# Chemical Undercutting of Ice on Highway Pavement Materials

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Experiments were conducted to investigate the destruction of the ice-substrate bonds by chemical undercutting. The undercutting experiments determined the undercut area, as a function of time, of three deicers at three temperatures on highway core samples and laboratory-produced specimens. Tests were conducted at temperatures of 25°F (−4°C), 15°F (−9°C), and 5°F (−15°C) using all the substrates in the as-received, but cleaned, condition. The three deicers—NaCl, $CaCl_2$, and ethylene glycol—were used for all temperature-substrate combinations. The substrates included portland cement concrete, dense-graded asphalt, open-graded asphalt, rubber-modified asphalt core samples, and laboratory-produced specimens made of portland cement concrete and dense-graded asphalt. Undercutting action was also investigated on smooth highway core samples and smooth laboratory-produced specimens at selected temperatures. Linear regression models with good predictive power were developed to predict the undercutting behavior of deicer material for given combinations of pavement type, surface condition, and temperature as a function of time. Using these regression models, the following conclusions were drawn: (a) at 25°F, sodium chloride produces larger undercut areas than does calcium chloride when applied to as-received core samples of dense-graded and open-graded asphalt; (b) however, at 25°F, calcium chloride produces more undercutting action than does sodium chloride when applied to as-received core samples of portland cement concrete and rubber-modified asphalt; (c) at 15°F and 5°F, calcium chloride produces more undercutting than does sodium chloride for all four as-received pavement core samples; and (d) at 25°F and 15°F, the as-received laboratory-produced specimens tended to be undercut more extensively than the corresponding core samples at these temperatures.

Deicing salts, primarily sodium chloride, have been applied to highways for control of snow and ice since early in this century. Before 1941, little straight salt was applied to the roadways; most was mixed with sand or other abrasives to freeze-proof stockpiles and to treat locally hazardous highway locations such as curves, hills, and intersections. Experiments were begun in New England in 1941 using NaCl alone as an ice preventive (*1*). The total amount of NaCl applied across the country remained relatively low until the mid-1950s when usage surged dramatically to around 1 million tons annually, partially in response to the public demand for better all-weather roadway conditions. This demand eventually led to the adoption of a bare pavement policy by the highway departments in the snow-belt states (*2*).

Currently, the economic well-being, livelihood, and strategic defense of the United States depend to a large extent on the year-round mobility of trucks, buses, and passenger cars on the nation's highway network. Winter conditions of ice and snow still cause serious disruptions in the economies of nearly all states. The great dependence on highway transportation for the movement of goods, services, and people has resulted in the demand for more rapid and effective clearance of ice and snow from the highways. As a result, there has been an increased use of chemicals and abrasives by highway agencies to assist in providing a clear roadway. The current usage of salt is approaching a rate of 10 million tons per year (*3*).

Sodium chloride has become the chemical of choice because it is effective at subfreezing temperatures (eutectic of −6°F), is substantially less expensive than other deicing materials, and is readily available. At temperatures near the freezing point of water, sodium chloride is an effective agent for the control of ice and light snow by processes that include melting, penetration through layers of ice or snow, and disbondment of ice or packed snow from pavement surfaces. However, concern has steadily been voiced over the last 12 years about the effects of heavy salt use on the roadside environment, water supplies, vehicles, and highway structures.

Removal of ice (and compacted snow) from highway surfaces has been accomplished in part by mechanical means (scraping) and in part by use of deicing chemicals or, in many locations, by a combination of these techniques. Neither the combination of these methods nor their singular use is completely satisfactory. Some chemical methods have potential side effects such as corrosion of vehicle and highway structures, and contamination of the roadside environment and water supplies, while mechanical methods do not provide complete ice removal.

Past work aimed at the development of methods for removal of ice from pavement surfaces has been rather narrow in scope (*4*). There is a small amount of basic data on the adhesive properties of ice, the mechanisms of adhesion, and the effects of different substrates on their adhesion. Proper application of existing technical information and the development of needed basic knowledge covering ice adhesion should provide a sound basis for the development of new, practical measures for ice removal. A much better understanding of the physical and chemical phenomenon observed at the ice-pavement interface is required before bond destruction can be achieved in an economical manner.

In late 1987, the Strategic Highway Research Program (SHRP) of the National Research Council funded a study entitled "Ice-Pavement Bond Disbonding—Fundamental Study." The overall objective of this research was to conduct a fundamental study of the ice-pavement bond structure and

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the mechanics of its formation, to provide a sound basis for the development of techniques and deicers for destroying or disrupting the ice-pavement bond once it has formed. Embedded within this overall objective were several specific objectives including one to characterize the physical and chemical processes that cause deterioration in the bond formed between ice and asphalt or portland cement concretes. Many of the study activities focused on investigations of techniques for the destruction of the bond between ice and highway pavement materials.

One such activity involved conducting laboratory tests to investigate the destruction of ice-substrate bonds by chemical undercutting. The highway pavement materials used during this activity consisted of laboratory-produced substrates and core samples taken from several in-service highway pavements. The results of these chemical undercutting tests are described.

## GENERAL DESCRIPTION OF UNDERCUTTING TESTS

The destruction of the ice-pavement bond by chemical undercutting is a physically complex process that is dependent on a number of variables, including the following: type of pavement material, pavement porosities and irregularities, heat transfer rates, brine concentration and associated density gradients, and chemical species diffusion rates. The experimental procedures used during the undercutting tests were designed to minimize and control as many of these variables as possible in order to generate reproducible data.

The main objective of the chemical undercutting experiments was to determine the influence of temperature and substrate condition on the time-dependent undercut area produced by three deicers at the ice-substrate interface. The three deicers used were ethylene glycol, aqueous sodium chloride (26.3 percent by weight saturated solution at 0°C), and aqueous calcium chloride (37.3 percent by weight saturated solution at 0°C). Six substrates were used in the tests and consisted of core samples taken from four types of highway pavements and two types of laboratory-produced specimens of highway pavement materials. Measurements of the undercutting action of the three deicers were made at three test temperatures of 25°F (−4°C), 15°F (−9°C), and 5°F (−15°C).

### Substrate Configurations and Undercutting Test Specimen Preparation

The substrates used in the undercutting tests included portland cement concrete, dense-graded asphalt, open-graded asphalt, rubber-modified asphalt core samples, and laboratory-produced specimens made of portland cement concrete and dense-graded asphalt. The portland cement concrete and dense-graded asphalt core samples were 4 in. (10.2 cm) in diameter and were obtained from the Connecticut Department of Transportation (DOT). The open-graded asphalt core samples were 6 in. (15.2 cm) in diameter and were obtained from the New York DOT. The rubber-modified asphalt (Plusride) core samples were 4 in. in diameter and were obtained from the Montana Department of Highways and from CALTRANS. All core samples were taken from in-service roads.

The laboratory-produced, dense-graded asphalt specimens were 4 in. in diameter and were supplied by Michigan Technological University through SHRP. These specimens were made in a Marshall test mold using AC20 asphalt and aggregate obtained from the SHRP asphalt-aggregate library in Austin, Texas.

The laboratory-produced portland cement concrete specimens had approximate dimensions of 6.5 × 8.5 × 1 in. deep (16.5 × 21.6 × 2.5 cm deep) and were made by researchers at the South Dakota School of Mines and Technology. These specimens were made in accordance with the mix design used by the South Dakota DOT for highway (nonbridge deck) pavement construction. The core samples were of varying lengths when received. Each core sample was cut to about a 2-in. (5.1-cm) length with a diamond saw in a plane parallel to the exposed, wearing surface. This process produced core samples with one end consisting of the as-received surface and the other end with a relatively smooth, not previously exposed surface. One end of the laboratory-produced dense-graded asphalt specimens was ground smooth, with a final grinding using 400-grit powder. The other end of the specimens was left in the as-compacted state. Three of the laboratory-produced portland cement concrete specimens were ground smooth, with a final grinding using 600-grit powder.

