## HIGHWAY RESEARCH BOARD

Bulletin 252

## Snow and Ice Control

## with

## Chemicals and Abrasives



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# N.R.C. HIGHWAY RESEARCH BOARD 

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## 1960

Washington, D. C.

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## Chemical Mixture Test Program in

## Snow and Ice Control

C. H. LANG, Chief Engineer, New York State Thruway Authority; and<br>W.E. DICKINSON, Chief Engineer, Calcium Chloride Institute

DURING THE WINTER of 1958-59, the New York State Thruway Authority, in conjunction with the Calcium Chloride Institute, conducted a research program on the use of chemical mixtures of calcium chloride and rock salt in winter maintenance. Previously, rock salt and sand abrasives were relied on to combat the winter storm conditions.

The Weedsport Maintenance Section was selected as the test area for using calcium chloride along with salt and abrasives, the purpose was to obtain (a) information on faster and more effective melting action; (b) data on economy of materials; and (c) information on handling, storing, and applying calcium chloride mixtures.

Weedsport Maintenance Section extends from MP 289 to MP 321 (approximately 32 mi ). To determine the effect of the calcium chloride, in this test program, results in a $10-\mathrm{mi}$ portion of the Syracuse Maintenance Section (MP 279 to MP 289) and in a 10-mi portion (MP 321 to MP 331) in the Manchester Section were compared to results in the Weedsport Test Section. Both the Syracuse and Manchester Sections were instructed to carry out their normal winter maintenance procedures using salt and abrasives. Report forms were filled out by supervisory personnel, noting weather and pavement conditions during storms in each test area. These reports, plow operator's reports, and summary reports from Section Supervisors were collected after each storm.

Calcium Chloride Institute recommended a mixture ratio of one part calcium chloride to three parts of rock salt by weight (1:3) for the chemical mixture. It was more practical to proportion and mix the two chemicals by volume in the field and a ratio of one part calcium chloride to two parts of salt (1:2) by volume was determined approximately the same. This mixture ( with some variations and with different proportions of abrasives) was used in the snow and ice operation.

## STORAGE OF BULK CALCIUM CHLORIDE

For the storage of the bulk calcium chloride, a wood frame structure of 80-90 tons capacity was added to an existing concrete block salt storage shed, utilizing one side wall of the salt shed. The storage shed front was rigged with an adjustable canvas, raised to unload or lowered to protect the calcium chloride from the weather. The 16 -ft shed allowed adequate area for the belt conveyor to be backed into the shed while unloading calcium chloride. (No difficulties were encountered with crusting or hardening of the calcium chloride during the winter.)

## HANDLING AND MLXING CHEMICALS

The normal method of loading the hoppers on the highway spreaders is with a $3 / 4$-yd front-end loader. The first method was as follows: bucket loads of calcium chloride, salt and abrasives were loaded into the spreaders in desired proportions; spreaders were loaded with alternate layers of calcium chloride, salt, and abrasives.

This method was not entirely satisfactory. It slowed loading time during a storm and confused the pay loader operator who was instructed to load materials from three piles in different proportions. A thorough mixing of chemicals was not obtained resulting in an uneven distribution of materials on the road.

The second method included premixing a stockpile of calcium and salt between storms with a front-end loader and a better mixture was obtained. It was handled a second time when loaded into the spreader which furthered the mixing.

The third and most effective mixing method was with the belt conveyor. It was
rigged with two hoppers: one was permanently bolted to the conveyor; a second hopper, on skids, was placed over the conveyor belt. Calcium chloride was loaded into one hopper and salt into the second; gates on each hopper were adjusted to obtain desired mixture. This resulted in a thorough, evenly distributed mixture which was then stockpiled prior to storms.

## FINDINGS OF THE CHEMICAL MIXTURES TEST PROGRAM

The following conclusions were made after observing the use of calcium chloride and salt mixtures in the Weedsport Maintenance Section for the past winter:

1. The chemical mixture has a much faster melting action than straight salt. This action results in a bare pavement sooner (with a comparable reduction in time and use of equipment). The farther the temperature dropped below 30F, the greater was the difference in time of melting action between the chemical mixture and the straight salt, favoring the mixture.
2. With temperatures in the mid 20 's after a storm ends, the pavement was cleaned in 15 to 20 min after spreading the chemical mixture.
3. The chemical mixture used with abrasives holds them to the pavement. It prevents the abrasives from being swept off by the wind and traffic much better then straight salt.
4. With a sudden drop in temperature, and slush on pavement, when using rock salt, the pavement can become glazed, thus requiring an additional application of salt to obtain a dry pavement. By using the chemical mixture no glazing occurred when similar temperature conditions were encountered.
5. Weedsport increased by about 20 percent the spread of chemicals per truck over that obtained with straight salt due less throw off and bounce. Formerly, the maximum spreading speed was about 25 mph . With mixtures, the spreading speed was increased to 30 mph . This speed increased the length of spread from an average of 15 to 18 mi . It decreased the amount of materials spread from about 750 lb per mi to 600 lb per mi.
6. A premixed (25-30 tons) stockpile of calcium chloride and salt was prepared during fair weather for use during the early part of storm. No protection from the weather was necessary. Crusting did not occur except after a rain, when the premixed pile developed a 2 -in. thick crust easily broken during later handling. Several times this type stockpile was successfully kept for over a week before using.
7. A satisfactory mixture for most all storm conditions was two parts mixed chemicals ( $1: 3$ calcium to salt, by weight) mixed with one part abrasives. This mixture was nearly as effective in melting action as clear chemical and provided abrasives for skid protection. This mixture is more economical than using straight salt and better results were obtained with it.
8. One observation noted from the use of calcium chloride with rock salt is the lack of visible salt residue, which with straight rock salt, is deposited on pavement and shoulders. This salt residue is apparent on the pavement for several days after a storm; it was, as late as spring, still obvious on the shoulders and mall along the pavement edge in Syracuse and Manchester Sections. It is assumed that it was because of the use of calcium chloride that very little of this salt re-crystallization was noted in the Weedsport Section.
9. It was found that spreaders could not be kept standing loaded with calcium chloride and salt for more than several hours in a warm garage without caking starting to occur in the spreader box. Therefore, spreaders were not preloaded with the chemical mixture. Immediately after a storm, each truck, spreader, and spreader box was rinsed free of all calcium and salt.
10. Some difficulty was encountered by calcium chloride caking on the wires of unprotected spreader motors, and motors of equipment used to load calcium chloride, by shorting the ignition. For this reason, there was difficulty at times starting equipment previously used. This difficulty was corrected to some extent by (a) covering openings around the spreader motor, such as around the exhaust pipe; and (b) by washing down the equipment with hot water after use.

## COST STUDIES

While it has been found that many benefits are obtained from using calcium chloride during winter operations, the second reason for this test program was to determine the economics of using calcium chloride. Tables have been prepared showing comparisons between the three maintenance sections (Syracuse, Weedsport, and Manchester) for the past several years and attempts have been made to establish what, if any, savings were realized. Note that there are many variables between each section as to traffic and weather conditions, particularly in weather conditions from one section to another and from year to year.

The winters in which there are many repeated snow storms and squalls are the years in which the salt consumption is the highest if the average temperatures are the same (Fig. 1). Often a storm producing 2 to 3 in . of snow will require as much salt to be spread as a storm producing 12 in . However, another factor in the amount of salt consumption is the variant winter temperatures. During the winter of 1957-58, the average temperature in the Syracuse Section for the months of December through March was 27.4F. During the same period in 1958-59, the average temperature was 23. 3 F , an average temperature drop of 4.1 F . Although the average number of days of snowfall and the total snowfall for the two seasons were about the same, during the 58-59 season, the consumption of salt in the Syracuse Section was 620 tons greater.

In Rochester, New York, the average temperature was 27. 8F during the 1957-58 winter and 24.0F during the 1958-59 season; a lower average temperature of 3.8F


Figure 1. Accumulation of snowfall - weather station at Hancock Field, Onondaga Co. Data for calcium chloride test progrom.

TABLE 1
COMPARISON OF SALT AND ABRASIVES USED ON HIGHWAYS FOR WINTER MAINTENANCE

| Section | Tons of Salt Used on Highway During Winter of 1957-58 1958-59 |  | $\begin{array}{cc} \text { Increase } & \text { 1958-59 } \\ \text { Over } & \text { 1957-58 } \\ \text { Tons } & \% \\ \hline \end{array}$ |  | Estimated Tons of Salt Weedsport Would Have Used in 1958-59 Tons $\%$ |  | Tons of Abrasives Used During$\text { 1957-58 } 1958-59$ |  | $\begin{gathered} \text { Tons Change } \\ \text { 1958-59 vs. } \\ 1957-58 \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Syracuse division | 12,650 | 15,490 | 2,840 | 22.5 | 4,408 | 22.5 | - | $\checkmark$ |  |
| Syracuse | 2, 610 | 3, 230 | 620 | 23.8 | 4,210 | 17.3 | 4,345 | 3,500 | 845 |
| Weedsport | 3, 590 | 3, $810^{1}$ | 220 | 6.1 | 4,210 | - | 3,440 | 3,720 |  |
| Manchester | 2,350 | 3,230 | 880 | 37.5 | 4,470 | 24.5 | 2,025 | 3,500 | +1,475 |

${ }^{1} 3,810$ tons includes 3, 040 tons rock salt and 770 tons of Calcium chloride.
during the 1958-59 season (Fig. 2). The salt consumption (adjacent to Rochester) in the Manchester Section was 880 tons greater during the 58-59 season.

It seems reasonable to conclude that lower temperatures encountered during the season of 1958-59 at both Syracuse and Rochester resulted in a greater use of salt.

Table 1 gives the summations of the total amount of salt used on the Thruway in the three sections for the past two years. Columns 3 and 4 show the tons and percent increase of 1958-59 over 1957-58's consumption. The Syracuse Division salt consumption for highways (1958-59) increased by 2,840 tons, a 22.5 percent increase over 1957-58. On this basis, Weedsport would have used an estimated 4, 408 tons of straight salt. Likewise by comparing with the Syracuse Section and adding their tons increase to the Weedsport total for 1957-58, 4, 210 tons is estimated or a 17.3 percent increase, if straight salt were used. By comparison with the Manchester Section, a total of 4,470 tons is netted, or a 24.5 percent increase. Averaging these last two figures,


Figure 2. Accumulated snowfall in Rochester, New York area. Data obtained from weather bureau Rochester municipal airport.
the estimated consumption of straight salt is 4,340 tons or a 20.9 percent increase over the previous winter.

On this basis, 530 tons of salt ( 17.6 percent) were saved by using a calcium chloride and salt mixture (Fig. 3). By noting the cost F.O. B. at Weedsport for the past winter, a cost comparison is obtained, as follows:

On a basis of straight salt estimated at 4,340 tons

$$
4,340 \text { tons } \quad \$ 13.65 / \text { ton } \quad \$ 59,241.00
$$

On using a total of 3,810 tons of calcium-salt mixture

| Salt | 3, 040 tons | \$13.65/ton | \$41,496. 00 |
| :---: | :---: | :---: | :---: |
| Calcium | 770 tons | 28.50 | 21,945.00 |
|  | 3,810 tons | Total cost | \$63,441.00 |

By comparing prices, the apparent increase cost resulting from the use of mixtures is \$4,200. Regarding this figure, it should be pointed out that it is not logical to assume that additional salt would have accomplished results equal to those of the mixture; its superiority over salt is indicated by the tests. It is difficult to estimate expenditures, had salt alone been used.

