezing of rain or meltwater. Varying thicknesses of ice crust may also build up by freezing rain, by rain falling on a cold surface, by freezing of a wet snow surface, or by freezing of a thin liquid film formed by pressure exerted by tires against the ice crystals (20).

If compaction and bonding of snow to the pavement surface by traffic are to be prevented, an application of salt to the road surface should be made as early as possible during the storm or preferably prior to the storm (1, 22, 56). Weak brine left from a previous salting tends to free the compacted snow from the road surface (1).

When a thick layer of ice or compacted snow is bonded to the pavement surface, greater quantities of chemicals and a longer period of time are required to remove it (56). Field tests indicate that the rate at which both calcium chloride and sodium chloride will effectively remove ice is inversely proportional to the ice thickness (31).

Type of Chemical

The characteristics presented earlier are the main factors influencing the amount of ice that can be melted by a chemical. Sodium chloride has a slow rate of solution and a high eutectic temperature (-6 F or -21 C), whereas calcium chloride is readily soluble and has a very low eutectic temperature (-59 F or -51 C).

When a solid chemical is spread on the ice and while chemical particles are going into solution, the resultant melting rate depends on the rate of solution of the chemical and the rate of ice solution (22). The rate of solution of the chemical depends on solubility and grain size. The rate of ice or snow solution into the existing brine depends on diffusion of ions from the concentrated portion of the brine to the less concentrated portion at the ice or snow contact surface. The rate of diffusion depends on the concentration gradient, the mobility of the ion, and the temperature (22).

Pellets of calcium chloride melt ice more rapidly than flakes. Because pellets have a higher concentration of $CaCl_2$, they melt about 20 percent more ice than an equal weight of flakes (56).

Field and laboratory studies indicate that a mixture of three parts sodium chloride and one part calcium chloride has a much faster melting action than sodium chloride alone and will melt a greater quantity of ice than either of the two chemicals alone (15, 17, 18, 31, 38). An example is shown in Figure 5 (15). It can be seen that a mixture of calcium and sodium chloride will melt ice to a greater depth in 2 hours at all temperatures down to -10 F (-23 C) than will either of the two chemicals alone.

The color of a chemical and impurities may influence the melting action, but the importance of these factors is not yet known (56).

State of De-Icing Chemical

Chemical de-icing salt can be supplied as either an aqueous solution or a granulated solid. An aqueous solution can be used very effectively on thin layers of ice or snow as a preventive and maintenance treatment before and during snowstorms (89) and especially during cold, dry periods (117). Efficiency is greatly improved by a better distribution and a closer contact with the pavement (89). Aqueous solutions are not suitable for treatment of thick layers of pure ice or hardened or packed snow.

The effectiveness of granulated de-icing chemicals depends on grading. In general, field tests have shown that the finer the salt is, the greater is the melting action because of its greater specific area (1). To be efficient, salt for ice and snow removal must be composed, on the one hand, of fine particles to initiate fast melting at the surface and, on the other hand, of coarse particles to penetrate the ice crust by slow melting and to break the bond between the pavement and the ice so that traffic can break up the ice sheet and cast it aside. Coarse particles will also act as an abrasive for a limited period of time immediately following the application (56).

Fine powder is undesirable because it is easily removed by traffic. It can also form a film of brine on the ice surface and thereby create hazardous traffic conditions. Fine powdered salt will cake more easily when left in the spreader or stored for long periods of time (56).

Effect of Concentration

Variations in the concentration will affect differently the de-icing chemicals (17) as shown in Figure 6. When the concentration is increased, more calcium chloride

Figure 2. Use of mixtures of sodium chloride and calcium chloride at various temperatures.

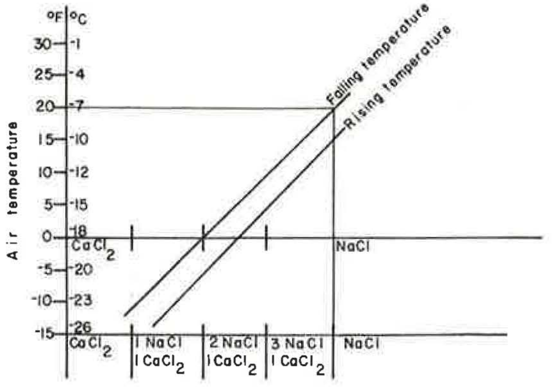


Figure 3. Mean effect of sand on melting capacity of sand-salt mixtures.

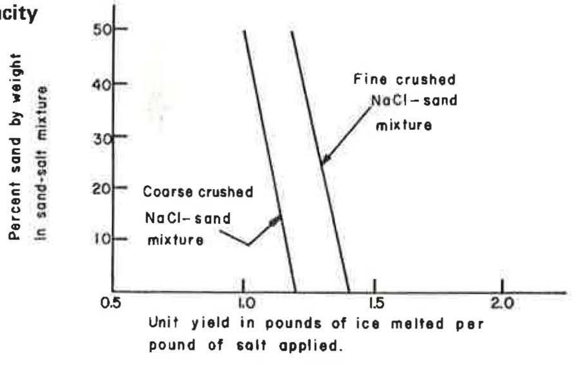


Figure 4. Average weight of snow as a function of air temperature.