The handling, cleaning, and storage of all substrate surfaces in this study were accomplished in accordance with protocols developed under SHRP (*5*). These protocols were followed to maximize measurement reproducibility. The substrates were cleaned just before ice was grown on the surfaces to minimize any surface contamination that might have taken place during storage. A special diagnostic method was used to characterize the surface condition of the substrates after being subjected to the cleaning procedures. The diagnostic technique, known as the drop-diameter method, was developed under SHRP (*5*) and provided contact angle measurements that were based on the diameter of a drop of test liquid.

Three undercutting test sites were made on the 4-in.-diameter core and laboratory-produced samples. Nine undercutting test sites were made on each of the portland cement concrete slabs.

Ice of 3⁄16-in. (0.48-cm) thickness was formed on the substrates in a prescribed manner. Before growing the ice, the substrates were placed in a refrigerator maintained at 39°F (4°C) and allowed to equilibrate to that temperature for at least 16 hr. Deionized water was also placed in the same refrigerator and allowed to equilibrate to that temperature. The substrates were then transferred to an ice growing chamber inside a walk-in cold room that was maintained at −9°C. The substrates rested on a thick aluminum plate inside the ice growing chamber. The chilled (4°C) deionized water was then added to the substrate surface whose edges had been dammed with aluminum tape to a height of ¼ in. (0.64 cm) above the substrate surface. Two 100-watt lamps were positioned above the specimens in the chamber and their power was gradually reduced with a Variac™. This procedure allowed the ice to grow slowly and from the substrate upward. Tapered holes were produced in the ice during freezing by use of Teflon™ plugs resting on the substrate surface. The configuration of a plug is shown in Figure 1a. The plugs were held in the correct relative position on the substrate with a ¼-in.-thick acrylic sheet that was prebored to accept the pre-

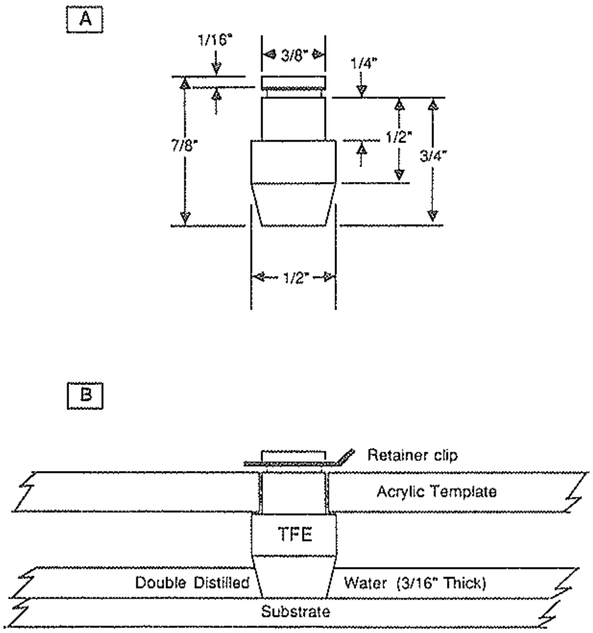


**FIGURE 1 Configuration of undercutting test specimen preparation: (a) teflon plug configuration, and (b) Sketch of experimental configuration.**

determined number of plugs. A sketch of this arrangement is shown in Figure 1b.

After the ice had frozen, the Teflon® plugs were removed from the ice. The substrate-ice samples were then removed from the ice growing chamber and placed in plastic bags where they remained until the walk-in cold room and the samples equilibrated to the undercutting test temperature.

A small quantity (0.3 to 0.4 mg) of the disodium salt of fluorescein was placed in each cavity before placement of liquid deicer in the cavity. The weight of dye relative to deicer weight was approximately 1 part dye to 1,000 parts deicer. The dye accordingly contributed slightly (less than 0.1 percent) to total ice melting capacities. Photographs were then taken with the aid of a UV light source at eight predetermined time points over a 1-hr period during the undercutting action. The 35-mm negatives used in the photographic process exhibited good contrast between the undercutting areas and the substrate material. The undercutting patterns observed on the highly textured surfaces, such as on the open-graded asphalt cores and laboratory-produced portland cement concrete specimens, were irregular in shape and followed the surface voids around the exposed surface aggregate. The undercutting patterns on the smoother substrates tended to be circular in shape.

Undercutting tests with the three deicers were performed at each of the three temperatures on each of the six substrates in the as-received, but cleaned, condition. Undercutting tests with the three deicers were also performed on the smooth highway core samples and laboratory-produced specimens at 25°F and 5°F. Three replicate tests were performed for each unique combination of substrate, deicer, and temperature at a given time point.

### Data Reduction

The data reduction technique used with the undercutting results followed an approach used successfully in other undercutting experiments (*6*). The 35-mm color slides of the undercutting action were projected onto a screen. The individual undercut areas were then traced onto a vellum paper sheet. An area determination was made by use of a planimeter. A digital clock with a liquid crystal display and a standardized area grid were included in the field of view of the substrate to provide a photographic record of the time lapsed during the tests and a standard reference area for use in determining the undercut area.

All measured undercut areas were adjusted to account for the surface area, at time zero, that the Teflon plug was in contact with the substrate. This area was subtracted from all measured undercut areas obtained from the 35-mm photographic records. The resulting differences were then normalized by dividing them by the appropriate weight of the deicer. These final results are herein referred to as adjusted undercut areas. The replicate results were averaged before construction of the plots.

## RESULTS

Plots of the average adjusted undercut area versus time were developed for each of the three deicer and six substrate combinations. Of these 18 plots, a selection is shown in Figures 2–9. Each figure shows the results for as-received and smooth surfaces for the three temperatures.

The tests conducted with each deicer involved primarily an evaluation of the effects of different types of substrates and their physical surface characteristics (particularly surface roughness) on the undercutting characteristics. All substrate surfaces were cleaned before testing by standardized procedures. Thus, the chemical properties of the substrate surfaces in all cases, including the core samples, do not reflect the chemical contamination that accompanies highway uses. The undercutting results should, however, reflect the chemical properties of the substrate material (i.e., asphalt or portland cement concrete). Potential differences might exist between core samples and laboratory-produced substrates of the same type of material. The core samples were exposed to long-term weathering and use effects; the laboratory-produced specimens were not exposed to these environmental impacts.

### Estimating Undercut Areas as a Function of Time

Linear regression analyses were performed on the data to investigate the relationship between the adjusted undercut area (in square centimeter per gram of deicer in solution) and time (in minutes). These analyses were performed separately for each deicer, substrate material, sample type, surface condition, and temperature combination. Thus, a total of 90 analyses are reported. All three replicate results at each of nine time points were used in these analyses. In a first step, the adjusted undercut area was regressed against time$^{1/2}$, time, and time$^2$. The residuals from each model were examined for