Estimated cost increase is also offset by other savings from chemical mixtures. Eliminating handling and applying of an estimated 530 tons of salt, these savings might be:

Average load per Highway Spreader

| 530 | tons |
| :---: | :--- |
| 6 | tons $/$ trip |$\quad 88.3$

6 tons
Approx. 88 trips with the highway spreader saved
Average distance traveled per spreader load (including dead haul) 25 mi .
88 trips $\times 25 \mathrm{mi} /$ trip $-2,200 \mathrm{mi}$ saved on highway spreader this year.
To verify the mileage saved on the highway spreaders, Table 2 gives the actual number of miles traveled in each section by the highway spreaders for the past two years. By comparing these figures, it shows that up to $2,600 \mathrm{mi}$ were saved by the Weedsport spreaders when compared with the Manchester Section. Likewise with


Figure 3. Accumulative curve - tons of chemicals used in Manchester, Weedsport and Syracuse sections during winters of 1957-58 and 1958-59.
the Syracuse Section, a savings of $3,200 \mathrm{mi}$ may be noted. These figures verify the distance of $2,200 \mathrm{mi}$ eliminated by not having to spread salt.

Table 3 gives data on manhours by the three maintenance sections during the winters of 1957-58 and 1958-59. As of this time, no data were available on the manhours in November and December of 1957, so the only comparisons that can be made are for January, February, and March for the two winters. From this Table, it can be seen that a large decrease occurred in total manhours in each section for the quarter of January to March, 1959, as compared with the corresponding period in 1958.

This large decrease in manhours for the 1958-59 winter is due to a reduction in personnel and to a change in the winter maintenance schedule from 1957-58. It should also be noted that the manhours in Syracuse Section do not include the manhours by the Syracuse Division Highway Crew, which are relied upon by the Syracuse Section for plowing operations during the winter.

The conclusions obvious from this comparison are that there is a larger decrease in total manhours in the Weedsport Section, from last year, than in either the Manchester and Syracuse Sections. If the use of chemical mixtures by the Weedsport Section has caused any of this reduction in manhours, this reduction would be the result of a decrease in overtime hours worked.

A comparison with the Manchester Section indicates a reduction of 1,504 $\mathbf{h r}$ for the Weedsport Section or a savings of approximately $\$ 2,940$. A better comparison would be to compare overtime in each section for each year, but the records for 1957-58

TABLE 2
COMPARISON OF TOTAL MILEAGE ON HIGHWAY SPREADERS BY
SECTION FOR WINTER SEASON

|  | Total Mileage |  | Increase in Mileage |  |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
| Section | On Highway <br> $1957-58$ | Spreaders <br>  | $\mathbf{1 9 5 8 - 5 9}$ | $1958-59$ <br> $(\mathrm{mi})$ |  | $1957-58$ <br> $(\%)$ |
| Syracuse ${ }^{1}$ | 28,100 | 36,700 | 8,600 | 30.6 |  |  |
| Weedsport | 37,600 | 42,990 | 5,390 | 14.3 |  |  |
| Manchester | 34,600 | 42,630 | 8,000 | 23.1 |  |  |

${ }^{1}$ Includes allowance for Division Reserve Spreader No. 338.

TABLE 3

| Total Manhours Worked During Winter Season 1957-58 |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Date | Syracuse No. of Hours | Section Accum. Hours | Weedsport <br> No. of Hours | Section Accum. Hours | Manchester <br> No. of Hours | Section <br> Accum. Hours |
| November 1957 |  | No | Information |  | Available |  |
| December 1957 |  | No | Information |  | Available |  |
| January 1958 | 6, 722 | $(6,722)$ | 8, 373 | $(8,373)$ | 7, 295 | $(7,295)$ |
| February 1958 | 5,421 | $(12,143)$ | 6,810 | $(15,183)$ | 6,128 | $(13,423)$ |
| March 1958 | 4, 109 | $(16,252)$ | 5,175 | $(20,358)$ | 4,708 | $(18,131)$ |
| Accuraulated hours for 3-month period January - March 1958. |  | $(16,252)$ |  | $(20,358)$ |  | $(18,131)$ |
| Total Manhours Worked During Winter Season 1958-59 |  |  |  |  |  |  |
| November 1958 | 5,918 | 5,918 | 5,919 | 5, 919 | 6, 008 | 6, 008 |
| December 1958 | 5,118 | 11, 036 | 5,355 | 11, 274 | 6,242 | 12, 250 |
| January 1959 | 5, 020 | 16, 056 | 6,954 | 18, 228 | 6,635 | 18,885 |
| February 1959 | 4,515 | 20,571 | 5,475 | 23, 703 | 5,114 | 23,999 |
| March 1959 | 3,703 | 24, 274 | 4,448 | 28, 151 | 4,405 | 28,404 |
| Accumulated hours for 3-month period January - March 1959. |  | 13,238 |  | 16,877 |  | 16,154 |
| Difference in accumulated hours between 1958 and 1959. |  | 3,041 |  | 3,481 |  | 1,977 |

were inadequate for this purpose. For the next winter test program, it will be possible to obtain a record of overtime worked by each section for a comparison with this winter's operation.

There are other advantages obtained by the use of calcium chloride which a monetary value is nearly impossible to assign. If the use of calcium chloride results in clear and bare pavement in a shorter time, this, in turn, would result in not only less overtime for the maintenance forces, but will also result in fewer accidents and slide-offs due to slippery pavement. While no records are available in Syracuse for obtaining a comparison of the slide-offs in previous years, it is believed that there were fewer property damage reports and fewer cases of automobile slide-offs from the pavement in 1958-59 than in previous years. This results in better public relations due to safer conditions for the traveling public. Certainly time and consequently economy is realized by normal traffic flow resulting from bare pavement.

Some comparison should be made as to the relative cost of the calcium chloride and salt. Prices delivered to the Weedsport Maintenance Area for the winter season are as follows:

$$
\begin{array}{lr}
\text { Calcium Chioride } & \$ 28.50 / \text { ton } \\
\text { Rock Salt, Grade CC } & 13.65 / \text { ton } \\
\text { Abrasives } & 2.00 / \text { ton }
\end{array}
$$

At this price of materials, the cost of a ton of calcium chloride and salt mixture at the $1: 3$ ratio, (by weight) is $\$ 17.36 /$ ton. This is an increase of $\$ 3.71$ per ton (27. 2 percent over the cost of a ton of straight salt. As noted previously, the 530 tons of salt saved was saving of 17.6 percent. Because the addition of calcium increases the cost 27.2 percent, approximately an additional 10 percent savings should be realized from the saving in time, labor, and equipment to obtain comparable costs with straight rock salt.

Abrasives with the chemical mixture provide a combination cheaper per ton than the cost of rock salt.

## Mixture Ratio:

2 parts chemical to 1 part abrasive (by volume)
Cost $\$ 10.95$ per ton
This mixture, while cheaper than straight salt, proved to be an excellent all around mixture. It was used under almost all storm conditions, with greater effectiveness than straight salt, and provided abrasives for skid protection.

Based on the following weights:
Calcium chloride 60 pcf
Rock salt 75 pcf
Abrasives 100 pcf

## FUTURE WINTER STORM PROCEDURES

To further compare data from the 1958-59 experiment using calcium chloride mixtures, it was decided to carry out the test program for another year. By utilizing past experience and proceeding with mixtures that have proven valuable and economical, it is believed that another winter of testing may prove that a comparable job can be obtained with a further reduction in cost.

Based upon the experiment, the following storm procedures are recommended for the 1959-60 winter season:

1. Ice and Sleet Storms: Use chemical mixture ( 1 to 2 parts calcium to salt by volume) with or without abrasives. The first spread on the pavement will be with clear chemical mixture. This is to be followed, if additional spreading is necessary, with a mixture of equal parts of chemical and abrasives.
2. Temperatures near 30F plus or minus and above: Use clear rock salt.
3. Temperatures in range of 25 to 30F: Use chemical mixture, with or without abrasives, depending upon the time of day and existing weather conditions.
4. Temperatures near 25 F and falling: Use chemical mixture with abrasives in varying proportions, depending upon the temperature. As the temperature decreases, increase the amount of abrasive to proportions as high as one part chemical mixture to two parts abrasives. Strive to discontinue the use of chemicals and obtain a dry pavement with abrasives. They tend to blot up the moistures on the pavement and also provide skid protection for moving traffic.
5. Temperatures below 20F, and dry snow conditions: Depend on plowing operations to maintain clear pavement and discontinue the use of any chemicals.
6. For heavy snow storms, temperatures range 20 to 30F: Depending upon the temperature as noted previously, apply salt, or mixtures with abrasives to pavement at the beginning of a storm to prevent packing and bonding of snow to pavement. Continue plowing operations until storm ends and clean pavement by use of procedures 1-5.

The above procedures are intended as a guide and their use depends on the observations and experience of supervisory personnel and on the existing traffic conditions.

## SUMMARY

The 1958-59 winter operations have definitely pointed to the benefits that can be obtained by the use of calcium chloride. The calcium chloride greatly speeded up the slower melting action of rock salt and a mixture of the two chemicals tends to combine the advantages of both chemicals making the mixture more effective than the use of either chemical alone. With the use of straight salt it has been felt that a great deal of melting action of the slower acting salt has been wasted due to the frequency of the plowing operations. With the calcium chloride starting the melting action immediately, many more benefits are obtained.

In summarizing the results of this test program, it should be stressed that while much was learned about the use of calcium chloride, different proportions and mixtures were experimented with, which are not always economical. With the test program being extended for another season, it is felt that the value of using calcium chloride will be further demonstrated not only by its performance, but also from the economic viewpoint. By utilizing the storm procedures obtained from the previous winter's test, it is felt that the economic's of using chemicals mixtures will be shown. The advantages of the use of abrasives in the mixtures were not fully recognized until late in the winter season and will definitely be utilized to full advantage next year.

# Use of Chemicals and Abrasives in Snow and Ice Removal from Highways 

D. R. BROHM ${ }^{1}$, Maintenance Section, Ontario Department of Highways, and<br>H. M. EDWARDS, Professor of Civil Engineering, Queen's University, Kingston, Ontario

> Ontario, like the other provinces of Canada and many of the northern states of the United States, faces each winter the tremendous task of removing snow and ice from highways and city streets. In recent years the demand for year-round bare pavements seems to have grown extensively and the maintenance groups who perform this work find their requirements increasing annually.

> Assuming that the demand for bare pavement will continue to exist and there is no reason to assume otherwise-and also therefore that the cost of this work is not likely to decrease-it was decided to study carefully this entire question of snow and ice removal from the highways. It was thought that such a study might provide some clues concerning the melting effect of the various chemicals currently used and also an evaluation of the effect of mixtures of chemicals and abrasives.

> Within the framework of this study no attempt was made to develop or investigate chemicals other than those currently in use, namely sodium chloride and calcium chloride. This does not mean that other chemicals have been ruled out rather it was thought that a better understanding of present practice might well lead to improved efficiency and economy.

> It may be argued that investigations of this kind have been performed by others. Nevertheless, review of the literature indicated that several gaps in the knowledge of this subject still exist. In fact, many of the test methods which have been used by others (1), were stated to be open to question which, of course, leads to the obvious conclusion that the results would also be somewhat suspect.