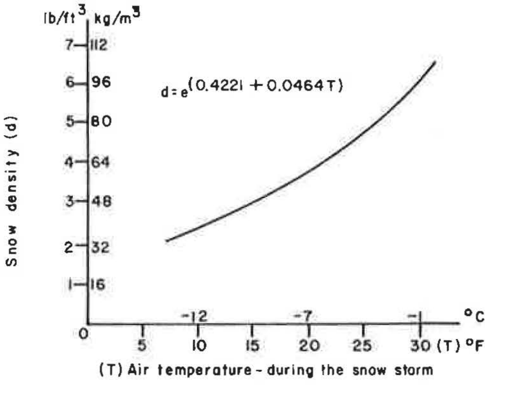
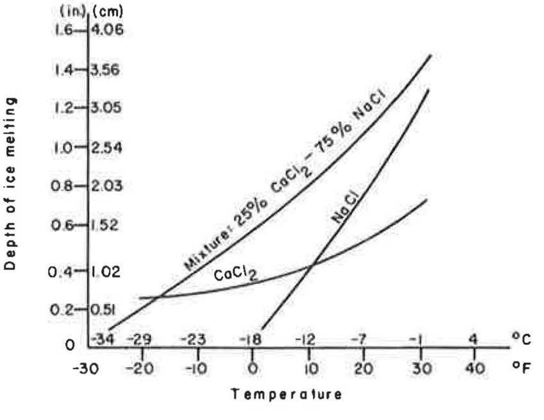


Figure 5. Depth of ice melted in 2 hours by salt particles of equal weight.



dissolves at a relatively uniform rate, whereas the rate at which sodium chloride dissolves decreases with increasing concentration. At low concentrations, the mean melts of all de-icing chemicals do not differ appreciably. As shown in Figure 7, the greatest melting efficiency occurs at low concentration (17).

A typical relationship between the application concentration of de-icing chemicals and the quantity of ice melted during a given time is shown in Figure 8, which indicates that a maximum total melt occurs for each reaction time and that a concentration in excess of this maximum would be truly wasteful (17).

Two undesirable phenomena can be observed when either too much or too little chemical is used (27). In the first case, the excess salt does not undergo reaction, and, in the second case, the ice is not completely melted. Schneider suggests use of the eutectic properties of the salt so that the prevailing temperature need not be taken into account and the melting will take place at maximum speed.

Effect of Time of Solution

In general, the longer the de-icing chemical is permitted to act, the greater the amount of melt is. The rate of melting by chloride is initially rapid, followed by a subsequent slowdown. With sodium chloride, the rate is initially slow and then increases, and a time could be reached when the rate with sodium chloride equals or becomes greater than that with calcium chloride (14, 15, 31). As shown in Figure 9, the exact comparison depends on temperature (15). In practice, when it is possible to permit a relatively longer reaction time a saving on chemical is possible (17).

Effect of Temperature

The temperature of the pavement is the principal factor influencing the amount of chemical required and the associated rate of melting (22, 56). The phase diagram (Fig. 10) indicates that the amount of chemical required to melt a given quantity of ice increases almost linearly with decreasing temperature. A typical relationship between reaction temperature and amount of ice melted is shown in Figure 11. It is interesting to note that the rate of melting increases rather rapidly with increasing temperature for each of the reaction times studied. In addition, as the reaction time increases, the effect of increasing temperature also becomes more pronounced (17).

Effect of Weather Conditions

As the pavement receives radiant heat from the sun, melting is accelerated and smaller amounts of chemical are required. Radiant heat from the sun can cause the pavement temperature to be as high as 10 F (6 C) higher than the surrounding air (56).

If chemicals are applied to roads during periods of strong winds and drifting snow, they will cause the snow to stick to the pavement, whereas an untreated surface may be swept clean by the wind.

Pavement temperatures are lower in shaded areas, and, consequently, greater quantities of chemical should be applied at such locations. The rate of ice melting may be decreased by factors such as evaporation, radiation due to clear skies at night, and prior cold periods (56).

Effect of Humidity

Calcium chloride melts ice at a faster rate partly because of its moisture-attracting ability. The presence of moisture initiates the ice-melting process. Calcium chloride will attract moisture easily at a relative humidity of 46 to 60 percent and at temperatures of 15 to 32 F (-9 to 0 C) (16).

Effect of Type of Road Surface

The melting process is more rapid on concrete surfaces than on asphalt surfaces (27) because a concrete surface gives up the necessary heat more rapidly (Fig. 12). However, asphalt pavements absorb more of the sun's radiation than do concrete, snow,

Figure 6. Effect of chemical concentration on mean total melt.

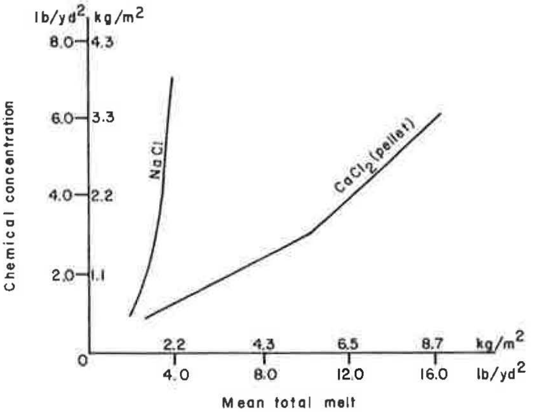


Figure 7. Effect of concentration on unit yield.