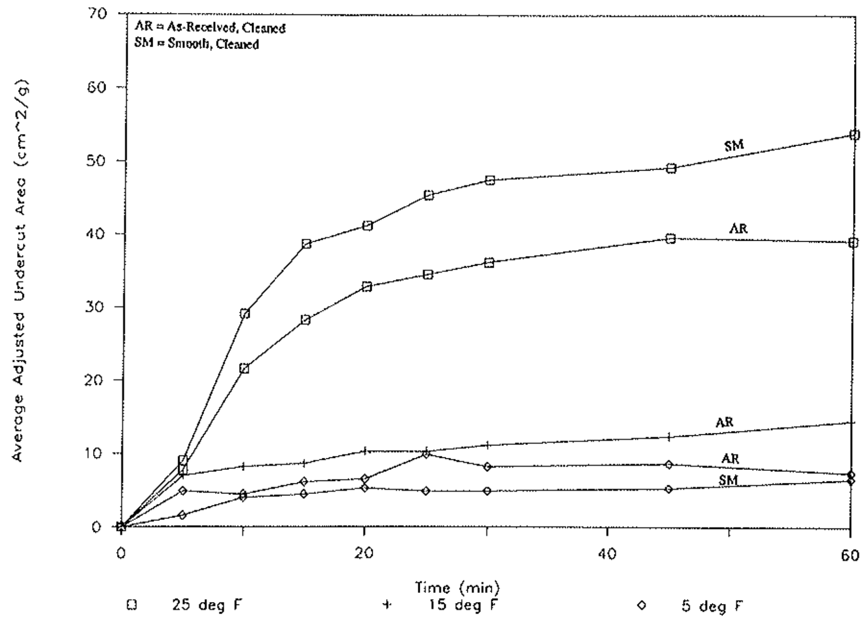


**FIGURE 2 Adjusted undercut area versus time: NaCl on core samples of dense-graded asphalt.**

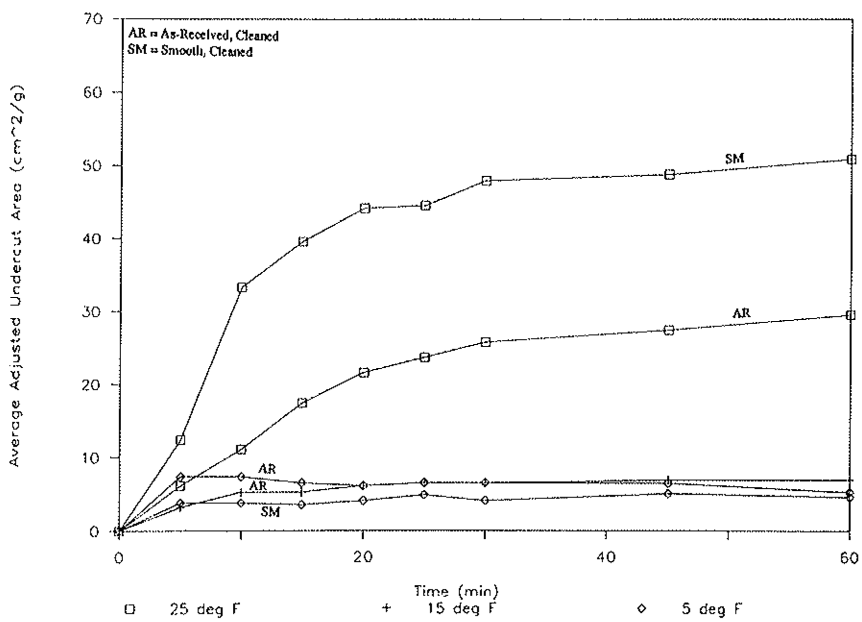


**FIGURE 3 Adjusted undercut area versus time: NaCl on core samples of open-graded asphalt.**

normality and, as a result, the square root of the adjusted undercut area was used. This approach considerably improved the normality of the model residuals.

The square root of the adjusted undercut area was therefore regressed against $time^{1/2}$, time, and $time^2$ for each of the 90 combinations of deicer, substrate type, sample type, and temperature. The regression model is given by the following:

$$(\text{adjusted undercut area})^{1/2} = A * \text{time}^{1/2} + B * \text{time} + C * \text{time}^2 \quad (1)$$

where $A$, $B$ and $C$ denote the regression coefficients. The model was forced through the origin, that is, the intercept was set to zero because at time zero, the undercut area was also zero.

The regression analyses were performed in a stepwise fashion. After considering all three variables, $time^{1/2}$, time, and $time^2$, if any of the coefficients $A$, $B$, or $C$ was not statistically significant at the 10 percent significance level, then the model was rerun without the corresponding variables.

Table 1 presents the final regression results, sorted by deicer, substrate material, sample type, surface condition, and