OUPON RECOGNIZING the difficulty others had experienced, it was decided to attempt to develop a testing method which would produce reliable reproducible results. On completion of this step in the study it was then possible to determine the effect on the melting action of the various chemicals of such variables as the time of reaction, the temperature of the ice or snow and the concentration of the chemical. It was thought that by means of carefully designed experiments it would be possible to develop mathematical expressions which would relate these principal variables. Such expressions would then permit an estimate to be made of the most efficient chemical application for a given set of conditions.

Since the literature appeared to be somewhat incomplete regarding melting comparisons of calcium chloride and sodium chloride under a variety of conditions it was

[^0]felt that such a comparison should be made. In addition, mixtures of the two chemicals were also treated in order to evaluate their melting action.

Finally, because mixtures of abrasives and chemicals are used by many agencies, a decision was made to test such mixtures in order to evaluate the melting action. Comparisons with melting results obtained when the chemical alone was used would be expected to give an indication of the effect of these treatments.

Certainly many other factors might very well be expected to affect the melting of ice and snow from pavement. However, it was decided to confine interests principally to a laboratory analysis of those factors previously outlined. Although field studies would have been desirable, and were in fact scheduled, the weather during the winter of 1957-58 did not cooperate and too little data were obtained to be of any real value.

## TESTING PROCEDURES

In designing the experiment, advice was obtained regarding the number of tests required to provide an adequate sample for subsequent statistical analysis. This preliminary study confirmed the decision to limit the number of variables in the study.

The chemicals used in the study were coarse crushed (C.C.) rock salt, fine crushed (F.C.) rock salt, flake calcium chloride and pellet calcium chloride. All of the chemicals were used as supplied except that the rock salt was graded to meet the requirements of grading curves currently specified by the Ontario Department of Highways. The sand used in the experimental work was graded to satisfy a specified grading curve of the same agency. Grading requirements for rock salt and sand and the test gradings are given in Appendix $F$.

Each of the chemicals was tested separately and, in addition, mixtures consisting of C.C. rock salt with both types of calcium chloride and both C.C. and F.C. rock salt with various quantities of sand were tested. Details of the mixtures used and the raw data results are given in Tables 1 to 5 of Appendix A.

The testing program consisted of measuring the amount of ice melted by the various chemicals and mixtures under known conditions of chemical concentration, time of reaction and temperature. In order to evaluate the testing method which differed from methods used by others, two test runs were made on different dates using the same material and the results were analyzed for significant differences.

The details of the laboratory equipment and testing technique are not included in this paper in the interest of brevity. However, the interested reader will find all the details in a report (2) to be published by the Ontario Joint Highway Research Program.

## ANALYSIS OF THE DATA

The first objective of the data analysis was to evaluate the effectiveness of the testing method. In order to make this evaluation, an analysis of variance was carried out on duplicate sets of data collected some eight months apart. These duplicate data consisted of complete sets of results using both C.C. and F.C. rock salt. In effect the results of this analysis had to be completed before additional testing could be undertaken.

The results obtained were most encouraging and indicated that the differences which occurred could largely be attributed to chance. Also this analysis indicated certain areas when the testing method could be refined in order to produce more reliable results.

Upon gaining reasonable assurance that the testing method was adequate, the remainder of the tests were performed and again the analysis of variance technique was used to evaluate the effects of the main variables, that is, time, temperature and concentration.

Similarly the same mathematical tool was used in determining the effect of adding various quantities of sand, the effect of mixing the chemicals and also for comparing the effectiveness of the various chemicals tested.

It should also be noted that an added advantage of this analysis technique is that by its use it was possible to determine the relative influence of the linear, quadratic and cubic components of the main variables under consideration, and in addition, the
interaction of these main variables could also be established.
Because of the extent of the data, it is not reasonable to present all of the graphical plots, and, in fact, such presentation would probably be more confusing than helpful. Therefore, many of the plots contained in the following section of the paper are simply typical illustrations of the tests and should be so interpreted.

## RESULTS

## Effects of Principal Variables

The analysis of variance indicated that each of the principal variables had highly significant effects on the results and hence it can be inferred that real differences in melting can be associated with the three variables for all chemicals tested. Further it was found that the principal portion of the main effect in each case was contributed by the linear component. Although in some cases the quadratic and cubic components were also found to be significant, it was felt that the very large effect of the linear component in all cases indicated that a linear function could be expected to express reasonably the melting action of the various chemicals and mixtures.

It was also found that the various two factor interactions were highly significant. This indicated that the isolation of a single variable cannot be undertaken but rather the results are dependent on the combined effect of the variables. Thus, it should be understood that the figures shown later in this report indicating mean effects must be qualified according to the interaction effect. This does to some extent limit the scope of the data but at the same time it is believed the results should be of considerable interest.

## Time Effect

The analysis of variance indicated that the effect of time was to contribute real differences to the results. This was to be expected since consideration of the raw data showed that the longer the chemical was permitted to act the greater the amount of melt.

Figure 1 is a representation of the effect of time for a single row of data in a cell. This plot tends to be typical of the results showing the time effect. It should be noted that in this plot the result is expressed in terms of what has been termed unit yield or unit melt which has been defined in this study as the weight of melted ice per unit weight of chemical applied.

Figure 2 shows the plot of an entire cell of data consisting of 16 points. These curves are essentially the same as the curve in Figure 1 except that the melt is given in terms of the total melt or pounds of ice melted per square yard of ice surface. Again the increase in total melt as time increases is quite evident.

To further illustrate this phenomenon Figure 3 has been prepared. The curves have been derived by plotting the mean melt results for each chemical for a given reaction time at all temperatures. This plot is of greater value in comparing the chemical types but it does tend to confirm what has been previously stated with regard to the relation between the amount of melt and time.

On the basis of these data it is apparent that where it is permissible to permit relatively long reaction times a saving of chemical is possible.

## Concentration Effect

The analysis showed clearly that variations in the rate at which chemical was applied produced significantly different melts. Figures 4 and 5 correspond to Figures 1 and 2 except that these curves are plots of a section of the regression surface developed later in this paper. These plots are representative of the other test results pertaining to concentration.

Figure 4 indicates that the greatest melting efficiency occurs at the low concentration. This then tends to indicate that attempts to melt large quantities of ice will be most uneconomical.


Figure 1. The time effect on unit yield ( tests $\mathrm{S}_{\mathrm{c}} \mathrm{S}_{0} \mathrm{~T}_{2} \mathrm{C}_{1}$ ).


Figure 3. Mean time effects.


Figure 2. The time effect on total melt (cell data $\mathrm{S}_{\mathrm{c}} \mathrm{S}_{\mathrm{o}} \mathrm{T}_{2}$ ).


Figure 4. The concentration effect on unit yield (tests $\mathrm{S}_{\mathrm{c}} \mathrm{S}_{\mathrm{O}}^{2} \mathrm{~T}_{4}$ ).

Figure 5 indicates that a maximum total melt occurred for each reaction time thus implying that concentrations in excess of this maximum would be truly wasteful.

Figure 6 gives a plot of the mean value of total melt for the various concentrations of the different chemicals. Each plotted point once again represents the mean of 16 test values. Since chemical types will be discussed separately it is sufficient to point out that pronounced variations in the effect of application rate do occur for the different chemicals tested.

## Temperature Effects

In order to show the temperature effect on melting of the ice samples, Figures 7 and 8 have been prepared.

Figure 7 gives the estimated unit yield results for the various time periods on the regression analysis. 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. Thus, on the basis of these data it would seem that C.C. rock salt is most effective in the range of 20 to 32 F .


Figure 5. The concentration effect on total melt (cell data $\mathrm{S}_{\mathrm{c}} \mathrm{S}_{0} \mathrm{~T}_{2}$ ).


Figure 6. Mean concentration effects.


Figure 7. The temperature effect at equilibrium and at specified time (cell data $\mathrm{S}_{\mathrm{c}} \mathrm{S}_{0} \mathrm{C}_{1}$ ).


Figure 8. Mean temperature effects.
In addition to the four time-curves plotted in Figure 7, a fifth has been plotted. This curve, often referred to as the "equilibrium curve" for sodium chloride, shows the melting capacity of sodium chloride (3). There is some suggestion that this curve has been used to estimate the actual melting effect of rock salt. The danger of such action is, of course, obvious from the data plotted. No doubt if reaction times were extended the equilibrium curve would be attained but it seems difficult to say what that time would be. Also, in a practical sense, it is questionable to what extent reaction times in excess of one or two hours are significant in present day snow and ice removal.

Figure 8, giving a plot of the mean values, has been presented to indicate the similarity of the effect of temperature on the various chemicals tested.

It should be noted that the temperature referred to in these tests is the temperature of the snow or ice cover immediately prior to the application of the chemical. This temperature, in the field, is unlikely to be the same as that of the surrounding air.

## Chemical Type Effect

In this discussion C. C. rock salt, F.C. rock salt, flake calcium chloride and pellet calcium chloride have been considered as separate chemical types for comparison purposes.

From the analysis of variance it was found that in comparing C.C. rock salt with F. C. rock salt, the mean melt values obtained in the tests of these chemicals differed significantly with the F.C. rock salt producing the greater melt. Similarly the comparison of flake and pellet calcium chloride resulted in an observation of significant differences in the mean melt with the pellet variety developing the greater melt.

In order to visualize the influence of reaction time, concentration and temperature on the four chemical types, reference should be made to Figures 3,6 and 8 respectively. It should be recalled that each point plotted on these curves represents the mean of 16 experimental results.

It is significant to note that in each of the plots the mean melt obtained from the calcium chloride tests is considerably greater than that of the rock salt. Also the pellet variety of calcium chloride consistently produced more melt than the flake calcium chloride. This latter situation might have been expected because of the difference in purity of the two products, but the purity alone does not explain the total difference since the curves are seen to diverge. It is probable that particle shape may influence the melting characteristics to some extent but no definite proof of this statement can be made at this time. Moreover it is apparent that in all cases the superiority of the pellet calcium chloride over the flake type increases as the time, concentration and temperature increases. This is particularly noticeable in Figure 8 where the two chemicals show essentially the same characteristic at low concentrations but at high concentrations are decidedly different.

Comparisons of the two types of rock salt shows that the F.C. rock salt is somewhat superior in practically all cases. However, at high concentrations the C.C. rock salt exhibited slightly higher melts than the F.C. type. Certain difficulties were encountered in obtaining an even spread due to "caking" of the F. C. rock salt and this factor may partially explain the latter differences. In addition, the variability of the F.C. rock salt results were always greater than for the other chemicals which provides further evidence of the difficulty in handling this material.

Of interest also, are the similarity of the curve plots in Figures 3 and 8. This similarity tends to indicate that the reaction time and the temperature variable influence the melting characteristics of the four chemical types in a similar manner. On the other hand variations in concentration affect the four chemicals in a decidedly different manner. With increasing concentration the melting of the calcium chloride samples increases at a relatively uniform rate whereas the rate of melting of the rock salt tends to decrease with increasing concentration. It should also be noted that at the low concentrations the mean melts of all of the chemicals tested do not differ appreciably. This fact should be of value in making decisions concerning the selection of a chemical for snow and ice melting purposes.

## Sand Effect

Due to time limitations it was only possible to examine rock salt-sand mixtures in this study. In each of the tests, the amount of chemical was the same as in the previous tests and only the quantity of sand was varied. The results of this analysis are given in Figure 9.