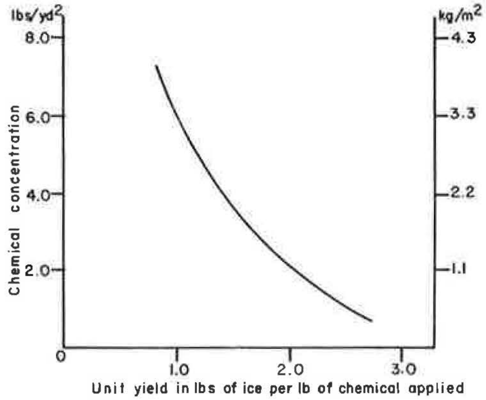


Figure 8. Effect of concentration on total melt.

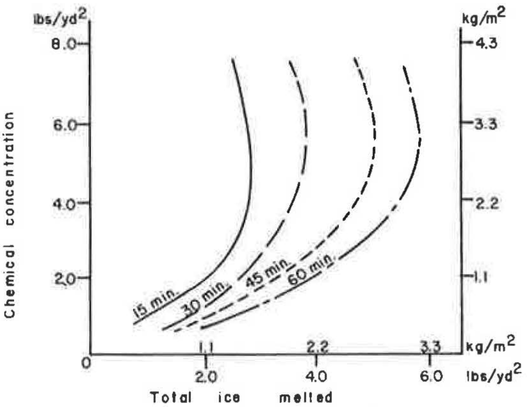


Figure 9. Relationship between amount of ice melted and time.

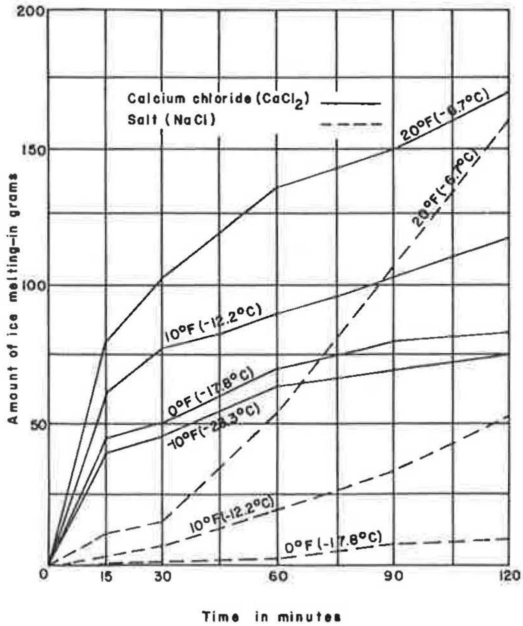
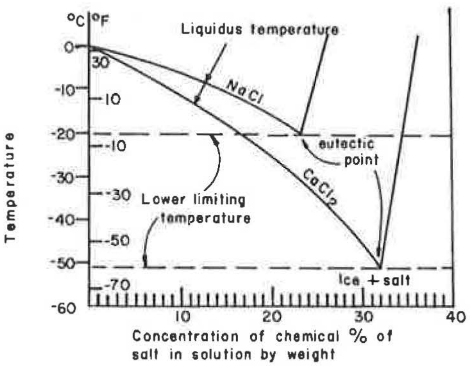


Figure 10. Phase diagram for sodium chloride and calcium chloride.



or ice surfaces. This phenomenon is demonstrated by the sometimes rapid disappearance of snow adjacent to bare pavement areas.

Effect of Topography

The topographic environmental conditions most likely to favor ice formation are those that screen the road surface from the sun: The more prolonged is the screening, the greater is the potential danger. The comparative screening effect at different sites can be assessed by determining the mean daily duration of direct sunshine available to the road surface under clear skies (77). The effect of "screened areas" could be minimized at the design stage of road construction by a design giving the side slopes the lowest possible gradient.

Effect of Traffic

Traffic helps in the removal of snow and ice by exerting pressure on the pavement where the melting system is at near equilibrium conditions. An increase in pressure will lower the melting point of ice and increase the rate of heat transfer to the melting system (1). Traffic also supplies heat from the automobile and tire friction (38), and it mixes the chemicals with the snow and breaks up ice layers that have been weakened by salt (56). Traffic aids the mechanical formation of slush, which is readily removed from the pavement surface by additional traffic (1).

The effect of traffic on snow removal depends greatly on the free water content of the snow (113). This effect can be seen in the following:

Free Water Content (percent)	Effect
<15	Compaction of snow into ice crust
15-30	Snow stays in a soft loose state
30	Adhesion of snow to tire
>30	Slush is easily removed by traffic

Note that only about 30 to 50 percent of the ice needs to be melted for traffic having a density of more than 30 vehicles per hour to cast the slush away from the pavement surface (7, 14, 17, 31).

Effect of Width of Application

In general, it was found that, for a given amount of salt, the rate of melting is greater when salt is applied in narrow strips. However, the amount of snow melted over a period of time is the same regardless of the width of application. An advantage of concentrated spreading is early exposure of a portion of road surface to the sun with the resulting absorption of heat and consequently increased melting rate (1). After a road is plowed, chemicals are usually applied on the middle third of the pavement (24, 28, 31) over a 1- to 3-ft narrow strip (17, 53, 59). However, when chemicals are spread before a snowfall or freezing rain, they should be applied uniformly over about 15 ft of road (53).

Time of Application

The most important factor contributing to the success of a salt treatment for snow clearing is timing (7). De-icing work in the first 30 min of a storm can be significant (22). A small amount of chemical mixed with loose snow will melt some of the snow. The wet, almost granular snow that results will not be packed by traffic and can be easily removed by plows. About 15 percent of the snow must be melted to preserve it in this loose state.