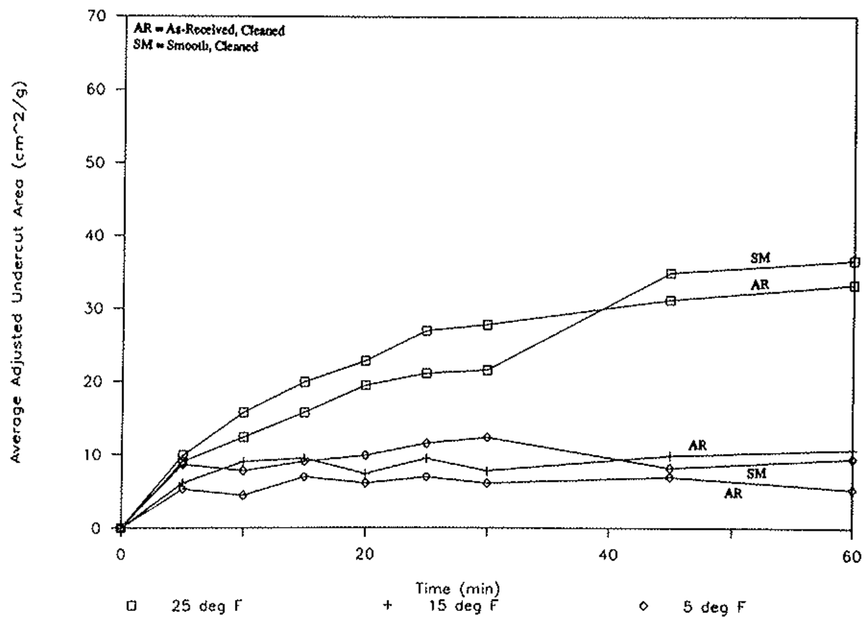


**FIGURE 4 Adjusted undercut area versus time: NaCl on core samples of rubber-modified asphalt.**

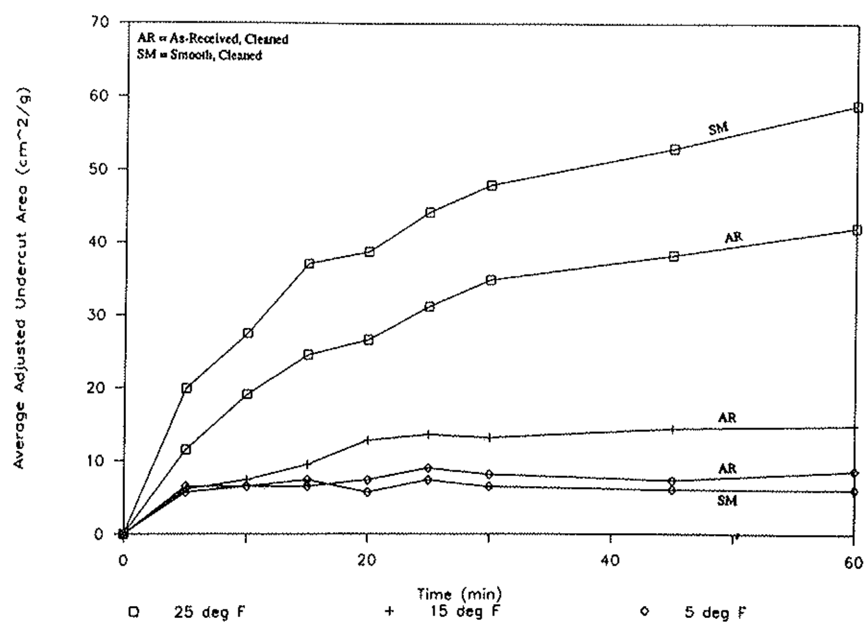


**FIGURE 5 Adjusted undercut area versus time: NaCl on core samples of portland cement concrete.**

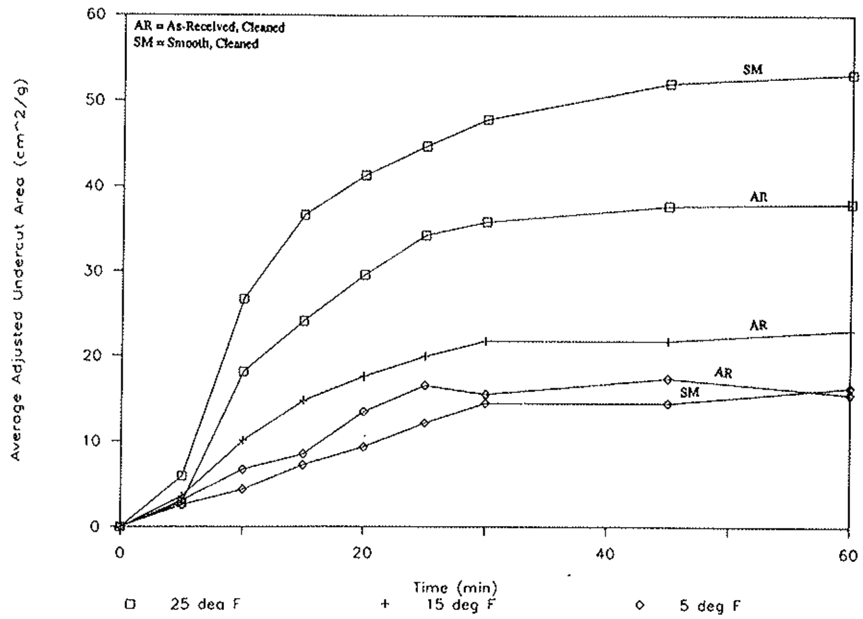


**FIGURE 6 Adjusted undercut area versus time: $CaCl_2$ on core samples of dense-graded asphalt.**

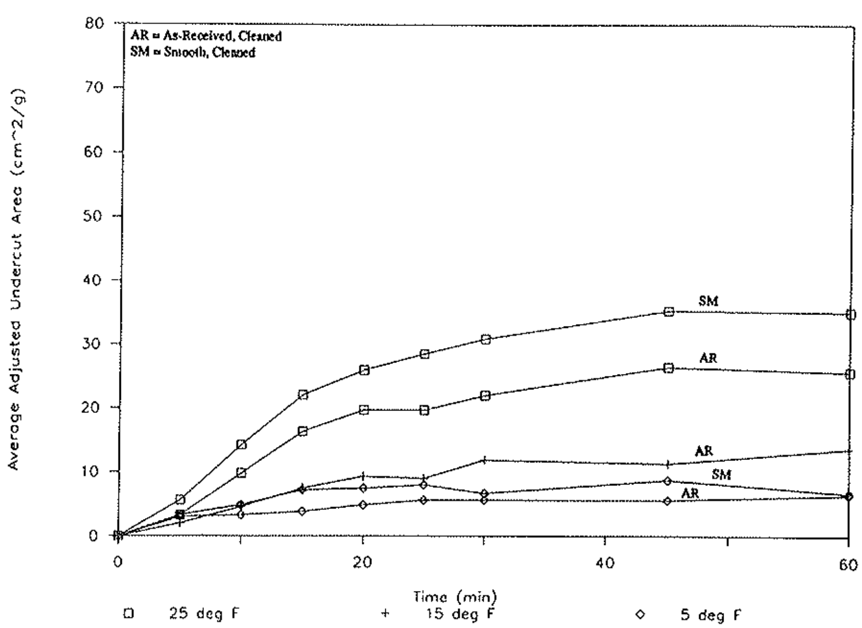


**FIGURE 7 Adjusted undercut area versus time: $CaCl_2$ on core samples of open-graded asphalt.**

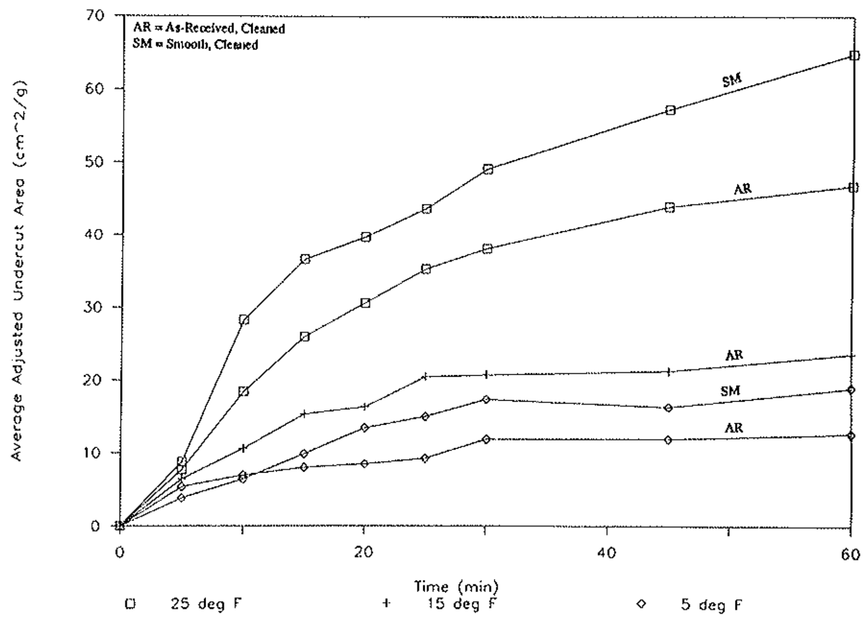


**FIGURE 8 Adjusted undercut area versus time: $CaCl_2$ on core samples of rubber-modified asphalt.**

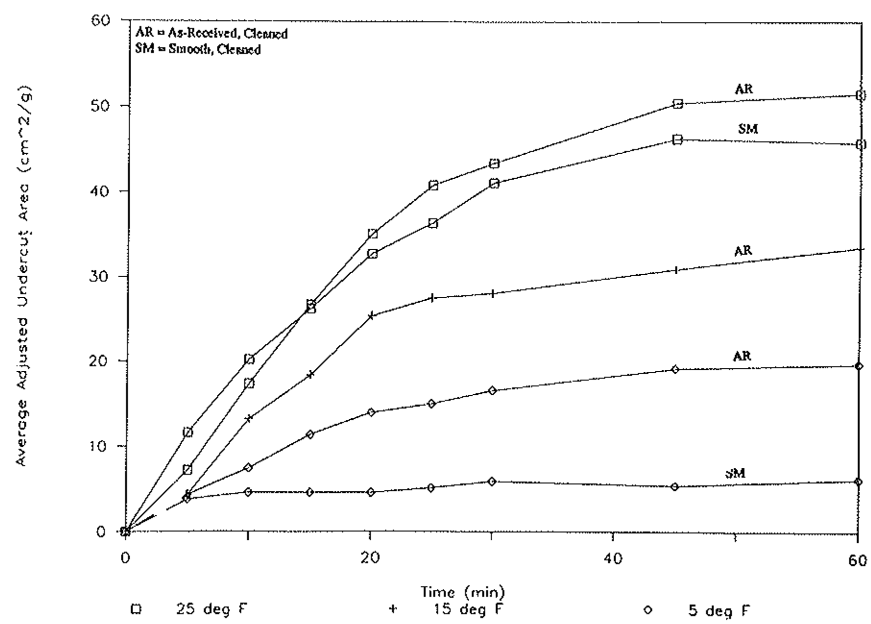


**FIGURE 9 Adjusted undercut area versus time: $CaCl_2$ on core samples of portland cement concrete.**

temperature. All models were statistically significant at the 10 percent level or better. For each model, Table 1 presents the number of test results on which each regression is based; the average values of the square root of the adjusted undercut area over time; the regression coefficients *A*, *B*, and *C*; and two measures of model fit. A missing entry for a regression coefficient indicates that the corresponding variable did not significantly contribute to the model at the 10 percent significance level. This procedure is equivalent to setting that coefficient to zero.

The last two columns are two measures of the fit of the model to the data. The root mean square error (RMSE), in the same units as the dependent variable, the square root of the adjusted undercut area, is an estimate of the standard deviation about the regression. It is a measure of the error with which any observed value of the square root of the adjusted undercut area could be predicted, at a given time interval after deicer application, using the estimated regression equation. Thus the smaller the RMSE, the smaller the error in the prediction.