It is quite evident from the plot and also from the analysis of variance that the principal effect of the sand was to retard the melting action of the chemicals tested. The effect of the sand on the F.C. rock salt was found to be more pronounced than on the C.C. rock salt within the range tested.

One would not expect the linear trends of the plotted curves to continue as the quantity of sand was increased but unfortunately the actual slope of the remainder of the curve cannot be established at this time because of lack of data.

On the basis of this part of the study it would appear that, where abrasives are necessary, mixtures with C.C. rock salt will produce better melting results than mixtures with F. C. rock salt but at the same time the effectiveness of the melting action of the salt is greatly reduced.

## Calcium Chloride - C. C. Rock Salt Mixtures

Since some discussion has taken place in recent years regarding the possibility of combining rock salt and calcium chloride for application on the road, it was decided to attempt to evaluate the effects of some mixtures of these chemicals.

The results of these tests are shown in Figures 10 and 11 and indicate the main results in terms of unit yield or unit melt. It must be clearly understood that these plots in no way reflect the conditions for a single set of conditions but rather are mean values obtained from 64 measurements. The reason for this approach was to enable comparisons to be made using the analysis of variance technique.

Figures 10 and 11 each contain a curve which shows a calculated or expected yield for the mixture. The values used in plotting these curves were determined by proportioning the melt data obtained when the two chemicals were tested separately. It is interesting to note that the difference between the combined chemical tests and the estimated values is reasonably small. This suggests, then, that a knowledge of the melting characteristics of the separate chemicals will enable estimates to be made of the melt which might be expected if the chemicals are combined. The results of these tests might well have been expected but were performed since there has been, on occasion, some suggestion that this was not the case. To be sure slight differences have been found to exist between the experimental and estimated results however " $t$ " tests failed to develop sufficient evidence to clearly indicate that these differences were truly significant.

A combination of " t " tests and analysis of variance results did indicate, however, that at all levels of the test of the mixtures significant differences in the melt did occur. In other words it is reasonable to suggest that the addition of increasing quantities of calcium chloride of either flake or pellet type to C.C. rock salt tends to improve the melting effect. This fact is clearly shown in Figures 10 and 11.

## Interactions

Comment must be made with regard to the two factor interactions evaluated in the


Figure 10. Mean flake calcium chloride admixture effect.


Figure 11. Mean pellet calcium chloride mixture effect.
analysis of variance. The interactions, for the most part, were found to be highly significant. In effect this means that the results depend on two interacting variables and therefore the effect of either variable should only be discussed at a fixed level of the other. Where significant interactions occur they are apparent by noting the tendency of curves to converge. The fact that interactions were found to be significant, indicates that generalized statements about the various variables cannot be made separately, and that care must be taken in drawing inferences from the data.

## DEVELOPMENT OF THE PREDICTION EQUATIONS

One of the primary objectives of this study was to attempt to develop mathematical expressions which, for the various chemicals and mixtures tested, would relate the main variables-reaction time, temperature and concentration-according to the melting effect. In order to undertake this task it was necessary to utilize the statistical technique known as regression analysis.

At the outset, a series of preliminary plots of the raw data were made to see whether a noticeable curve shape was indicated. Also reference was made to the analysis of variance which indicated a significant linear effect. Earlier analysis showed that smaller variations occurred when unit yield data were used as opposed to total melt in formation. Finally it was found that the concentration-temperature interaction which was significant when arithmetic data were used was not significant when the logarithms of the unit yields were analyzed. Based on these preliminary tests it was decided that the expression relating the main variables with the unit yield should take a logarithmic form.

It was realized, however, that the quadratic and cubic components were significant in some cases and therefore, the mathematical model selected might not be absolutely perfect. Nevertheless, it was apparent that, within the range of variables tested, the contributions of the quadratic and cubic components were numerically quite small. Moreover, it was believed that the loss in degrees of freedom, if these latter components were included, would offset any improvements to the model which might occur by their inclusion in the model. There is some suggestion that if the testing ranges were extended, consideration of a quadratic or possibly a cubic model should be given; however, for this study there seemed to be logical arguments for selecting a linear logarithmic model.

In performing the analysis it was decided that there would be considerable merit in developing a series of expressions relating unit yield to chemical concentration and temperature for each of the levels of reaction time tested. With this kind of information it would then be possible to determine, for a specified reaction time, the melting effect of the various chemicals and mixtures for any concentration-temperature combination.

It was also decided that to make the equation more useful in a practical sense, it would be desirable to express the yield in terms of inches of snow melted. Since total melt was a direct function of unit melt no difficulty was encountered in this transformation. However, in order to express the melt in terms of inches of snow melted, data reported by Nichols and Price (4) were used. These reports suggest that the specific gravity of newly fallen snow can be taken as 0.06 and this value was used in determining the equivalent depth of snow in this study. The concentration of the chemical was transformed into units of pounds per square yard.

The mathematical expression which was finally derived was of the following form:
where
$\log X=\log D+Q D+R T+Z$
$\mathbf{X}=$ the depth of fresh fallen snow in inches
$\mathrm{D}=$ the concentration of the chemical or mixture applied to the ice or snow surface in pounds per square yard $\mathrm{T}=$ the temperature of the snow in ${ }^{0} \mathrm{~F}$
$\mathbf{Q}$ and $\mathbf{P}=$ parameters based on the analysis of the experimental data

$$
\mathrm{Z}=\mathrm{a} \text { constant developed in the regression analysis }
$$

Values of $\mathbf{Q}, \mathbf{R}$ and $\mathbf{Z}$ for a wide variety of conditions are given in Tables 6 and 7 of Appendix C.

In order to illustrate some of the results obtained from using the prediction equations Tables 8 and 9 have been included in Appendix D. These tables by no means represent all possible comparisons, but rather are included simply to give some indication of predicted melting capacities of the various chemicals and mixtures tested (ㅇ, 6).

## PRACTICAL APPLICATION OF THE PREDICTION EQUATIONS

The prediction equations developed and the values of melting capacity previously discussed are certainly of interest. However, it was thought that these data would be of much greater value to the maintenance engineer if they could be presented in a slightly different form.

In an attempt to satisfy this requirement, Tables 10 through 17 are given in Appendix E. Tables 10 to 13 refer to a $15-\mathrm{min}$ melting time and Tables 14 to 17 to a $60-\mathrm{min}$ melting time. It was thought that the linearity of the time effect previously referred to was sufficiently well established so that information for melting times lying between these limits could be interpolated by using a direct proportion.

The tables of Appendix $E$ were prepared using the prediction equations and expressing the results in terms of pounds of chemical per mile necessary to melt various thicknesses of fresh fallen snow at the temperatures studied. In keeping with present practices in the province of Ontario, it was assumed that the chemical would be applied over a $3-\mathrm{ft}$ wide strip of pavement along the center line. It was further assumed that 50 percent melt would be sufficient to produce a slush which would be removed by traffic action. This latter concept has been based on the results of studies reported by Price (5).

In the development of these tabulations, care has been taken not to include any values outside of the range of the test data. Although the possibility of extrapolating the equations was considered, it was believed that such action would be misleading. The principal area of deficiency of data was found to occur with the lower concentrations. In keeping with this criterion it was therefore impossible to extend the data to include applications of less than 500 lb per mile. For this reason in all of the tables of Appendix E , a solid black line has been drawn to indicate the lower limit of the test information.

Similarly, studies of present practice with rock salt, indicated that application rates in excess of $1,000 \mathrm{lb}$ per mile were rarely reported. Therefore, the maximum application rate contained in Appendix E was taken to be 1,000 lb per mile. No similar information was apparent regarding present practice in the use of calcium chloride with the result that the same upper limit was chosen for this material. This in no way suggests that the limit is feasible for calcium chloride application-it undoubtedly is not-but selection of this value permits comparisons to be made.

In reviewing the data, it was apparent that a broader range of reaction times might well have been selected. Unfortunately at the start of the work, very little guiding information was available with the result that the time factor appears to need additional study in order to extend the range. This in no way invalidates the study but merely places a restriction on its application.

Consideration of the tables of Appendix E indicates quite clearly that attempts to remove large depths of snow by melting with chemicals would be an extremely expensive proposition. Thus, it seems reasonable to suggest that chemicals can be expected to be most useful in removing relatively small depths of snow. In the case of heavy snow fall it would seem that mechanical removal will be necessary with the added consideration that chemicals might be of some assistance in reducing the possibility of ice forming on the road surface. No data are available from this study concerning this latter situation but there appears to be reason to suggest that research regarding quantities of chemical required and the time of application would be most useful.

It is also apparent from these tables that the chemicals lose much of their effectiveness at low temperatures. Rock salt is most effective in the 20 to 32 F range while
calcium chloride does function somewhat more satisfactorily at lower temperatures. In the final analysis, however, the decision must be made on the basis of cost. By using these tables, it is possible to compare costs. In addition, the tables provide a simple means for determining the amount of chemical necessary for a variety of conditions. This too, should be of value in selecting the best application rate and consequently in obtaining the greatest effectiveness for the chemical available.

## CONCLUSIONS

The primary objective of this study was an attempt to evaluate, in the laboratory, the ice and snow melting properties of chemicals and chemical mixtures which are commonly used by street and highway authorities.

At the outset, it was necessary to develop a testing procedure which would provide reasonably reliable and reproducible data, since other investigators suggested that certain erroneous results were due to deficiencies in the testing method. Statistical analyses of the data reported in this paper indicated reasonable assurance that the test method used would meet the specification of reproducible results. A warning should be issued at this point that the results reported in this study may be expected to differ considerably from those obtained by other researchers since different testing methods have been employed.

The three main variables, reaction time, temperature and concentration, considered in this study to be measures of the melting properties of the chemical, were found to produce results which would have been expected. However, the statistical analysis of the data indicated significant interaction effects which implied that no single variable could be considered separately. This simply means that each variable contributed significantly to the ice and snow melting characteristics of the chemical or mixture and in some way each variable influences the effect of the others.

Comparisons of the mean melting results indicated a greater melting action by calcium chloride when compared with rock salt. This was particularly noticeable at low temperatures and for short time intervals. This implies that, on the basis of melting comparison, some benefit can be derived from the use of calcium chloride particularly where rock salt is evidently ineffective. Nevertheless economic considerations must also be taken into account and tabular values of the necessary rates of application have been provided for this purpose.

Consideration of the data indicates that F.C. rock salt has superior melting characteristics to C.C. rock salt. This conclusion however is based entirely on melting tests and it is reasonable to suggest that other factors such as storage and spreading difficulties will have to be assessed before a final decision can be made regarding the relative merits of the two differently graded rock salts.

Rather interesting results were obtained by mixing rock salt and calcium chloride. Certainly there seems to be some advantage in these mixtures in that the effect of the of the calcium chloride would appear to be one of extending the useful temperature range of rock salt so that it becomes effective at lower temperatures. The data for these tests were somewhat limited but there is reason to suggest that some value might derive from additional studies of rock salt-calcium chloride mixtures.

The effect of mixing sand with rock salt was generally one of inhibiting the melting action. The melt retarding effect of the sand was found to be almost directly proportional to the percentage of sand used in the mixture. It is possible that traffic might counteract this retardation effect to some extent by bringing more salt into contact with the ice. This theory was not tested, and therefore, no definite statement concerning the traffic variable can be made at this time. However, on the basis of the tests performed it appears that attempts to obtain combined abrasive and melting action by mixing rock salt and sand will certainly result in a reduction in melting effect because of the dispersion of the salt in the sand.