Combined Effects

The interaction of factors influencing the rate of melt was, for the most part, found to be highly significant (17). Therefore, no single variable could be considered separately; i.e., the effect of each variable on the rate of melt is only valid at some fixed levels of other variables.

EFFICIENT SNOW AND ICE CONTROL BY USE OF CHEMICALS

For efficient snow and ice control,[1] it is necessary (a) to determine the optimum desired service level at which costs to the user (in terms of losses arising from accidents, delays, and immobilization) and to government (i.e., maintenance costs) are at a minimum and (b) to establish the type of organization required for a control system that will yield maximum effectiveness at minimum cost.

The system should encompass purchasing and storage methods, types and number of machines, and types and quantity of de-icing compounds and abrasives to be used. It should also give personnel qualification and training programs, application procedures and methods, standards for minimum performance, and methods for control of operation costs and quality of service.

RATE OF APPLICATION OF DE-ICING CHEMICALS

Because no two storms are alike, no single set of standards can be written for spreading rates to satisfy all storm conditions. As a general rule, chemicals should be applied only in quantities sufficient to produce a 30 percent melt condition within a maximum of 30 min for light traffic conditions (113, 120). With this amount and increasing traffic, the time of solution will decrease accordingly. An adequate spreader should have a feeder capable of spreading chemicals at a rate ranging between 200 and 3,000 lb/lane with a precision of 50 lb (63).

Main roads and arteries carrying a daily vehicular traffic of 1,000 or more generally require bare pavement conditions; this involves snowplowing, spreading of different combinations of chemicals and abrasives, and removal of partially melted snow and ice (24).

Quantities of chemicals recommended for ice control and snow removal are given in various reports (1, 5, 20, 24, 31, 38, 53, 56, 59, 63, 78, 113, 120). The given rates for application of chemicals (Table 4) are generally valid for a solution time of less than 30 min. References are given by subject area in the following listing:

1. Objectives, 3, 22, 25, 46, 56, 61, 76, 106, 120, 136;
2. Detection and sensing system, 83, 85, 86, 87, 106, 133;
3. Classification and properties of snow and ice, 8, 20, 23, 32, 38, 45, 65, 133;
4. Sodium chloride, 15, 20, 22, 25, 56, 94, 115, 117;
5. Calcium chloride, 13, 15, 20, 49, 56, 63, 75, 89, 96, 116;
6. Sodium and calcium chloride mixtures, 14, 15, 28, 31, 36, 54, 56, 62, 79, 120;
7. Treated and untreated abrasives, 2, 5, 6, 7, 17, 20, 54, 61;
8. Other chemicals, 26, 27, 40, 43, 95;
9. Comparative tests, 14, 17, 26, 30, 31, 82, 106, 117;
10. Specifications, 63, 64, 94, 111, 112, 115, 116;
11. Sampling and Testing, 14, 45, 64, 72, 106, 120;
12. Factors influencing the rate of melting, 1, 14, 17, 27, 56, 76, 77, 106, 120, 133;
13. Storage, handling, and mixing, 15, 20, 24, 31, 48, 71, 73, 114, 123, 132;
14. Snow and ice control, 7, 17, 20, 27, 29, 37, 42, 90, 118, 125, 126;
15. Rate of application, 1, 5, 7, 17, 24, 27, 31, 56, 120;
16. Recommended practice, 7, 17, 53, 59, 62, 74, 76, 80, 110, 130, 138;
17. Effect of salt on environment, 52, 67, 81, 102, 104, 119, 124, 139;
18. Effect of salt on materials and structures, 9, 11, 21, 41, 43, 47, 91, 92, 106;

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[1] The original manuscript contained an appendix available in Xerox form at cost of reproduction and handling from the Highway Research Board. When ordering, refer to XS-43, Highway Research Record 425.

Figure 11. Effect of mean temperature on mean total melt.

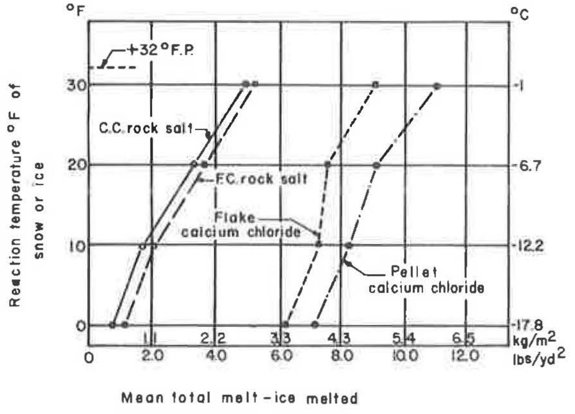

Figure 12. Effect of surface type on time to thaw ice crusts with sodium chloride.

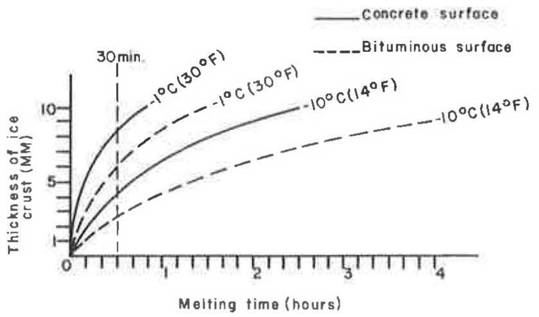

Table 4. Recommended application rates for de-icing salts.