TABLE 1 LINEAR REGRESSION RESULTS FOR UNDERCUTTING MODELS

**Deicer Material: NaCL**

| Substrate Material | Sample Type | Surface Condition | Temperature (deg F) | Number of Tests | Mean Sqrt(Area) | Regression Coefficients: Sqrt(Time) (A) | Regression Coefficients: Time (B) | Regression Coefficients: Time*2 (C) | Measures of Model Fit: Root Mean Square Error | Measures of Model Fit: R-Squared (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Dense-Graded Asphalt | Core | As Received, Cleaned | 25 | 27 | 4.76 | 1.046 | | | 1.115 | 70.6 |
| | | | 15 | 27 | 2.83 | 1.546 | -0.211 | 0.0013 | 0.301 | 92.6 |
| | | | 5 | 27 | 2.32 | 0.982 | -0.082 | | 0.358 | 85.7 |
| | | Smooth and Cleaned | 25 | 27 | 5.45 | 2.064 | -0.146 | | 0.404 | 97.0 |
| | | | 5 | 27 | 1.87 | 0.863 | -0.093 | 0.0004 | 0.201 | 93.3 |
| | Lab | As Received, Cleaned | 25 | 27 | 6.06 | 2.349 | -0.173 | | 0.978 | 86.0 |
| | | | 15 | 27 | 3.67 | 1.405 | -0.101 | | 0.292 | 96.4 |
| | | | 5 | 24 | 2.39 | 1.520 | -0.228 | 0.0015 | 0.280 | 91.6 |
| | | Smooth and Cleaned | 25 | 27 | 5.34 | 1.180 | | | 1.604 | 61.8 |
| | | | 5 | 27 | 1.93 | 1.342 | -0.221 | 0.0015 | 0.351 | 79.3 |
| Open-Graded Asphalt | Core | As Received, Cleaned | 25 | 27 | 3.91 | 0.868 | | | 0.739 | 81.2 |
| | | | 15 | 27 | 2.13 | 1.081 | -0.128 | 0.0005 | 0.164 | 96.0 |
| | | | 5 | 27 | 2.26 | 1.635 | -0.262 | 0.0015 | 0.315 | 86.5 |
| | | Smooth and Cleaned | 25 | 27 | 5.55 | 2.217 | -0.170 | | 0.334 | 97.8 |
| | | | 5 | 27 | 1.82 | 1.099 | -0.158 | 0.0009 | 0.233 | 88.6 |
| Rubber-Modified Asphalt | Core | As Received, Cleaned | 25 | 27 | 4.24 | 1.584 | -0.110 | | 0.326 | 96.5 |
| | | | 15 | 27 | 2.61 | 1.650 | -0.251 | 0.0016 | 0.259 | 93.2 |
| | | | 5 | 27 | 2.17 | 1.255 | -0.165 | 0.0007 | 0.281 | 88.5 |
| | | Smooth and Cleaned | 25 | 27 | 4.00 | 1.292 | -0.067 | | 0.473 | 92.9 |
| | | | 5 | 27 | 2.73 | 1.624 | -0.221 | 0.0010 | 0.448 | 82.6 |
| Portland Cement Concrete | Core | As Received, Cleaned | 25 | 27 | 4.65 | 1.690 | -0.112 | | 0.513 | 93.3 |
| | | | 15 | 27 | 2.95 | 1.160 | -0.088 | | 0.528 | 82.6 |
| | | | 5 | 27 | 2.43 | 1.483 | -0.215 | 0.0012 | 0.249 | 92.5 |
| | | Smooth and Cleaned | 25 | 27 | 5.50 | 2.038 | -0.141 | | 1.252 | 75.2 |
| | | | 5 | 27 | 2.25 | 1.496 | -0.226 | 0.0012 | 0.238 | 92.0 |
| | Lab | As Received, Cleaned | 25 | 27 | 5.07 | 1.122 | | | 1.120 | 74.9 |
| | | | 15 | 27 | 3.50 | 1.417 | -0.111 | | 0.324 | 94.7 |
| | | | 5 | 27 | 2.19 | 1.268 | -0.171 | 0.0008 | 0.230 | 92.1 |
| | | Smooth and Cleaned | 25 | 27 | 6.42 | 2.777 | -0.260 | 0.0006 | 0.289 | 98.7 |
| | | | 5 | 27 | 2.30 | 1.407 | -0.211 | 0.0013 | 0.232 | 92.9 |

**Deicer Material: CaCl2**

| Substrate Material | Sample Type | Surface Condition | Temperature (deg F) | Number of Tests | Mean Sqrt(Area) | Regression Coefficients: Sqrt(Time) (A) | Regression Coefficients: Time (B) | Regression Coefficients: Time*2 (C) | Measures of Model Fit: Root Mean Square Error | Measures of Model Fit: R-Squared (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Dense-Graded Asphalt | Core | As Received, Cleaned | 25 | 27 | 4.47 | 1.264 | | -0.0010 | 0.646 | 91.1 |
| | | | 15 | 27 | 3.52 | 0.992 | | -0.0008 | 0.231 | 97.8 |
| | | | 5 | 27 | 3.00 | 0.851 | | -0.0007 | 0.234 | 97.0 |
| | | Smooth and Cleaned | 25 | 27 | 5.35 | 1.513 | | -0.0013 | 0.475 | 96.1 |
| | | | 5 | 27 | 2.72 | 0.726 | | -0.0004 | 0.292 | 94.9 |
| | Lab | As Received, Cleaned | 25 | 27 | 5.15 | 1.430 | | -0.0011 | 0.401 | 97.0 |
| | | | 15 | 27 | 4.26 | 0.936 | | | 0.954 | 72.6 |
| | | | 5 | 24 | 3.42 | 1.515 | -0.130 | | 0.238 | 97.2 |
| | | Smooth and Cleaned | 25 | 27 | 6.54 | 1.446 | | | 1.366 | 77.1 |
| | | | 5 | 27 | 1.32 | 0.506 | -0.037 | | 0.071 | 98.2 |
| Open-Graded Asphalt | Core | As Received, Cleaned | 25 | 27 | 3.64 | 1.008 | | -0.0008 | 0.271 | 97.4 |
| | | | 15 | 27 | 2.52 | 0.564 | | | 0.549 | 78.8 |
| | | | 5 | 27 | 1.91 | 0.757 | -0.058 | | 0.350 | 80.8 |
| | | Smooth and Cleaned | 25 | 27 | 4.13 | 0.917 | | | 1.566 | 52.2 |
| | | | 5 | 27 | 2.25 | 0.973 | -0.083 | | 0.302 | 89.2 |
| Rubber-Modified Asphalt | Core | As Received, Cleaned | 25 | 27 | 4.80 | 1.070 | | | 0.874 | 83.4 |
| | | | 15 | 27 | 3.58 | 1.345 | -0.094 | | 0.255 | 97.1 |
| | | | 5 | 27 | 2.68 | 1.280 | -0.147 | 0.0007 | 0.279 | 93.2 |
| | | Smooth and Cleaned | 25 | 27 | 5.54 | 1.906 | -0.113 | | 0.471 | 96.4 |
| | | | 5 | 27 | 3.07 | 0.849 | | -0.0007 | 0.255 | 96.5 |
| Portland Cement Concrete | Core | As Received, Cleaned | 25 | 27 | 5.02 | 1.369 | | -0.0010 | 0.284 | 98.5 |
| | | | 15 | 27 | 4.07 | 0.911 | | | 0.920 | 77.6 |
| | | | 5 | 27 | 3.18 | 1.127 | -0.071 | | 0.184 | 98.2 |
| | | Smooth and Cleaned | 25 | 27 | 4.89 | 1.079 | | | 1.361 | 64.3 |
| | | | 5 | 27 | 1.98 | 1.174 | -0.168 | 0.0010 | 0.201 | 92.8 |
| | Lab | As Received, Cleaned | 25 | 27 | 4.76 | 1.343 | | -0.0011 | 0.326 | 97.7 |
| | | | 15 | 27 | 4.23 | 1.691 | -0.130 | | 0.304 | 96.9 |
| | | | 5 | 27 | 2.65 | 0.588 | | | 0.630 | 73.1 |
| | | Smooth and Cleaned | 25 | 27 | 5.77 | 1.622 | | -0.0014 | 0.575 | 95.1 |
| | | | 5 | 27 | 3.17 | 0.886 | | -0.0007 | 0.344 | 94.3 |