By means of a regression analysis it has been possible to develop mathematical expressions relating the melting characteristics of the chemicals with the main variables tested. These mathematical expressions have been used to develop the tabulations showing the amount of chemical required to melt various quantities of snow under
a variety of conditions of temperature and melting time. By means of these tables it is also possible to make cost comparisons of the various chemicals tested when used under a given set of conditions.

The test data indicate rather conclusively that the melting of snow by means of chemicals should be considered only when the fall of snow is relatively light. It is apparent that heavy falls of snow will necessitate the use of mechanical methods for snow removal.

Although considerable confidence can be placed in the mathematical expressions developed in this study, there is a possibility that improvements in the mathematical model are possible. Extension of the testing program to include low concentrations and longer melting periods might very well produce results which would indicate modification to the model developed in this study. However, until additional information becomes available, it is believed that the proposed equations, if used within the range of the variables tested, will provide reasonable estimates of the ice and snow melting capacities of the chemicals listed.

## FURTHER RESEARCH

This study by no means provides a solution to all of the problems of snow and ice removal from highways. Consideration has only been given to those factors relating to the problem which could be measured in the laboratory. Although it would have been desirable to introduce into the study other factors which are more closely related to field conditions it was felt that an intense study of limited scope would be preferable to a broader but less intense analysis.

Many factors were derived from the study, perhaps the most important of these were related to gaps in the knowledge rather than additions to it. It was felt that a statement about possible future research might be of value to those interested in the problems of winter maintenance. The following paragraphs contain some thoughts regarding problems which are as yet unsolved or only partially solved.

Based on this study it would seem that studies at low concentrations and longer time periods would be useful and informative. In addition, much more data are required concerning the relative effectiveness of mixing calcium chloride and rock salt. Since only two rock salt gradings were investigated and were found to produce different results, this aspect of the work should receive further attention in order to determine whether an ideal grading can be found.

It was observed qualtitatively in this study, that the rate of penetration of the chemicals differed considerably. The effect of this phenomenon in the field certainly warrants additional study. Similarly the brine solutions formed were found to be somewhat more viscous than water and the nature of the effect of these solutions on the various pavement surfaces with regard to possible skidding would seem to be of interest.

The effect of the chemicals in preventing bonding of ice or packed snow to the pavement also appears to be worthy of study since this use of chemicals would seem to be important in the case of heavy snow fall.

Probably the most important subject for study is the effect of traffic on a chemically treated or untreated snow or ice covered road surface. Many statements have been made regarding this matter, but quantitative data on the subject are rather meager.

Many other factors, too numerous to mention, also require investigation. It is hoped that the present study will shed a little more light on the subject and will encourage others to undertake additional studies in this very complex field of snow and ice removal from highways.

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## Appendix $A$

TABLE 1
OBSERVED MELT FOR SALT AND SALT-SAND MIXTURES (C.C. ROCK SALT)

|  |  | C.C. Rock Salt Without Additives |  |  |  | 75\% C. C. Rock Salt $\mathbf{2 5} \%$ Sand |  |  |  | $50 \%$ C.C. Rock Salt $50 \%$ Sand |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $\mathrm{t}_{1}{ }^{1}$ | $\mathrm{t}_{2}$ | ts | ts | $t_{1}$ | $\mathrm{ta}_{2}$ | $t_{3}$ | $t_{4}$ | $t_{1}$ | $t_{8}$ | $t_{3}$ | $\mathrm{t}_{4}$ |
| T | C1 | $0.34{ }^{2}$ | 0.56 | 0.63 | 0.68 | 0.18 | 0.42 | 0.54 | 0.37 | 0.19 | 0.19 | 0.26 | 0.41 |
|  | C2 | 0.33 | 0.41 | 0.46 | 0.60 | 0.04 | 0.08 | 0.10 | 0.18 | 0.14 | 0.23 | 0.28 | 0.19 |
|  | C3 | 0.20 | 0.23 | 0.31 | 0.33 | 0.02 | 0.02 | 0.09 | 0.13 | 0.04 | 0.05 | 0. 05 | 0.07 |
|  | C4 | 0.10 | 0.17 | 0.20 | 0.28 | 0.04 | 0.09 | 0.08 | 0.11 | 0.02 | 0.02 | 0.03 | 0.02 |
| T | C1 | 0.82 | 1.01 | 1.34 | 1.50 | 0.74 | 0.99 | 1.21 | 1.41 | 0.66 | 0.98 | 0. 96 | 1.44 |
|  | C2 | 0.65 | 0.90 | 0.99 | 1.26 | 0.50 | 0.70 | 0.99 | 1.11 | 0.62 | 0.93 | 1.04 | 1.28 |
|  | C3 | 0.42 | 0.52 | 0.65 | 0.76 | 0. 25 | 0.47 | 0.53 | 0.73 | 0.18 | 0.20 | 0.24 | 0.59 |
|  | C4 | 0.26 | 0.35 | 0.41 | 0.51 | 0.15 | 0.24 | 0.37 | 0.34 | 0.06 | 0.07 | 0.11 | 0.14 |
| T2 | C1 | 1.44 | 1.89 | 2.51 | 2.91 | 1.41 | 1.70 | 2.30 | 2.65 | 1.40 | 1.86 | 2. 24 | 2. 48 |
|  | C2 | 1.27 | 1.66 | 1.80 | 2.14 | 1.02 | 1.30 | 1.73 | 2.00 | 0.93 | 1.36 | 1.65 | 1.94 |
|  | C3 | 0.72 | 0.96 | 1.14 | 1.40 | 0.72 | 0.90 | 1.10 | 1.30 | 0.65 | 0.80 | 1.17 | 1.35 |
|  | C4 | 0.47 | 0.63 | 0.79 | 0.87 | 0.50 | 0.46 | 0.60 | 0.83 | 0.20 | 0.20 | 0.45 | 0.46 |
| Ts | C1 | 2. 50 | 2.98 | 3.56 | $4.7 \%$ | 2.33 | 2. 99 | 3.94 | 4.36 | 2.23 | 2.97 | 3. 51 | 4.40 |
|  | C2 | 1.81 | 2.28 | 2.62 | 3.26 | 1.68 | 2.26 | 2.78 | 3.48 | 1.81 | 2.52 | 2.87 | 3.41 |
|  | C3 | 1.17 | 1.55 | 1.79 | 2.12 | 1.15 | 1.59 | 1.94 | 2.24 | 1.08 | 1.38 | 1.81 | 2. 06 |
|  | C4 | 0.62 | 0.82 | 1.12 | 1.27 | 0.64 | 0.78 | 1.10 | 1.24 | 0.48 | 0.68 | 0.81 | 0.85 |

[^1]TABLE 2
OBSERVED MELT FOR SALT AND SALT-SAND MIXTURES (F.C. ROCK SALT)

|  |  | F.C. Rock Salt Without Addntives |  |  |  | 75\% F.C. Rock Salt $25 \%$ Sand |  |  |  | 50\% F.C. Rock Salt 50\% Sand |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $t_{1}{ }^{1}$ | $\mathrm{t}_{2}$ | ts | ts | $\mathrm{t}_{1}$ | $\mathrm{t}_{2}$ | $t_{3}$ | $t_{4}$ | $\mathrm{t}_{1}$ | $\mathrm{t}_{2}$ | ts | t |
| To | C1 | 1.06 ${ }^{\text {a }}$ | 1.34 | 1.42 | 1.59 | 0.70 | 0.81 | 1.03 | 0.97 | 0.57 | 0.77 | 0.79 | 1.07 |
|  | C2 | 0.68 | 0.77 | 0.96 | 1.01 | 0.37 | 0.44 | 0.61 | 0.61 | 0.28 | 0.35 | 0.37 | 0.41 |
|  | C3 | 0.29 | 0.42 | 0.53 | 0.51 | 0.18 | 0.21 | 0.24 | 0.24 | 0.14 | 0. 20 | 0.22 | 0.19 |
|  | C4 | 0.11 | 0.13 | 0.13 | 0.15 | 0.12 | 0.15 | 0.13 | 0.13 | 0.10 | 0.10 | 0.15 | 0.13 |
| T | C1 | 1.33 | 1. 71 | 1.99 | 2.29 | 1.04 | 1.70 | 1. 54 | 1.91 | 0.75 | 1.21 | 1.58 | 1.95 |
|  | C2 | 0.84 | 1.16 | 1.25 | 1.57 | 0.83 | 1.12 | 1. 20 | 1.33 | 0.72 | 1.03 | 1.21 | 1.47 |
|  | C3 | 0.52 | 0.66 | 0.78 | 1.00 | 0.32 | 0.36 | 0.34 | 0.44 | 0.33 | 0.30 | 0.36 | 0.35 |
|  | C4 | 0.22 | 0.31 | 0.28 | 0.27 | 0.16 | 0.15 | 0.18 | 0.17 | 0.17 | 0.16 | 0.18 | 0.16 |
| T2 | C1 | 1.67 | 2.52 | 2.81 | 3.33 | 2.28 | 2.63 | 3.05 | 3.44 | 1.91 | 2.23 | 2.88 | 3. 20 |
|  | C2 | 1.43 | 2.00 | 2.40 | 2.52 | 1.62 | 1.91 | 2.46 | 2.79 | 0.92 | 1.67 | 1.76 | 1.78 |
|  | C3 | 0.91 | 1.12 | 1.38 | 1.57 | 0.77 | 0.76 | 1.20 | 1.52 | 0.53 | 0.50 | 0.60 | 0.45 |
|  | C4 | 0.42 | 0.56 | 0.75 | 0.93 | 0.24 | 0.28 | 0.28 | 0.27 | 0.22 | 0.24 | 0.21 | 0. 25 |
| Ts | C1 | 3.22 | 2.98 | 4.43 | 4.73 | 3.43 | 3.71 | 4.31 | 4.48 | 3.18 | 3.64 | 4.31 | 4.59 |
|  | C2 | 1.60 | 2.25 | 2.76 | 3.34 | 2.09 | 2.66 | 3.82 | 3.50 | 2.44 | 2.92 | 3.38 | 4.06 |
|  | C3 | 1.12 | 1.52 | 1.83 | 2.06 | 1.26 | 1.64 | 1.95 | 2.27 | 1.08 | 1.26 | 1.52 | 1.55 |
|  | C4 | 0.72 | 0.94 | 1.31 | 1.47 | 0.44 | 0.44 | 0.86 | 0.61 | 0.38 | 0.40 | 0.42 | 0.40 |

${ }_{2}^{1}$ For coding system see Appendux $B$.
${ }^{2}$ All melt quantities are expressed in terms of unit melt (unit yield). This quantity has been defined as the number of grams of ice melted per gram of chemical applied.