	Rate of Application (lb/mile of two-lane road)			
Air Temperature	Before Snowfall or Freezing Rain	To Melt 1 In. of Loose Snow	Removal of Thin Crusts After Plowing	Thick Crust of Hard-Packed Snow and Ice
25 F or higher in shade or 20 to 25 F in sun and on warm pavement	200 to 400 lb of NaCl or 200 to 400 lb of 1:3 mixture of $CaCl_2$ and NaCl if NaCl is removed by wind or traffic	1,000 lb NaCl or 600 lb of 1:3 mixture	300 lb NaCl or 150 lb of 1:3 mixture	600 lb NaCl or 300 lb of 1:3 mixture
25 F and higher if temperature is falling, 20 to 25 F in shade, or 10 to 20 F in sun or on warmer pavement	200 to 400 lb of NaCl or 200 to 400 lb of 1:3 mixture of $CaCl_2$ and NaCl if NaCl is removed by wind or traffic	1,500 to 2,000 lb NaCl or 1,200 lb of 1:3 mixture	300 to 500 lb NaCl or 300 lb of 1:3 mixture	600 to 1,000 lb NaCl or 600 lb of 1:3 mixture
20 to 25 F with falling temperature, 10 to 20 F in shade, or 0 to 10 F in sun or on warmer pavement	250 to 500 lb NaCl of 1:3 mixture	1,500 lb of 1:3 mixture	500 lb of 1:3 mixture	1,000 lb of 1:3 mixture
Below 10 F in shade	No application	No application	600 lb of 1:3 mixture	1,200 lb of 1:3 mixture

Editor's Note: Although at one time, to avoid snowplowing during a snowfall, chemicals were applied alone, Committee A3E04 no longer recommends this practice in light of current knowledge of the effects of high concentration levels on the environment.

19. Effect of salt on soils and vegetation, 12, 33, 58, 97, 99, 100, 121, 134, 140;
20. Effect of salt on corrosion and inhibitors, 9, 10, 19, 25, 34, 42, 43, 44, 51, 55, 60, 68, 69, 82, 105, 106;
21. Cost analysis and economics, 7, 42, 46, 125, 127, 131, 138;
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REFERENCES

1. Amberg, C. R., and Williams, L. E. Rock Salt for Ice and Snow Control. Ceramic Res. Dept., New York State College of Ceramics, Alfred, Bull. 3, 1948.
2. Calcium Chloride for Ice Control. Calcium Chloride Assn., 1949.
3. Skid Resistance of $CaCl_2$—Abrasives Mixtures. Eng. Exp. Station, Iowa State Univ., 1949.
4. Pearce, D. C. A Bibliography on Snow and Ice. National Research Council of Canada, NRC 2534, 1951.
5. Salt Treatment of Snow and Ice on Roads. Road Research Laboratory, England, Road Note 18, 1953.
6. Recommended Practice for Snow Removal and Treatment of Icy Pavements. HRB Current Road Problems, No. 9-3 R, 1954.
7. Nichols, R. J., and Price, W. I. J. Salt Treatment for Clearing Snow and Ice. The Surveyor, London, 1956.
8. Gold, L. W. The Strength of Snow in Compression. National Research Council of Canada, NRC 3930, 1956.
9. L'emploi du sel pour le déglaçage des rues. Comité des Affaires Municipales de la Société de Génie de Détroit, 1956.
10. Wirshing, R. J. Effect of De-Icing Salts on the Corrosion of Automobiles. HRB Bull. 150, 1967, pp. 14-17.
11. Verbeck, G. J., and Klieger, P. Studies of "Salt" Scaling of Concrete. HRB Bull. 150, 1957, pp. 1-13.
12. Hayward, H. E., and Bernstein, L. Plant-Growth Relationships on Salt-Affected Soils. Botanical Review, Vol. 24, 1958.
13. Calcium Chloride. Industrial Chemicals Div., Allied Chemical, Technical and Engineering Service Bull. 16, 1958.
14. Kersten, M. S., Pederson, L. P., and Toddie, A. J., Jr. A Laboratory Study of Ice Removal by Various Chloride Salt Mixtures. HRB Bull. 220, 1959, pp. 1-13.
15. Dickinson, W. E. Ice-Melting Properties and Storage Characteristics of Chemical Mixtures for Winter Maintenance. HRB Bull. 220, 1959, pp. 14-24.
16. Eberhard, J. An Evaluation of the Relative Merits of Sodium and Calcium Chloride for Highway Ice Treatment. Eng. Exp. Station, Ohio State Univ., 1959.
17. Brohm, D. R., and Edwards, H. M. Use of Chemicals and Abrasives in Snow and Ice Removal From Highways. HRB Bull. 252, 1960, pp. 9-30.
18. Lang, C. H., and Dickinson, W. E. Chemical Mixture Test Program in Snow and Ice Control. HRB Bull. 252, 1960, pp. 1-8.
19. Webster, H. A. Automobile Body Corrosion Control Problems. Corrosion, Vol. 17, No. 2, 1961.
20. Schneider, T. R. Snowdrifts and Winter Ice on Roads. National Research Council of Canada, Tech. Trans. 1038, 1962.
21. Effects of De-Icing Chemicals on Structures: A Symposium. HRB Bull. 323, 1962.
22. Technical Analysis of Salt (Sodium Chloride) for Ice and Snow Removal. Salt Institute, 1962.
23. Boyd, D. W., Gold, L. W., and Williams, G. P. Radiation Balance During the Snow Melt Period at Ottawa, Canada. National Research Council of Canada, NRC 7152, 1962.
24. Current Practices for Highway Snow and Ice Control. HRB Current Road Problems, No. 9-4 R, 1962.
25. Salt for Ice and Snow Removal. Salt Institute, 1962.