*(continued on next page)*

TABLE 1 LINEAR REGRESSION RESULTS FOR UNDERCUTTING MODELS (*continued*)

**Deicer Material: Ethylene Glycol**

| Substrate Material | Sample Type | Surface Condition | Temperature (deg F) | Number of Tests | Mean Sqrt(Area) | Regression Coefficients Sqrt(Time) (A) | Time (B) | Time*2 (C) | Measures of Model Fit Root Mean Square Error | R-Squared (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Dense-Graded Asphalt | Core | As Received, Cleaned | 25 | 27 | 2.96 | 0.252 | 0.129 | -0.0013 | 0.167 | 99.0 |
| | | | 15 | 27 | 2.51 | 0.573 | | | 0.232 | 96.3 |
| | | | 5 | 27 | 1.84 | 0.633 | -0.056 | 0.0005 | 0.184 | 95.9 |
| | | Smooth and Cleaned | 25 | 27 | 3.59 | 0.323 | 0.169 | -0.0020 | 0.253 | 98.3 |
| | | | 5 | 27 | 2.02 | 0.788 | -0.082 | 0.0006 | 0.165 | 96.9 |
| | Lab | As Received, Cleaned | 25 | 27 | 3.45 | 0.538 | 0.098 | -0.0013 | 0.187 | 98.9 |
| | | | 15 | 27 | 2.62 | 0.593 | | | 0.641 | 77.6 |
| | | | 5 | 27 | 2.04 | 0.520 | | | 0.242 | 94.1 |
| | | Smooth and Cleaned | 25 | 27 | 2.57 | 1.092 | -0.105 | 0.0004 | 0.193 | 96.6 |
| | | | 5 | 27 | 1.94 | 0.786 | -0.093 | 0.0008 | 0.209 | 95.0 |
| Open-Graded Asphalt | Core | As Received, Cleaned | 25 | 27 | 2.43 | 0.548 | | | 0.557 | 78.7 |
| | | | 15 | 27 | 2.24 | 0.558 | | -0.0002 | 0.140 | 98.4 |
| | | | 5 | 27 | 2.59 | 1.504 | -0.223 | 0.0015 | 0.316 | 90.3 |
| | | Smooth and Cleaned | 25 | 27 | 3.09 | 0.693 | | | 0.802 | 72.4 |
| | | | 5 | 27 | 1.92 | 0.772 | -0.075 | 0.0004 | 0.159 | 96.3 |
| Rubber-Modified Asphalt | Core | As Received, Cleaned | 25 | 27 | 3.00 | 0.683 | | | 0.402 | 92.4 |
| | | | 15 | 27 | 2.51 | 0.866 | -0.052 | | 0.126 | 98.6 |
| | | | 5 | 27 | 1.85 | 0.913 | -0.121 | 0.0008 | 0.273 | 88.6 |
| | | Smooth and Cleaned | 25 | 27 | 3.17 | 0.720 | | | 0.906 | 72.4 |
| | | | 5 | 27 | 1.97 | 0.943 | -0.117 | 0.0007 | 0.298 | 87.2 |
| Portland Cement Concrete | Core | As Received, Cleaned | 25 | 27 | 3.42 | 0.611 | 0.074 | -0.0010 | 0.164 | 99.1 |
| | | | 15 | 27 | 2.80 | 0.709 | | -0.0003 | 0.178 | 98.3 |
| | | | 5 | 27 | 1.87 | 0.675 | -0.067 | 0.0006 | 0.241 | 93.4 |
| | | Smooth and Cleaned | 25 | 27 | 3.75 | 0.971 | | -0.0005 | 0.265 | 97.9 |
| | | | 5 | 27 | 1.91 | 0.940 | -0.126 | 0.0009 | 0.391 | 79.4 |
| | Lab | As Received, Cleaned | 25 | 27 | 3.31 | 0.607 | 0.063 | -0.0009 | 0.192 | 98.7 |
| | | | 15 | 27 | 2.88 | 0.747 | | -0.0004 | 0.098 | 99.5 |
| | | | 5 | 27 | 1.91 | 0.610 | -0.042 | 0.0003 | 0.154 | 97.3 |
| | | Smooth and Cleaned | 25 | 27 | 3.99 | 0.779 | 0.072 | -0.0012 | 0.218 | 98.8 |
| | | | 5 | 27 | 1.62 | 0.845 | -0.103 | 0.0004 | 0.150 | 94.1 |

The last column in Table 1 presents the $R^2$ value for each regression model. This figure, in percent, is the proportion of the variation in the data that is explained by the model. That is, the higher the $R^2$ value (maximum is 100 percent), the better the model fits the data. Of the 90 regression models, 82 have an $R^2$ value above 75 percent, that is, they have good predictive power.

Using the results of these regression analyses, the undercutting action of a deicer on a pavement can be predicted under given conditions (i.e., temperature, pavement type, and surface condition) as a function of time. For example, Figure 10 shows the observed and predicted adjusted undercut areas for the three deicers on as-received, cleaned core samples of portland cement concrete at 25°F. The equations used for the three deicers are (from Table 1):

$$\text{NaCl: Area} = (1.690\ \text{Time}^{1/2} - 0.112\ \text{Time})^2 \quad (2)$$

$$\text{CaCl}_2\text{: Area} = (1.369\ \text{Time}^{1/2} - 0.0010\ \text{Time}^2)^2 \quad (3)$$

$$\text{Ethylene Glycol: Area} = (0.611\ \text{Time}^{1/2} + 0.074\ \text{Time} - 0.0010\ \text{Time}^2)^2 \quad (4)$$

The equations from Table 1 were used to compute estimated adjusted undercut areas for all comparisons made in the following sections.

### Effects of Substrate Surface Texture (As-Received Versus Smooth) on Undercutting Results

Comparisons were made of the undercutting results obtained for as-received and smooth substrate pairs of the same material. These comparisons were made for 25°F and 5°F results only because tests were not run on smooth surfaces at 15°F. Ratios of undercutting results for as-received to smooth substrate surfaces were formed at 20 and 60 min for a given substrate-deicer-temperature combination using the coefficients in Table 1. The results at 25°F and 5°F are presented in Table 2, for the six substrates and three deicers.

Table 2 indicates that the extent of undercutting at 25°F was considerably less on as-received substrates than on smooth substrates in a majority [75 percent of the cases (27 out of 36 ratios) are below 1], with ratios ranging from 0.4 to 2.4. At 5°F, no clear-cut conclusions can be drawn from comparisons of undercutting results for as-received and smooth substrate surfaces. For one-third of the results, the ratio is below 1. For the remainder of the cases, the ratios vary widely, ranging from 1.0 to 8.5. The inconsistencies of the ratios are caused, in large part, by the fact that the undercut areas are quite small at 5°F and are subject to more error in measurement than at 25°F. In addition, the small undercutting patterns at 5°F are approximately of the same dimensions as the surface irregularities (surface voids or asperities) of some of the as-received samples. The undercutting patterns at 5°F may thus

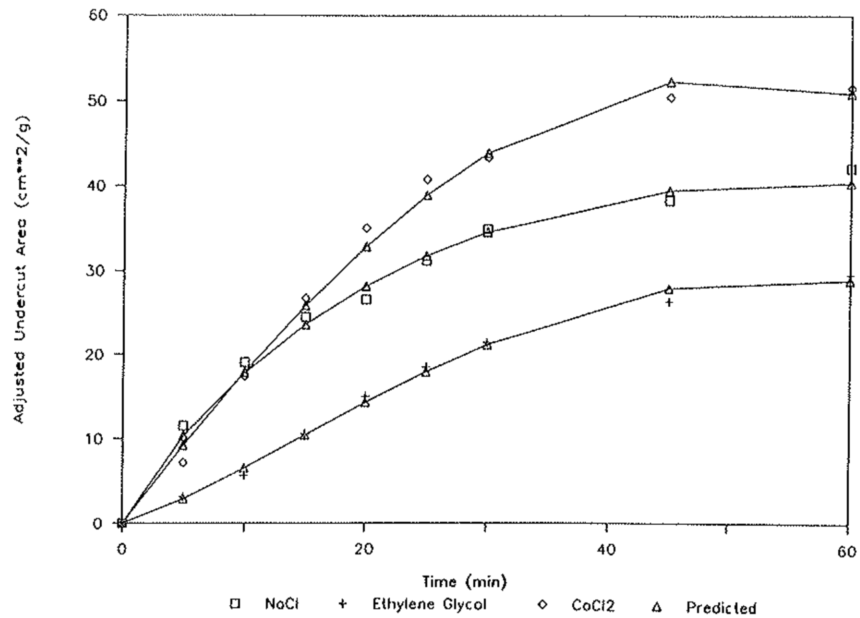


**FIGURE 10 Observed and predicted adjusted undercut areas for three deicers on cleaned, as-received portland cement concrete core samples at 25°F.**