TABLE 3
OBSERVED MELT FOR FLAKE AND PELLET CALCIUM CHLORIDE


[^2]TABLE 4
OBSERVED MELT FOR FLAKE CALCIUM CHLORIDE-C.C. ROCK SALT MDXTURES

|  |  | 10\% Calcium Chloride 90\% Rock Salt |  |  |  | 20\% Calcium Chloride 80\% Rock Salt |  |  |  | 30\% Calcium Chlortde 70\% Rock Salt |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $t_{1}{ }^{1}$ | $\mathrm{t}_{2}$ | ts |  | $t_{1}$ | $\mathrm{t}_{5}$ | ts | $t_{4}$ | $\mathrm{t}_{1}$ | $\mathrm{t}_{2}$ | ts | 4 |
| To | C1 | 0. $52{ }^{2}$ | 0.70 | 0.96 | 1.00 | 0.97 | 1.21 | 1.28 | 1.34 | 1.08 | 1.17 | 1.41 | 1.41 |
|  | C2 | 0.51 | 0.63 | 0.71 | 0.75 | 0.70 | 0.81 | 0.90 | 0.94 | 0.94 | 1.08 | 1.27 | 1.31 |
|  | C3 | 0.45 | 0.53 | 0.63 | 0.67 | 0.57 | 0.64 | 0.77 | 0.82 | 0.73 | 0.84 | 0.92 | 1.02 |
|  | C4 | 0. 26 | 0.34 | 0.49 | 0.48 | 0.39 | 0.45 | 0.55 | 0.61 | 0.62 | 0.64 | 0.80 | 0.83 |
| T | C1 | 1.05 | 1.32 | 1.64 | 1.78 | 1.43 | 1.74 | 2.01 | 1.99 | 1.53 | 1.69 | 1.83 | 2.15 |
|  | C2 | 0.96 | 1.18 | 1.23 | 1.43 | 1.37 | 1.41 | 1.73 | 1.87 | 1.24 | 1.45 | 1.61 | 1.88 |
|  | C3 | 0.65 | 0.75 | 0.91 | 1.03 | 0.80 | 0.98 | 1.08 | 1.33 | 1.03 | 1.31 | 1.48 | 1.62 |
|  | C4 | 0.46 | 0.49 | 0.59 | 0. 68 | 0.61 | 0.68 | 0.82 | 0.89 | 0.81 | 0.89 | 1.05 | 1.16 |
| T | C1 | 1.48 | 1.72 | 2.09 | 2.51 | 2. 01 | 2.30 | 2.73 | 3.42 | 1.83 | 2.38 | 2. 77 | 2.99 |
|  | C2 | 1.23 | 1.48 | 1.76 | 2.04 | 1.57 | 1.75 | 2.06 | 2. 23 | 1.66 | 1. 81 | 2.18 | 2.29 |
|  | C3 | 0.91 | 1.12 | 1.32 | 1.62 | 1.07 | 1.30 | 1.47 | 1.65 | 1.19 | 1.49 | 1.77 | 1.85 |
|  | C4 | 0.61 | 0.64 | 0.79 | 1.00 | 0.76 | 0.92 | 1.05 | 1.24 | 0.96 | 1.06 | 1. 27 | 1.46 |
| T3 | C1 | 2.63 | 3.54 | 4.50 | 5.29 | 2. 69 | 2.91 | 3.81 | 4. 59 | 2.98 | 3.37 | 3.80 | 4.87 |
|  | C2 | 1.61 | 2.19 | 2.54 | 2.76 | 1.95 | 2.34 | 2.84 | 3. 32 | 1.97 | 2. 59 | 2. 86 | 3.70 |
|  | C3 | 1.34 | 1.58 | 1.96 | 2.46 | 1.42 | 1.68 | 1.85 | 2. 25 | 1.67 | 2.02 | 2. 22 | 2.51 |
|  | C4 | 0.87 | 1.00 | 1. 29 | 1.38 | 0.99 | 1.18 | 1.31 | 1.45 | 1.14 | 1.40 | 1.59 | 1.74 |

${ }^{1}$ For coding system see Appendix B.
${ }^{2}$ All melt quantities are expressed in terms of unit melt (unit yield). This quantity has been defined as the number of grams of ice melted per gram of chemical applied.

TABLE 5
OBSERYED MELT FOR PELLET CALCIUM CHLORIDE-C.C. ROCK SALT MIXTURES

|  |  | 10\% Calcium Chloride $90 \%$ Rock Salt |  |  |  | 20\% Calcium Chloride 80\% Rock Salt |  |  |  | $30 \%$ Calctum Chloride 70\% Rock Salt |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $t_{2}{ }^{1}$ |  | $\mathrm{ts}_{3}$ | $\mathrm{t}_{4}$ | $\mathrm{t}_{1}$ |  | $t s$ | $t_{4}$ | $t_{1}$ | $\mathrm{t}_{2}$ | ts | 4 |
| To | C1 | $0.64{ }^{2}$ | 0.73 | 0.89 | 0.75 | 0.79 | 0.96 | 1.17 | 1.10 | 1.09 | 1.32 | 1.27 | 1.38 |
|  | C2 | 0.46 | 0.54 | 0.62 | 0.78 | 0.59 | 0.76 | 0.80 | 0.97 | 0.86 | 0.91 | 1.09 | 1.02 |
|  | C3 | 0.37 | 0.44 | 0.52 | 0.54 | 0.57 | 0.65 | 0.71 | 0.80 | 0.74 | 0.92 | 1.04 | 1.12 |
|  | C4 | 0. 24 | 0.37 | 0.43 | 0.44 | 0.37 | 0.47 | 0.50 | 0.53 | 0.52 | 0.69 | 0.79 | 0.88 |
| Tı | C1 | 1.04 | 1.28 | 1.48 | 1.61 | 1.17 | 1.54 | 1.59 | 1.99 | 1.41 | 1.52 | 1.64 | 1.79 |
|  | C2 | 0.88 | 1.05 | 1.18 | 1.33 | 0.95 | 1.08 | 1.20 | 1.35 | 1.27 | 1.43 | 1.60 | 1. 71 |
|  | C3 | 0.65 | 0.71 | 0.88 | 1.08 | 0.80 | 0.96 | 1.03 | 1.25 | 1.00 | 1.14 | 1.39 | 1.51 |
|  | C4 | 0.41 | 0.49 | 0.57 | 0.67 | 0.54 | 0.63 | 0.72 | 0.90 | 0.68 | 0.86 | 1.06 | 1. 21 |
| T2 | C1 | 1.80 | 2.07 | 2.47 | 3.23 | 1.82 | 2.32 | 3.32 | 3.41 | 2.08 | 2.44 | 2.76 | 3.41 |
|  | C2 | 1.29 | 1.58 | 2. 00 | 2.23 | 1.39 | 1.65 | 1.95 | 2. 19 | 1.60 | 1.87 | 2.46 | 2. 66 |
|  | C3 | 0.91 | 1.22 | 1.42 | 1. 52 | 1.09 | 1.36 | 1. 64 | 1.77 | 1.22 | 1.43 | 1.83 | 2.02 |
|  | C4 | 0.58 | 0.71 | 0.90 | 1.06 | 0.74 | 0. 89 | 1. 17 | 1.25 | 0.98 | 1.89 | 1.39 | 1.56 |
| Ts | C1 | 2.32 | 2.90 | 3.66 | 4. 24 | 2. 28 | 3.52 | 4.14 | 4.52 | 2.49 | 3. 29 | 4.02 | 4.41 |
|  | C2 | 1.76 | 2.27 | 2.64 | 3.28 | 1.56 | 2.13 | 2. 39 | 2. 75 | 2.00 | 2.47 | 2.87 | 3. 20 |
|  | C3 | 1.18 | 1.65 | 1.80 | 2.10 | 1.39 | 1.73 | 2.01 | 2. 35 | 1.65 | 1.80 | 2.10 | 2. 32 |
|  | C4 | 0.84 | 1.01 | 1.24 | 1.43 | 1.10 | 1.30 | 1.50 | 1.74 | 1.22 | 1.47 | 1.61 | 1.89 |

[^3]
## Appendix B

## CODING SYSTEM

The following is a list indicating the symbols used in coding the various test data as well as the significance of the symbols.

## Chemical

$S_{c}=$ Coarse crushed rock salt (C.C. rock salt)
$\mathbf{S}_{\mathbf{f}}=$ Fine crushed rock salt (F.C. rock salt)

## Temperature

$\mathrm{T}_{0}=$ Test Temperature 0 F
$T_{1}=$ Test Temperature +10 F
$\mathrm{T}_{\mathbf{2}}=$ Test Temperature +20 F
$\mathrm{T}_{\mathbf{3}}=$ Test Temperature +30 F
Time
$\mathbf{t}_{1}=$ Test melting time of 15 minutes
$\mathrm{t}_{2}=$ Test melting time of 30 minutes
$\mathrm{t}_{3}=$ Test melting time of 45 minutes
$\mathrm{t}_{4}=$ Test melting time of $\mathbf{6 0}$ minutes
Concentration (Rate of Application of Chemical to Ice Surface)
$C_{1}=0.72 \mathrm{lb}$ of chemical per square yard of ice
$C_{2}=1.80 \mathrm{lb}$ of chemical per square yard of ice
Cs $=3.60 \mathrm{lb}$ of chemical per square yard of ice
$C_{4}=7.20 \mathrm{lb}$ of chemical per square yard of ice

## Sand Additive

$S_{0}=100 \%$ salt $-0 \%$ sand
$S_{1}=75 \%$ salt $-25 \%$ sand
$S_{z}=50 \%$ salt $-50 \%$ sand

## Appendix C

TABLE 6
PREDICTION EQUATION PARAMETERS

| 15-min Reaction Time |  |  |  |
| :---: | :---: | :---: | :---: |
|  | Q | R | Z |
| C.C. rock salt without additives | -0.0831 | +0.0263 | -0.7905 |
| F.C. rock salt without additives | -0.1133 | +0.0191 | -0.4804 |
| Pellet calcium chloride with C. C. Rock salt |  |  |  |
| 100\% calcium chloride | -0.0278 | +0.0084 | -0.1496 |
| 90\% salt - 10\% calcium chloride | -0.0658 | +0.0182 | -0. 5966 |
| 80\% salt - $20 \%$ calcium chloride | -0.0492 | +0.0146 | -0.5229 |
| 70\% salt - 30\% calcium chloride | -0.0483 | +0.0121 | -0.3930 |
| Flake calcium chloride with |  |  |  |
| C.C. rock salt |  |  |  |
| 100\% calcium chloride | -0.0367 | +0.0065 | -0.0860 |
| 90\% salt - 10\% calcium chloride | -0.0578 | +0.0178 | -0.6076 |
| 80\% salt - $20 \%$ calcium chloride | -0.0601 | +0.0137 | -0.4238 |
| 70\% salt - $30 \%$ calcium chloride | -0.0447 | +0.0112 | -0.3787 |
| 60-min Reaction Time |  |  |  |
| C.C. rock salt without additives | -0.0750 | +0.0254 | -0.5218 |
| F.C. rock salt without additives | -0.1150 | +0.0222 | -0.2843 |
| Pellet calcium chloride with C.C. Rock Salt |  |  |  |
| 100\% calcium chloride | -0.0125 | +0.0071 | -0. 0092 |
| 90\% salt - $10 \%$ calcium chloride | -0.0600 | +0.0208 | -0.4367 |
| 80\% salt - $20 \%$ calcium chloride | -0.0531 | +0.0172 | -0.3397 |
| 70\% salt - 30\% calcium chloride | -0.0386 | +0.0141 | -0.2743 |
| Flake calcium chloride with |  |  |  |
| C.C. rock salt |  |  |  |
| 100\% calcium chloride | -0.0267 | +0.0066 | -0.0182 |
| 90\% salt - 10\% calcium chloride | -0. 0619 | +0.0190 | -0.3879 |
| 80\% salt - $20 \%$ calcium chloride | -0.0603 | +0.0156 | -0. 2745 |
| 70\% salt - $30 \%$ calcium chloride | -0.0472 | +0.0137 | -0.2332 |