26. Comparison of Chemicals for Ice Control. Industrial Chemicals Div., Allied Chemical, Information Service Bull. CC-5-1162, 1962.
27. Schneider, T. R. The Calculation of the Amount of Salt Required to Melt Ice and Snow on Highways. National Research Council of Canada, Tech. Trans. 1004, 1962.
28. Miller, L. Calcium Chloride-Salt Snow and Ice Control Test, Winter 1960-61. HRB Proc., Vol. 41, 1962, pp. 321-332.
29. Edwards, H. M., and Brohm, D. R. A Study of the Effects of Chemicals and Abrasives in Snow and Ice Removal From Highways. Ontario Joint Highway Res. Programme, Rept. 17, 1963.
30. De Quervain, M. R. Dissolution or Prevention of Ice Crusts, Ice, and Snow: Properties, Processes, and Applications. M.I.T. Press, Cambridge, 1963.
31. Himmelman, B. F. Ice Removal on Highways and Outdoor Storage of Chloride Salts. Highway Research Record 11, 1963, pp. 1-22.
32. Williams, G. P. Evaporation From Water, Snow and Ice. National Research Council of Canada, DBR Tech. Paper 164, 1963.
33. Holmes, F. W. Effects of Use of Snow Control Chemicals on Street Trees. Proc. 39th Annual Meeting New Jersey Federation of Shade Tree Commissioners, Atlantic City, 1964.
34. Conrardy, W. P. Chemical Deicing of Aircraft Runways. Highway Research Record 61, 1964, pp. 19-35.
35. Non-Chemical Methods of Snow and Ice Control on Highway Structures. NCHRP Rept. 4, 1964.
36. Lang, C. H., and Dickinson, W. E. Snow and Ice Control With Chemical Mixtures and Abrasives. Highway Research Record 61, 1964, pp. 14-18.
37. Winter Maintenance Practices in Canada: 1963. Canadian Good Roads Assn., Tech. Publ. 20, 1964.
38. Coulter, R. G. Understanding the Action of Salt. Public Works, Vol. 96, No. 9, 1965.
39. Craik, D. W., and Yuill, G. K. De-Icing Chemicals Corrosion Investigation. Mech. Eng. Dept., Univ. of Manitoba, 1965.
40. Chemical Means for Prevention of Accumulation of Ice, Snow and Slush on Runways. Monsanto Research Corp., Dayton; NTIS, Springfield, Va., AD 615 420D, 1965.
41. Protective Coatings to Prevent Deterioration of Concrete by De-Icing Chemicals. NCHRP Rept. 16, 1965.
42. The Use of Highway Salt and Its Effect on Pavements. Massachusetts Highway Salt Study, Commonwealth of Massachusetts, 1965.
43. Boies, D. B., and Bortz, S. Economical and Effective De-Icing Agents for Use on Highway Structures. NCHRP Rept. 19, 1965.
44. Highway Salt and Automobiles. Massachusetts Highway Salt Study, Commonwealth of Massachusetts, 1965.
45. Minsk, L. D. Snow and Ice Properties Pertinent to Winter Highway Maintenance. Highway Research Record 94, 1965.
46. Snow Removal and Ice Control in Urban Areas. American Public Works Association, APWA Research Foundation Project 114, Vol. 1, 1965.
47. Physical Factors Influencing Resistance of Concrete to De-Icing Agents. NCHRP Rept. 27, 1966.
48. Hogbin, L. E. Loss of Salt Due to Rainfall on Stockpiles Used for Winter Road Maintenance. Road Research Laboratory, England, RRL Rept. 30, 1966.
49. Calcium Chloride Handbook. Dow Chemical Co., 1966.
50. Doyen, A., and Sehaballie, R. Considérations relatives au traitement hivernal des chaussées. Technique Routière, Vol. 11, No. 3, 1966.
51. Salmins, G. Does Salt Corrode Cars? Engineering and Contract Record, Nov. 1966.
52. Environmental Considerations in Use of De-Icing Chemicals. Highway Research Record 193, 1967.
53. Manuel de l'entretien. Ministère de la Voirie du Québec, 1967.