TABLE 2 RATIOS OF UNDERCUTTING RESULTS FOR AS-RECEIVED TO SMOOTH SUBSTRATE SURFACES AT 20 AND 60 min AFTER APPLICATION

**a) Ratios of as-received to smooth results at 25 deg F**

| Substrate Material | Sample Type | Ratio at 20 min. NaCl | CaCl2 | Ethylene Glycol | Ratio at 60 min. NaCl | CaCl2 | Ethylene Glycol |
|---|---|---|---|---|---|---|---|
| Dense-Graded Asphalt | Core | 0.5 | 0.7 | 0.6 | 1.2 | 0.7 | 0.8 |
| Open-Graded Asphalt | | 0.4 | 1.0 | 0.6 | 0.9 | 0.5 | 0.6 |
| Rubber-Modified Asphalt | | 1.2 | 0.6 | 0.9 | 0.9 | 1.1 | 0.9 |
| Portland Cement Concrete | | 0.7 | 1.4 | 0.8 | 0.7 | 0.7 | 0.8 |
| Dense-Graded Asphalt | Lab | 1.8 | 0.8 | 1.7 | 0.7 | 0.4 | 2.4 |
| Portland Cement Concrete | | 0.5 | 0.7 | 0.7 | 1.1 | 0.7 | 0.8 |

**b) Ratios of as-received to smooth results at 5 deg F**

| Substrate Material | Sample Type | Ratio at 20 min. NaCl | CaCl2 | Ethylene Glycol | Ratio at 60 min. NaCl | CaCl2 | Ethylene Glycol |
|---|---|---|---|---|---|---|---|
| Dense-Graded Asphalt | Core | 1.6 | 1.3 | 0.8 | 1.2 | 1.0 | 0.9 |
| Open-Graded Asphalt | | 1.8 | 0.7 | 2.0 | 1.2 | 0.9 | 1.6 |
| Rubber-Modified Asphalt | | 0.6 | 0.8 | 0.8 | 0.7 | 0.7 | 0.9 |
| Portland Cement Concrete | | 1.1 | 2.6 | 1.0 | 1.5 | 3.3 | 1.2 |
| Dense-Graded Asphalt | Lab | 1.6 | 8.5 | 1.3 | 1.8 | 5.0 | 1.3 |
| Portland Cement Concrete | | 1.0 | 0.5 | 1.0 | 0.7 | 1.2 | 2.8 |

Note: Undercut areas were estimated using the regression models from Table 1.

reflect behavior over one or two surface irregularities rather than behavior over an average population of irregularities. At 25°F, however, the larger undercutting patterns should more closely reflect the average surface condition.

### Effects of Substrate Material on Undercutting Results

The determination of the effects of substrate material on undercutting characteristics of the three deicers is best made by examining the undercutting results at fixed times after application. These results, for both pavement core samples and laboratory-produced specimens, are presented in Table 3 (Parts a through e) for each of the substrate, deicer, and temperature combinations at 20 and 60 min after deicer application. These results were obtained using the regression coefficients presented in Table 1. From the estimated undercut areas presented in Table 3, the following observations can be made:

- Of the three deicers investigated, ethylene glycol produced the smallest estimated undercut area on both laboratory-produced specimens and pavement core samples at 20 and 60 min after application. This result is true both for smooth and as-received substrates at 25°F.

TABLE 3 ESTIMATED UNDERCUT AREAS ($cm^2$ PER 1 g OF DEICER IN SOLUTION) AT 20 AND 60 min AFTER APPLICATION

**a) Smooth and Cleaned Samples at 25 deg F**

| Substrate Material | Sample Type | Undercut Area at 20 min. NaCl | CaCl2 | Ethylene Glycol | Undercut Area at 60 min. NaCl | CaCl2 | Ethylene Glycol |
|---|---|---|---|---|---|---|---|
| Dense-Graded Asphalt | Core | 40 | 39 | 16 | 53 | 50 | 31 |
| Open-Graded Asphalt | | 42 | 17 | 10 | 49 | 50 | 29 |
| Rubber-Modified Asphalt | | 20 | 39 | 10 | 36 | 64 | 31 |
| Portland Cement Concrete | | 40 | 23 | 17 | 54 | 70 | 34 |
| Dense-Graded Asphalt | Lab | 28 | 42 | 9 | 84 | 125 | 12 |
| Portland Cement Concrete | | 56 | 45 | 20 | 67 | 59 | 37 |

**b) Smooth and Cleaned Samples at 5 deg F**

| Substrate Material | Sample Type | Undercut Area at 20 min. NaCl | CaCl2 | Ethylene Glycol | Undercut Area at 60 min. NaCl | CaCl2 | Ethylene Glycol |
|---|---|---|---|---|---|---|---|
| Dense-Graded Asphalt | Core | 5 | 9 | 5 | 6 | 16 | 12 |
| Open-Graded Asphalt | | 4 | 7 | 4 | 5 | 7 | 9 |
| Rubber-Modified Asphalt | | 11 | 12 | 5 | 9 | 18 | 9 |
| Portland Cement Concrete | | 7 | 5 | 4 | 6 | 6 | 9 |
| Dense-Graded Asphalt | Lab | 5 | 2 | 4 | 6 | 3 | 12 |
| Portland Cement Concrete | | 7 | 13 | 4 | 9 | 18 | 4 |

**c) As-received, Cleaned Samples at 25 deg F**

| Substrate Material | Sample Type | Undercut Area at 20 min. NaCl | CaCl2 | Ethylene Glycol | Undercut Area at 60 min. NaCl | CaCl2 | Ethylene Glycol |
|---|---|---|---|---|---|---|---|
| Dense-Graded Asphalt | Core | 22 | 27 | 10 | 66 | 37 | 25 |
| Open-Graded Asphalt | | 15 | 18 | 6 | 45 | 25 | 18 |
| Rubber-Modified Asphalt | | 24 | 23 | 9 | 32 | 69 | 28 |
| Portland Cement Concrete | | 28 | 33 | 14 | 40 | 51 | 29 |
| Dense-Graded Asphalt | Lab | 50 | 35 | 15 | 61 | 50 | 29 |
| Portland Cement Concrete | | 25 | 31 | 13 | 75 | 40 | 29 |

**d) As-received, Cleaned Samples at 15 deg F**

| Substrate Material | Sample Type | Undercut Area at 20 min. NaCl | CaCl2 | Ethylene Glycol | Undercut Area at 60 min. NaCl | CaCl2 | Ethylene Glycol |
|---|---|---|---|---|---|---|---|
| Dense-Graded Asphalt | Core | 10 | 17 | 7 | 15 | 22 | 20 |
| Open-Graded Asphalt | | 6 | 6 | 6 | 7 | 19 | 14 |
| Rubber-Modified Asphalt | | 9 | 17 | 8 | 11 | 23 | 13 |
| Portland Cement Concrete | | 12 | 17 | 9 | 14 | 50 | 20 |
| Dense-Graded Asphalt | Lab | 18 | 18 | 7 | 23 | 53 | 21 |
| Portland Cement Concrete | | 17 | 25 | 10 | 18 | 28 | 20 |

**e) As-received, Cleaned Samples at 5 deg F**

| Substrate Material | Sample Type | Undercut Area at 20 min. NaCl | CaCl2 | Ethylene Glycol | Undercut Area at 60 min. NaCl | CaCl2 | Ethylene Glycol |
|---|---|---|---|---|---|---|---|
| Dense-Graded Asphalt | Core | 8 | 12 | 4 | 7 | 16 | 11 |
| Open-Graded Asphalt | | 7 | 5 | 8 | 6 | 6 | 14 |
| Rubber-Modified Asphalt | | 7 | 9 | 4 | 6 | 13 | 8 |
| Portland Cement Concrete | | 8 | 13 | 4 | 9 | 20 | 11 |
| Dense-Graded Asphalt | Lab | 8 | 17 | 5 | 11 | 15 | 16 |
| Portland Cement Concrete | | 7 | 7 | 4 | 6 | 21 | 11 |

Note: Undercut areas were estimated using the regression models from Table 1.