TABLE 7
PREDICTION EQUATION PARAMETERS
(Various Reaction Times for C.C. and F.C. Rock Salt Without Additives)

| Reaction Time in <br> Minutes | $\mathbf{Q}$ | $\mathbf{R}$ | Z |
| :--- | :---: | :---: | :---: |
| C. C. rock salt |  |  |  |
| 15 | -0.0831 | +0.0263 | -0.7905 |
| 30 | -0.0784 | +0.0250 | -0.6645 |
| 45 | -0.0755 | +0.0253 | -0.5967 |
| 60 | -0.0749 | +0.0254 | -0.5218 |
| F. C. rock salt |  |  |  |
| 15 | -0.1133 | +0.0191 | -0.4804 |
| 30 | -0.1141 | +0.0199 | -0.3701 |
| 45 | -0.1137 | +0.0215 | -0.3292 |
| 60 | -0.1149 | +0.0222 | -0.2843 |

## Appendix D

TABLE 8
PREDICTED ${ }^{\mathbf{1}}$ 60-MIN MELTING CAPACITIES OF VARIOUS MELTING MIXTURES
(Temperature 0 F )

| Chemical | Application Rate, lb per sq yd |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0.72 | 1. 50 | 3.00 | 5.00 | 7. 20 |
| C. C. rock salt without additives | $0.19{ }^{2}$ | 0.35 | 0.54 | 0.63 | 0.62 |
| F.C. rock salt without additives | 0.31 | 0.52 | 0.71 | 0.69 | 0.56 |
| Flake calcium chloride | 0. 66 | 1.31 | 2.39 | 3.53 | 4.44 |
| Pellet .alcium chloride | 0. 69 | 1.41 | 2. 70 | 4. 24 | 5. 73 |
| Flake cal.fum chloride - C.C. |  |  |  |  |  |
| Rock salt mixtures |  |  |  |  |  |
| calcrum chloride <br> $80 \%$ rock salt - $20 \%$ | 0.27 | 0. 50 | 0.80 | 1.00 | 1.06 |
| calcıum chloride $70 \%$ roch salt - $30 \%$ | 0.35 | 0.65 | 1.05 | 1.33 | 1.41 |
| calcium chloride | 0.39 | 0.75 | 1.27 | 1.70 | 1.92 |
| Pellet calcium chloride-C.C. rock salt mixtures |  |  |  |  |  |
| cal. um chloride <br> $80 \%$ rock salt $-20 \%$ | 0. 24 | 0.45 | 0.73 | 0.92 | 0.97 |
| calcium chloride <br> $70 \%$ rock salt - $30 \%$ | 0.30 | 0. 57 | 0. 95 | 1. 24 | 1.37 |
| calcuum chloride | 0.36 | 0.70 | 1. 22 | 1.70 | 2.02 |

${ }^{1}$ Calsulated from the prediction equation.
${ }^{2}$ Melting capacities are expressed in inches of fresh snow having a specific gravity of 0.06 .

TABLE 9
PREDICTED ${ }^{1}$ 60-MIN MELTING CAPACITIES OF VARIOUS CHEMICAL MIXTURES (Temperature +30 F)

| Chemical | Application Rate, lb per sq yd |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0.72 | 1.50 | 3.00 | 5.00 | 7. 20 |
| C.C. rock salt without additives | 1. $10^{2}$ | 2.01 | 3.10 | 3.66 | 3.61 |
| F.C. rock salt without additives | 1.43 | 2.43 | 3.26 | 3. 20 | 2.57 |
| Flake calcium chloride | 1. 04 | 2. 07 | 3.78 | 5.57 | 7. 00 |
| Pellet calcium chloride | 1.13 | 2. 30 | 4.41 | 6.92 | 9.36 |
| Flake calcium chloride-C.C. rock salt mixtures $90 \%$ rock salt - $10 \%$ |  |  |  |  |  |
| calcıum chloride <br> $80 \%$ rock salt $-20 \%$ | 0.99 | 1.84 | 2.98 | 3. 73 | 3.93 |
| calcıum chloride $70 \%$ rock salt - $30 \%$ | 1.02 | 1.90 | 3. 09 | 3. 89 | 4.13 |
| calcium chloride | 1.00 | 1.92 | 3. 27 | 4.38 | 4.97 |
| Pellet calcium chloride - C.C. rock salt muxtures $\mathbf{9 0 \%}$ rock salt - $\mathbf{1 0 \%}$ calcium |  |  |  |  |  |
| chloride $80 \%$ rock salt - $20 \%$ calcium | 1.01 | 1. 88 | 3.08 | 3.87 | 4.02 |
| chloride $70 \%$ rock salt - $30 \%$ calcium | 0.99 | 1.88 | 3.13 | 4.08 | 4.49 |
| chloride | 0.95 | 1.85 | 3.25 | 4.52 | 5.36 |

[^4]
## Appendix E

TABLE 10

## APPLICATION RATES ${ }^{1,2}$ OF CHEMICALS FOR SNOW REMOVAL <br> (C.C. Rock Salt Reaction Time $=\mathbf{1 5} \mathbf{~ m i n}$ )

| Snow ${ }^{3}$ Depth in Inches | Temperature $\mathbf{F}$ |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0 | +10 | +15 | +20 | +22 | +24 | +26 | +28 | +30 |
| 0.10 | $\overline{624}$ |  |  |  |  |  |  |  |  |
| 0.20 |  | 685 | 500 |  |  |  |  |  |  |
| 0.30 |  |  | 589 | 545 |  |  |  |  |  |
| 0.40 |  |  |  | 764 | 659 | 580 | 500 |  |  |
| 0.50 |  |  |  | 1000 | 861 | 747 | 650 | 562 |  |
| 0.60 |  |  |  |  |  | 932 | 800 | 677 | 607 |
| 0.70 |  |  |  |  |  |  | 966 | 852 | 720 |
| 0.80 |  |  |  |  |  |  |  | 983 | 870 |
| 0.90 |  |  |  |  |  |  |  |  | 983 |

${ }^{1}$ The prediction equation has been used to determine the rate of chemical application.
${ }^{2}$ Application rates are expressed in pounds per mile assuming 50 percent melt on a 3-ft strip of pavement center line.
${ }^{3}$ The specific gravity of fresh fallen snow has been assumed to be 0.06 .
${ }^{4}$ Application rates above the solid line are below the minimum concentration tested in the laboratory. Application rates greater than 1,000 lb per mile have not been included but may be obtained from the prediction equations.

TABLE 11
APPLICATION RATES ${ }^{1,2}$ OF CHEMICALS FOR SNOW REMOVAL
(F.C. Rock Salt Reaction Time $=15 \mathrm{~min}$ )

| Snow ${ }^{3}$ Depth in Inches | Temperature $\mathbf{F}$ |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0 | +10 | +15 | +20 | +22 | +24 | +26 | +28 | +30 |
| 0.10 | $\overline{641}^{4} \begin{array}{r}615 \\ 896\end{array}$ |  | $668$$896$ |  |  |  |  |  |  |
| 0.20 |  |  |  |  |  |  |  |  |
| 0.30 |  |  |  |  |  |  |  |  |
| 0.40 |  |  | 500 |  |  |  |  |  |
| 0.50 |  |  | 668 | 606 | 545 |  |  |  |
| 0.60 |  |  | 852 | 756 | 659 | 606 | 545 |  |
| 0.70 |  |  |  | 931 | 826 | 739 | 659 | 571 |
| 0.80 |  |  |  |  | 1,000 | 879 | 782 | 694 |
| 0.90 |  |  |  |  |  |  | 913 | 809 |
| 1.00 |  |  |  |  |  |  |  | 931 |

${ }^{2}$ The prediction equation has been used to determine the rate of chemical application.
${ }^{2}$ Application rates are expressed in pounds per mile assuming 50 percent melt on a 3-ft strip of pavement center line.
${ }^{3}$ The specific gravity of fresh fallen snow has been assumed to be 0.06 .
${ }^{4}$ Application rates above the solid line are below the minimum concentration tested in the laboratory. Application rates greater than $1,000 \mathrm{lb}$ per mile have not been included but may be obtained from the prediction equations.

TABLE 12

## APPLICATION RATES ${ }^{1,2}$ OF CHEMICALS FOR SNOW REMOVAL (Flake Calcium Chloride Reaction Time $=15 \mathrm{~min}$ )

| Snow ${ }^{3}$ Depth in Inches | Temperature $\mathbf{F}$ |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0 | +5 | +10 | +15 | +20 | +25 | +30 |
| 0.10 |  |  |  |  |  |  |  |
| 0.20 |  |  |  |  |  |  |  |
| 0.30 |  |  |  |  |  |  |  |
| 0.40 |  |  |  |  |  |  |  |
| 0.50 | $562{ }^{4}$ | 519 |  |  |  |  |  |
| 0.60 | 686 | 633 | 589 | 636 | 500 |  |  |
| 0.70 | 809 | 747 | 686 | 633 | 589 | 536 | 500 |
| 0.80 | 931 | 861 | 791 | 730 | 677 | 624 | 571 |
| 0.90 |  | 984 | 905 | 835 | 765 | 712 | 659 |
| 1.00 |  |  | 1,000 | 931 | 861 | 791 | 730 |
| 1.10 |  |  |  |  | 967 | 879 | 809 |
| 1.20 |  |  |  |  |  | 967 | 887 |
| 1.30 |  |  |  |  |  |  | 976 |

${ }_{2}^{1}$ The prediction equation has been used to determine the rate of chemical application.
${ }^{2}$ Application rates are expressed in pounds per mile assuming 50 percent melt on a 3-ft strip of pavement center line.
${ }^{3}$ The specific gravity of fresh fallen snow has been assumed to be 0.06 .
${ }^{4}$ Application rates above the solid line are below the minimum concentration tested in the laboratory. Application rates greater than $1,000 \mathrm{lb}$ per mile have not been included but may be obtained from the prediction equations.

TABLE 13
APPLICATION RATES ${ }^{1,2}$ OF CHEMICAIS FOR SNOW REMOVAL
(Pellet Calcium Chloride Reaction Time $=15 \mathrm{~min}$ )

| Snow ${ }^{3}$ Depth in Inches | Temperature F |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0 | +5 | +10 | +15 | +20 | +25 | +30 |
| 0.10 |  |  |  |  |  |  |  |
| 0.20 |  |  |  |  |  |  |  |
| 0.30 |  |  |  |  |  |  |  |
| 0.40 | 518 |  |  |  |  |  |  |
| 0.50 | 650 | 589 | 536 |  |  |  |  |
| 0.60 | 790 | 712 | 641 | 580 | 519 |  |  |
| 0.70 | 931 | 835 | 756 | 659 | 615 | 554 | 500 |
| 0.80 |  | 966 | 870 | 782 | 712 | 641 | 580 |
| 0.90 |  |  | 984 | 887 | 800 | 720 | 650 |
| 1.00 |  |  |  | 1,000 | 896 | 809 | 730 |
| 1.10 |  |  |  |  | 1,000 | 896 | 809 |
| 1. 20 |  |  |  |  |  | 984 | 879 |
| 1.30 |  |  |  |  |  |  | 967 |

${ }^{1}$ The prediction equation has been used to determme the rate of chemical application.
${ }^{2}$ Application rates are expressed in pounds per mile assuming 50 percent melt on a 3-ft strip of pavement center line.
${ }^{3}$ The spectfic gravity of fresh fallen snow has been assumed to be 0.06 .