54. Le chlorure de calcium et l'entretien d'hiver. Allied Chemical, 1967.
55. Fromm, H. J. The Corrosion of Auto-Body Steel and the Effects of Inhibited De-Icing Salts. Department of Highways, Ontario, Rept. RR135, Nov. 1967.
56. Manual on Snow Removal and Ice Control in Urban Areas. National Research Council, Ottawa, November 1967.
57. Manuel des équipes de déneigement. Salt Institute, 1967.
58. Roberts, E. C., and Zybura, E. L. Effect of Sodium Chloride on Grasses for Roadside Use. Highway Research Record 193, 1967, pp. 35-42.
59. Use of Salt for Snow and Ice Control. Maintenance Div., Ontario Ministry of Transportation and Communications, 1967.
60. Palmer, J. D., and West, L. H. De-Icing Salt Field Test Site Visit. Report No. 7, 1968.
61. Hegmon, R. R., and Meyer, W. E. The Effectiveness of Antiskid Materials. Highway Research Record 227, 1968, pp. 50-56.
62. The Mixer's Manual. Calcium Chloride Institute, 1968.
63. Standard Specification for Calcium Chloride. ASTM Designation D98-68, 1968.
64. Standard Methods of Sampling and Testing Calcium Chloride for Roads and Structural Applications. ASTM Designation D345-68, 1968.
65. Chae, Y. S. Viscoelastic Properties of Snow and Sand. Jour. Engineering Mech. Div., Proc. ASCE, Dec. 1968.
66. Dickinson, W. E. Snow and Ice Control—A Critical Look at Its Critics. Highway Research Record 227, 1968, pp. 48-49.
67. Hutchinson, F. E. Effect of Highway Salting on the Concentration of Sodium and Chloride in Rivers. Research in the Life Sciences, Winter 1968.
68. Corrosion and Its Prevention in Motor Vehicles. Anti-Corrosion Methods and Materials, London, Vol. 15, No. 4, 1968.
69. Corrosion Inhibitor Study (Summary). Department of Highways of Ontario, Feb. 13, 1968.
70. Minsk, L. D. Electrically Conductive Asphalt for Control of Snow and Ice Accumulation. Highway Research Record 227, 1968, pp. 57-63.
71. The Snowfighter's Salt Storage Handbook. The Salt Institute, 1968.
72. Garland, L. A., and Dalby, G. A. Calibration of the Messfix Model 100—Brake Efficiency, Recorder to Read Coefficient of Sliding Friction. SRVIC Snow Removal and Ice Control Ltd., 1968.
73. Efficient Storage and Handling of Bulk Calcium Chloride. Dow Chemical Ltd., 1969.
74. Winter Traffic Moves Safely on Highways Treated With Chemical De-Icers. Dow Chemical Ltd., 1969.
75. Winter Safety for Sidewalks and Pavement... With Calcium Chloride De-Icers. Dow Chemical Ltd., 1969.
76. Manuel du déneigement et de la lutte contre le verglas dans les régions urbaines. Comité associé de la recherche géotechnique du Conseil National de Recherche, 1969.
77. Milloy, M. H., and Humphreys, J. S. The Influence of Topography on the Duration of Ice-Forming Conditions on a Road Surface. Road Research Laboratory, England, Rept. LR 274, 1969.
78. Kelley, J. F. Massachusetts Is First in the U.S. With Industry Pre-Mix of Salt and Calcium Chloride. New England Construction, Jan. 1969.
79. Carr, F. H. Massachusetts Finds Premixed Chemicals a Boon in Winter Maintenance. Better Roads, July 1969.
80. Technique pour la lutte contre la neige et la glace. Division du sel Sifto, produits chimiques Domtar Ltée, 1969.
81. Hutchinson, F. E. The Influence of Salts Applied to Highways on the Levels of Sodium and Chloride Ions Present in Water and Soil Samples. Office of Water Resources Research, U.S. Dept. of Interior, 1969.
82. Corrosion des véhicules automobiles et influence des fondants chimiques. Rapport préparé par un groupe de recherche routière de l'O.C.D.E., Oct. 1969.

83. Ice Detector Provides Early Warning. Control Engineering, Vol. 16, 1969.
84. Williamson, P. J. The Formation and Treatment of Ice on Road Surfaces. Institution of Civil Engineers, London, Suppl. Vol., Proc. Paper 7224A, 1969.
85. Sensing System Predicts Bridge Icing. Machine Design, Vol. 41, March 20, 1969.
86. Highway Monitor Predicts Frost and Warns of Snow and Ice. Product Engineering, Vol. 40, March 1969.
87. Stockley, N. H. Liverpool's Road Ice Detection System. Roads and Road Construction, England, Vol. 47, July 1969.
88. Moss, C. R. Routing Methodology for Snow Plows and Cindering Trucks. Pennsylvania Transportation and Traffic Safety Center, TTSC 7015, 1970.
89. Scotto, G. E. Liquid Treatments of Commercial $CaCl_2$ in Winter Road Maintenance. HRB Spec. Rept. 115, 1970, pp. 156-171.
90. Johnson, C. W., De Long, A. G., and Crow, J. M. Snow and Ice Control on Roads in New Mexico. New Mexico State Highway Commission, Jan. 1970.
91. Stewart, C. Deterioration in Salted Bridge Decks. HRB Spec. Rept. 116, 1970.
92. Spellman, D. L. Chlorides and Bridge Deck Deterioration. Highway Research Record 328, 1970.
93. Watkins, L. H. Control of Road Snow and Ice by Salt and Electrical Road Heating. HRB Spec. Rept. 115, 1970, pp. 146-155.
94. Standard Specification for Sodium Chloride. ASTM Designation D 632-70, 1970.
95. Grant, C. L. Salt, Phase I in a Study of Effective Ice Control. Better Roads, Oct. 1970.
96. Calcium Chloride New Briquettes Solve Old Problems. Dow Chemical Co., 1970.
97. Hanes, R. E., Zelazny, L. W., and Blaser, R. E. Salt Tolerance of Trees and Shrubs to De-Icing Salts. Highway Research Record 335, 1970, pp. 16-19.
98. Button, E. F. Metabolic Index as a Diagnostic Tool in Tree Health Determination. Highway Research Record 335, 1970, pp. 6-8.
99. Verghese, K. G., Hanes, R. E., Zelazny, L. W., and Blaser, R. E. Sodium Chloride Uptake in Grasses as Influenced by Fertility Interaction. Highway Research Record 335, 1970, pp. 13-15.
100. Zelazny, L. W., Hanes, R. E., and Blaser, R. E. Effects of De-Icing Salts on Roadside Soils and Vegetation. Highway Research Record 335, 1970, pp. 9-12.
101. Dunnery, D. A. Chemical Melting of Ice and Snow on Paved Surfaces. HRB Spec. Rept. 115, 1970, pp. 172-176.
102. Environmental Impact of Highway De-Icing. Environmental Protection Agency, Water Quality Office, Dec. 1970.
103. Hanes, R. E., Zelazny, L. W., and Blaser, R. E. Effects of De-Icing Salts on Water Quality and Biota—Literature Review and Recommended Research. NCHRP Rept. 91, 1970.
104. Judd, J. H. Lake Stratification Caused by Runoff From Street De-Icing. Water Research, Vol. 4, Aug. 1970.
105. Salt Still Dominates in De-Icing Field. Canadian Chemical Processing, Vol. 54, 1970.
106. Forbes, C. E., Stewart, C. F., and Spellman, D. L. Snow and Ice Control in California. HRB Spec. Rept. 115, 1970, pp. 177-195.
107. Arpin, J. V. Le déneigement et la lutte contre le verglas—Situation urbaine. Service de la Voie Publique, Ville de Montréal, 1970.
108. Winters, F. Pavement Heating. HRB Spec. Rept. 115, 1970. pp. 129-145.
109. Laberge, J. Matériaux d'entretien d'hiver. Service de la Voie Publique, Ville de Montréal, 1970.
110. Etude sur la technique d'application des fondants et abrasifs. Direction générale de l'entretien, Ministère de la Voirie, Québec, 1970.
111. Salt for Spreading on Highways for Winter Maintenance: Part I—Rock Salt. British Standard Institution, 1970.
112. Salt for Spreading on Highways for Winter Maintenance: Part II—Salt Other Than Rock Salt. British Standard Institution, 1970.
113. Schaerer, P. A. Compaction or Removal of Wet Snow by Traffic. HRB Spec. Rept. 115, 1970, pp. 97-103.