- However, as the substrate temperature decreases, the previous conclusion holds true in most cases at 20 min but not at 60 min after application.

Comparisons involving the smooth substrates (Table 3, Parts a and b) should reflect the differences caused by different chemical properties of the substrate materials (i.e., dense-graded asphalt and portland cement concrete). These comparisons reflect the following:

- No consistent relationship exists between the undercutting results obtained on dense-graded asphalt and those ob-

tained on portland cement concrete for either laboratory-produced specimens or pavement core samples.

- The smooth dense-graded, open-graded, and rubber-modified asphalt core samples cannot be consistently ranked on the undercutting action produced by either of the three chemical deicers.

The results indicate that a complex interaction exists between chemical deicers and the chemical properties of the smooth substrate surfaces.

At 25°F and 15°F, the two laboratory-produced specimens in the as-received condition were generally undercut more than the corresponding core samples at those temperatures (Table 3, Parts c and d). This pattern holds true at 20 min after deicer application; however, at 60 min, this pattern becomes more inconsistent.

Comparisons of the undercutting results for the four as-received core samples should be indicative of undercutting to be expected under field conditions without contamination. The results in Table 3, Parts c, d, and e, indicate the following:

- At 25°F, when applied on dense-graded and open-graded asphalt, sodium chloride produces larger undercut areas than does calcium chloride.
- However, when applied on portland cement concrete and rubber-modified asphalt at 25°F, calcium chloride produces more undercutting action than does sodium chloride.
- At 15°F and 5°F, calcium chloride produces more undercutting than does sodium chloride for all four as-received pavement core samples.

## COMPARISON WITH LITERATURE UNDERCUTTING RESULTS

The principal comparable study of undercutting reported in the literature is that of Trost et al. (*7*). The experimental approach taken by these authors is similar to that described herein. That is, the ice penetration action of the chemical deicer was not part of the chemical undercutting process as it was in another undercutting study (*8*). In the study by Trost et al., small, solid deicer particles (0.5 mm unit in dimension) were placed at the bottom of a cylindrical cavity formed in a larger cylinder of ice. The ice cylinder was prepared separately and then frozen onto various substrates via a thin film of water which was frozen to bond the ice cylinder to the substrates. Substrates tested were glass, brick, portland cement concrete, and asphalt. Solid forms of sodium chloride, calcium chloride, sodium hydroxide, urea, and calcium-magnesium-acetate (CMA) were used in the experiments. The quantities of deicer used ranged from 50 to 500 mg and the test temperatures were −5°C (23°F) and −10°C (14°F). These temperatures are close to two of the three temperatures used in the present study.

Trost et al. observed no significant differences in the extent or rate of undercutting with the different substrates, with the exception that initiation of undercutting was slower on glass.

The undercutting results obtained in the present study with aqueous solutions of sodium chloride and calcium chloride were compared with those obtained by Trost et al. for the solid form of these deicers. Before the comparisons could be made, it was necessary to develop a basis for comparing the aqueous deicers with solid forms of the same deicer. In the present study, adjusted undercut areas are reported in square centimeters undercut by 1 g of deicer in solution. The melting capacity of 1 g of deicer in solution is, of course, less than that of 1 g of an essentially dry form of the deicer.

A substantial portion of the rationale proposed and developed by Trost et al. is that the maximum extent of undercutting is a direct function of ice melting capacity. Consequently, it was decided to normalize the rest results on the basis of ice melting capacities and to compare the resultant data. A comparison of the results obtained for sodium chloride and calcium chloride with those of Trost et al. is presented in Table 4, where the undercutting data for 60 min are normalized on the basis of ice melting capacities. The deicer weights tabulated for the present study were determined by adjusting the aqueous deicer weights to equivalent weights of the solid form of the deicers.

The comparisons presented in Table 4 indicate that the Trost et al. study and the study reported herein yield similar undercutting results when like deicer weights are considered. The present study indicates, however, that the physical characteristics of the substrates have a substantial impact on undercutting.

## CONCLUSIONS

Linear regression models were developed to predict the undercutting behavior of each deicer for given combinations of pavement type, surface condition, and temperature as a function of time. These models have, overall, good predicting power, with $R^2$ values ranging from 52 to 99 percent. Of the 90 estimated regression models, 82 have an $R^2$ value greater than 75 percent. On the basis of these models, the examination of the undercutting data generated with pavement core

TABLE 4 COMPARISON OF UNDERCUTTING RESULTS FOR TWO DEICERS FROM TWO LITERATURE SOURCES

**a) Deicer Material: Sodium Chloride**

| Source of Data | Temperature (deg F) | Deicer, Solid Weight (mg) | Undercut Area (cm2 per gram of Ice Melting Capacity) |
|---|---|---|---|
| Present Results | 25 | 65 | 5.2[a]/4.7[b] |
| Trost et al. | 23 | 50 | 5.9 |
| Present Results | 15 | 45 | 5.8[a] |
| Trost et al. | 14 | 50 | 6.2 |

**b) Deicer Material: Calcium Chloride**

| Source of Data | Temperature (deg F) | Deicer, Solid Weight (mg) | Undercut Area (cm2 per gram of Ice Melting Capacity) |
|---|---|---|---|
| Present Results | 25 | 110.5 | 6.6[a]/4.3[b] |
| Trost et al. | 23 | 100 | 3.6 |
| Present Results | 15 | 95 | 6.5[b] |
| Trost et al. | 14 | 100 | 5.9 |

[a] Average value for smooth laboratory substrates of dense-graded asphalt and portland cement concrete.

[b] Average value for as-received laboratory substrates of dense-graded asphalt and portland cement concrete.

samples and laboratory-produced substrates and three deicers revealed some practical considerations.

A consistent temperature pattern was found during chemical undercutting. For a given deicer and substrate, the undercut area at a fixed time following application of the deicer decreased with decreasing temperature.

At 25°F, sodium chloride is the deicer of choice on in-service dense-graded and open-graded asphalt pavements. However, calcium chloride is the deicer of choice on in-service rubber-modified asphalt and portland cement concrete pavements. At 15°F and 5°F, calcium chloride is the deicer of choice on all in-service pavement types considered in this study. These results would suggest that the rate of chemical application should be varied by pavement type and temperature to achieve a desired undercutting area at a selected time interval after application of a chemical.

The laboratory-produced specimens of portland cement concrete and dense-graded asphalt in the as-received and cleaned condition were undercut more extensively at both 25°F and 15°F than the four pavement core samples in the as-received and cleaned condition. These results would indicate that care should be used when estimating undercutting characteristics on in-service highways from undercutting data obtained from tests performed with laboratory-produced specimens.

In a majority of the cases investigated, the extent of chemical undercutting by NaCl, $CaCl_2$, and ethylene glycol at 25°F on as-received (textured) highway core samples and laboratory-produced substrates was considerably less than that on smooth substrate surfaces of the same materials.

The undercutting results achieved for sodium chloride and calcium chloride generally agreed with similar data reported in the literature when like deicer weights were considered and when the undercutting results were normalized on the basis of ice melting capacities.

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