- Application rates above the solid line are below the minimum concentration tested in the laboratory. Application rates greater than 1,000 lb per mile have not been included but may be obtamed from the prediction equations.

TABLE 14
APPLICATION RATES ${ }^{1,2}$ OF CHEMICALS FOR SNOW REMOVAL
(C. C. Rock Salt Reaction Time $=60 \mathrm{~min}$ )

| Snow ${ }^{3}$ Depth in Inches | Temperature $F$ |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0 | +10 | +15 | +20 | +22 | +24 | +26 | +28 | +30 |
| 0.10 | $668$ |  |  |  |  |  |  |  |  |
| 0.20 |  |  |  |  |  |  |  |  |  |
| 0.30 |  | 545 |  |  |  |  |  |  |  |
| 0.40 |  | 774 | 536 |  |  |  |  |  |  |
| 0.50 |  | 983 | 694 | 500 |  |  |  |  |  |
| 0.60 |  |  | 861 | 615 | 536 |  |  |  |  |
| 0.70 |  |  |  | 730 | 642 | 562 | 500 |  |  |
| 0.80 |  |  |  | 861 | 747 | 650 | 571 | 500 |  |
| 0.90 |  |  |  | 1,000 | 862 | 747 | 650 | 571 | 500 |
| 1.00 |  |  |  |  | 975 | 844 | 738 | 642 | 562 |
| 1.10 |  |  |  |  |  | 949 | 826 | 720 | 632 |
| 1.20 |  |  |  |  |  |  | 922 | 800 | 694 |
| 1.30 |  |  |  |  |  |  | 1,000 | 879 | 765 |
| 1.40 |  |  |  |  |  |  |  | 959 | 835 |
| 1.50 |  |  |  |  |  |  |  |  | 905 |
| 1.60 |  |  |  |  |  |  |  |  | 975 |

${ }^{1}$ The prediction equation has been used to determine the rate of chemical application.
${ }^{2}$ Application rates are expressed in pounds per mile assuming 50 percent melt on a 3-ft strip of pavement center line.
${ }^{3}$ The specific gravity of fresh fallen snow has been assumed to be 0.06 .
${ }^{4}$ Application rates above the solid line are below the minimum concentration tested in the laboratory. Application rates greater than $1,000 \mathrm{lb}$ per mile have not been included but may be obtained from the prediction equations.

TABLE 15
APPLICATION RATES ${ }^{i, 2}$ OF CHEMICALS FOR SNOW REMOVAL (F.C. Rock Salt Reaction Time $=60 \mathrm{~min}$ )

| Snow ${ }^{3}$ Depth in Inches | Temperature F |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0 | $+10$ | +15 | $+20$ | +22 | +24 | +26 | +28 | +30 |
| 0.10 |  |  |  |  |  |  |  |  |  |
| 0.20 |  |  |  |  |  |  |  |  |  |
| 0. 30 | 607 |  |  |  |  |  |  |  |  |
| 0.40 | 880 |  |  |  |  |  |  |  |  |
| 0. 50 |  | 607 |  |  |  |  |  |  |  |
| 0.60 |  | 747 | 554 |  |  |  |  |  |  |
| 0. 70 |  | 941 | 668 | 500 |  |  |  |  |  |
| 0.80 |  |  | 800 | 581 | 518 |  |  |  |  |
| 0.90 |  |  | 941 | 668 | 589 | 518 |  |  |  |
| 1.00 |  |  |  | 765 | 668 | 589 | 518 |  |  |
| 1.10 |  |  |  | 871 | 756 | 668 | 589 | 518 |  |
| 1.20 |  |  |  | 985 | 853 | 747 | 651 | 572 | 518 |
| 1.30 |  |  |  |  | 950 | 827 | 721 | 633 | 563 |
| 1.40 |  |  |  |  |  | 914 | 800 | 695 | 615 |
| 1.50 |  |  |  |  |  | 1,000 | 880 | 756 | 668 |
| 1.60 |  |  |  |  |  |  | 959 | 827 | 721 |
| 1.70 |  |  |  |  |  |  |  | 897 | 782 |
| 1.80 |  |  |  |  |  |  |  | 967 | 844 |
| 1.90 |  |  |  |  |  |  |  |  | 914 |
| 2. 00 |  |  |  |  |  |  |  |  | 976 |

${ }^{1}$ The prediction equation has been used to determine the rate of chemical application.
${ }^{2}$ Application rates are expressed in pounds per mile assuming 50 percent melt on a 3-ft strip of pavement center line.
${ }^{3}$ The specific gravity of fresh fallen snow has been assumed to be 0.06 .
*Application rates above the solid line are below the minimum concentration tested in the laboratory. Application rates greater than 1, 000 lb per mile have not been included but may be obtamed from the predıction equations.

TABLE 16
APPLICATION RATES ${ }^{1,2}$ OF CHEMICALS FOR SNOW REMOVAL (Flake Calcium Chloride Reaction Time $=\mathbf{6 0} \mathrm{min}$ )

| Snow ${ }^{3}$ Depth in Inches | Temperature $\mathbf{F}$ |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0 | +5 | +10 | +15 | $+20$ | +25 | +30 |
| 0.10 |  |  |  |  |  |  |  |
| 0.20 |  |  |  |  |  |  |  |
| 0.30 |  |  |  |  |  |  |  |
| 0.40 |  |  |  |  |  |  |  |
| 0.50 |  |  |  |  |  |  |  |
| 0.60 | 572 | 527 |  |  |  |  |  |
| 0.70 | 677 | 624 | 562 | 527 |  |  |  |
| 0.80 | 774 | 712 | 651 | 598 | 554 | 510 |  |
| 0.90 | 880 | 809 | 739 | 677 | 624 | 580 | 536 |
| 1.00 | 985 | 905 | 826 | 765 | 703 | 651 | 598 |
| 1.10 |  | 1,000 | 914 | 844 | 774 | 712 | 660 |
| 1.20 |  |  |  | 932 | 853 | 783 | 721 |
| 1.30 |  |  |  | 1,000 | 949 | 853 | 791 |
| 1.40 |  |  |  |  | 1,000 | 923 | 853 |
| 1.50 |  |  |  |  |  | 1,000 | 923 |
| 1.60 |  |  |  |  |  |  | 985 |

${ }^{1}$ The prediction equation has been used to determine the rate of chemical application.
${ }^{2}$ Application rates are expressed in pounds per mile assuming 50 percent melt on a 3-ft strip of pavement center line.
${ }^{3}$ The specific gravity of fresh fallen snow has been assumed to be 0.06 .
4 Application rates above the solid line are below the minimum concentration tested in the laboratory. Application rates greater than $1,000 \mathrm{lb}$ per mile have not been meluded but may be obtained from the prediction equations.

TABLE 17
APPLICATION RATES ${ }^{2}$ 2 OF CHEMICALS FOR SNOW REMOVAL (Pellet Calcium Chioride Reaction Time $\mathbf{=} \mathbf{6 0} \mathbf{~ m i n}$ )

| Snow ${ }^{3}$ Depth in Inches | Temperature $F$ |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0 | +5 | $+10$ | +15 | +20 | +25 | +30 |
| 0.10 |  |  |  |  |  |  |  |
| 0.20 |  |  |  |  |  |  |  |
| 0.30 |  |  |  |  |  |  |  |
| 0.40 |  |  |  |  |  |  |  |
| 0.50 |  |  |  |  |  |  |  |
| 0.60 | 545 | 500 |  |  |  |  |  |
| 0.70 | 642 | 589 | 536 | 500 |  |  |  |
| 0.80 | 739 | 677 | 624 | 571 | 528 |  |  |
| 0.90 | 826 | 765 | 704 | 642 | 589 | 545 | 500 |
| 1.00 | 923 | 870 | 773 | 712 | 680 | 607 | 554 |
| 1.10 |  | 940 | 861 | 792 | 730 | 669 | 615 |
| 1.20 |  |  | 940 | 871 | 792 | 730 | 659 |
| 1.30 |  |  |  | 940 | 871 | 800 | 730 |
| 1.40 |  |  |  | 1,000 | 931 | 861 | 791 |
| 1.50 |  |  |  |  | 1,000 | 923 | 844 |
| 1.60 |  |  |  |  |  | 985 | 905 |
| 1.70 |  |  |  |  |  |  | 959 |

${ }^{2}$ The prediction equation has been used to determine the rate of chemical application.
${ }^{2}$ Application rates are expressed in pounds per mile assuming 50 percent melt on a 3-ft strip of pavement center line.
${ }^{3}$ The specffic gravity of fresh fallen snow has been assumed to be 0.06 .
Application rates above the solid line are below the minimum concentration tested in the laboratory. Appilication rates greater than 1, 000 lb per mile have not been included but may be obtained from the prediction equations.

## Appendix $F$

TABLE 18
GRADING DATA


THE National Academy of Sciences-National Research CounCIL is a private, nonprofit organization of scientists, dedicated to the furtherance of science and to its use for the general welfare. The Academy itself was established in 1863 under a congressional charter signed by President Lincoln. Empowered to provide for all activities appropriate to academies of science, it was also required by its charter to act as an adviser to the federal government in scientific matters. This provision accounts for the close ties that have always existed between the Academy and the government, although the Academy is not a governmental agency.

The National Research Council was established by the Academy in 1916, at the request of President Wilson, to enable scientists generally to associate their efforts with those of the limited membership of the Academy in service to the nation, to society, and to science at home and abroad. Members of the National Research Council receive their appointments from the president of the Academy. They include representatives nominated by the major scientific and technical societies, representatives of the federal government, and a number of members at large. In addition, several thousand scientists and engineers take part in the activities of the research council through membership on its various boards and committees.

Receiving funds from both public and private sources, by contribution, grant, or contract, the Academy and its Research Council thus work to stimulate research and its applications, to survey the broad possibilities of science, to promote effective utilization of the scientific and technical resources of the country, to serve the government, and to further the general interests of science.

The Highway Research Board was organized November 11, 1920, as an agency of the Division of Engineering and Industrial Research, one of the eight functional divisions of the National Research Council. The Board is a cooperative organization of the highway technologists of America operating under the auspices of the Academy-Council and with the support of the several highway departments, the Bureau of Public Roads, and many other organizations interested in the development of highway transportation. The purposes of the Board are to encourage research and to provide a national clearinghouse and correlation service for research activities and information on highway administration and technology.


[^0]:    ${ }^{1}$ Formerly Research Assistant, Ontario Joint Highway Research Program, Queen's University, Kingston, Ontario

[^1]:    ${ }^{2}$ For coding system see Appendix B.
    ${ }^{2}$ All melt quantities are expressed in terms of unit melt (unit yield). This quantity has been defined as the number of grams of ice melted per gram of chemical applied.

[^2]:    ${ }^{1}$ For coding system see Appendix B.
    ${ }^{2}$ All melt quantities are expressed in terms of unit melt (unit yield). This quantity has been defined as the number of grams of ice melted per gram of chemical applied.

[^3]:    ${ }^{2}$ For coding system see Appendix $B$.
    all melt quantities are expressed in terms of unit melt (unit yield). This quantity has been defined as the number of grams of ice melted per gram of chemical applied.

[^4]:    ${ }^{1}$ Calculated from the prediction equation.
    ${ }^{2}$ Melting capacities are expressed in inches of fresh snow having a specific gravity of 0. 06 .