114. Storing Road De-Icing Salt. Salt Institute, 1971.
115. Norme pour le chlorure de sodium (sel gemme). Bureau de Normalisation du Québec, BNQ 2410-200, Feb. 1971.
116. Norme pour le chlorure de calcium. Bureau de Normalisation du Québec, BNQ 2410-100, Nov. 1971.
117. Kyser, J. O. Brine Solution Removes Stubborn Ice. Public Works, Jan. 1971.
118. Hode Keyser, J., and Lachambre, G. Utilisation du sel de déglaçage. Ville de Montréal, 1971.
119. Facts You Should Know About Effects of De-Icing Salt on the Environment. Reporter of the American Public Works Association, 1971.
120. Caird, J. C., and Young, R. Field Test Report on Calsel 31 Road De-Icer/Anti-Icer. Allied Chemical (Canada) Ltd., 1971.
121. Salt Pollution Control Begins With Proper Storage. Rural and Urban Roads, Vol. 9, No. 7, July 1971.
122. Pryzby, S. R. De-Icing With Salt: Some Pros and Cons. Public Works, March 1971.
123. Tail-Gate Slot Restricter Cuts Salt Use. Rural and Urban Roads, Vol. 9, No. 7, July 1971.
124. Walker, W. H. Limiting Highway Salt Pollution of Area Water Supplies. Rural and Urban Roads, Vol. 9, No. 3, March 1971.
125. Tighe, D., and Webber, D. B. Planning Airport Snow and Ice Removal Using Operations Research Techniques. Highway Research Record 359, 1971, pp. 9-15.
126. Snow Removal and Ice Control Techniques at Interchanges. NCHRP Rept. 127, 1971.
127. Briser la glace. Allied Chemical, 1971.
128. New Ideas Ride With the Plows and Spreader Crews. Rural and Urban Roads, Vol. 9, No. 7, July 1971.
129. Area Maintenance Crews Ready to Fight Snow and Ice. Rocky Mountain Construction, Vol. 62, No. 17, Aug. 1971.
130. Snow Removal and Ice Control Manual. City Engineering Department, Vancouver, B.C., 1971.
131. Marsters, G. F. Canada-Wide Snow Bill, How Much? Civic Administration, 1971.
132. McCullough, T. A General Method for Stockpile Volume Estimates. National Sand and Gravel Assn., Circular 112, 1971.
133. Les avertisseurs de verglas. Revue générale des routes et des aérodromes, Oct. 1971.
134. Hutchinson, F. E. Dispersal of Soil-Bound Sodium From Highway Salting. Public Works, Vol. 103, No. 2, Feb. 1972.
135. Williams, G. P. Summary of Current Research on Snow and Ice in Canada. National Research Council of Canada, Tech. Memo. 106, 1972.
136. Smith, R. W., Ewens, W. E., and Clough, D. J. Effectiveness of Studded Tires. Highway Research Record 352, 1971, pp. 39-49.
137. Bishop, R. R. The Development of a Corrosion Inhibitor for Addition to Road De-Icing Salt. Transportation and Road Research Laboratory, England, Rept. LR 489, 1972.
138. Chandler, P. L., and Luoto, D. S. Managerial Aspects of a Chemical Reduction Program. Published in this Record.
139. Interim Report of the Special Commission on Salt Contamination of Water Supplies and Related Matters. Commonwealth of Massachusetts, 1973.
140. Brandt, G. H. Potential Impact of Sodium Chloride and Calcium Chloride De-Icing Mixtures on Roadside Soils and Plants. Published in this Record.