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ANALYSIS OF THE EFFECTIVENESS OF THE USE OF LIQUID DEICING REAGENTS TO REDUCE THE FREEZING FORCE OF ICE FORMATIONS ABOVE THE ROAD SURFACE

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ABSTRACT

One of the key problems of winter maintenance of highways in Central Asia and Kazakhstan remains the inefficiency of traditional methods of dealing with snow and ice in conditions of variable temperature and high humidity. In particular, various types of snow and ice formations are observed on a number of sections of the road network, which cannot be removed mechanically without damaging the coating. In this regard, there was a need to evaluate the effectiveness of the use of deicing reagents in liquid form. The article presents the results of experimental studies conducted by the authors on sections of the Almaty - Ust-Kamenogorsk highway and on the entrance roads to Almaty and Ust-Kamenogorsk. The physico-mechanical characteristics of snow and ice rolling and the effectiveness of anti-icing solutions based on bischofite ($MgCl_2 \cdot 6H_2O$) with concentrations of 5, 10, 15 and 18% were studied. Field measurements were carried out with an interval of 10 minutes, recording changes in the coefficient of adhesion. Correlations have been established between the concentration of the reagent, the time of action and the adhesion parameters, as well as the distribution rates of solutions depending on the density and thickness of the ice.

INTRODUCTION

The winter period is the most unfavorable in terms of ensuring continuous and safe transport operation. The unevenness of roads due to untimely snow removal and the reduction of the coefficient of adhesion lead to an increase in braking distance and, consequently, to a higher risk of loss of vehicle control. The probability of road traffic accidents on pavements fully or partially covered with snow or ice is 4.5 and 1.5 times higher, respectively, compared to clean dry pavements. Considering that winter slipperiness resulting from icing of road surfaces occupies a significant part of the road operation period, ensuring proper quality of road maintenance is one of the priority tasks of road operating services.

Within the territory of the Republic of Kazakhstan, there are a considerable number of road sections where the use of specialized equipment for removing snow and ice deposits is limited due to technical reasons. Moreover, under conditions of long-term pavement operation, the effectiveness of alternative methods for combating ice has not been sufficiently supported by empirical data and requires additional scientific justification.



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Currently, many methods for combating snow accumulation and slipperiness on highways

are known. The use of chemical deicing reagents is considered the most economically reasonable and effective way to eliminate snow and ice formations. The application of friction materials such as sand and waste provides only short-term improvement in pavement adhesion (within 1–1.5 hours), after which their effectiveness decreases significantly. Similarly, the use of solid chemical reagents yields insufficient results due to their limited active duration.

For the climatic conditions of the Republic of Kazakhstan, characterized by a long winter period and variable weather conditions (alternation of daytime thawing and nighttime freezing), the use of liquid deicing reagents (VN RK 6.1-001-2024, 2024) represents an optimal solution. However, this technology has not yet become widespread. On the one hand, this is due to the lack of comprehensive scientific studies confirming the effectiveness of liquid reagents under conditions of frequent alternation of thawing and freezing, which promotes the formation of dense and hard-to-remove ice. On the other hand, there are no methodological recommendations for applying this technology under specific climatic and road-operating conditions, and the material and technical base remains insufficiently developed, including the lack of specialized equipment for distributing liquid reagents as well as facilities for their preparation and storage.

In this regard, within the framework of this study, it is planned to conduct a field analysis of the application of liquid reagents on various sections of highways in order to assess their effectiveness under snow and ice conditions typical for Kazakhstan.

MATERIALS AND METHODS

In 2022, based on the considerations outlined above, field experimental studies were conducted by researchers from the Kazakh Automobile and Road Institute (KazARI) and D. Serikbayev East Kazakhstan Technical University (EKSTU) to determine the effect of chemical deicing reagents on the destruction of snow–ice formations. The study was carried out on sections of the Almaty–Ust-Kamenogorsk highway, as well as on entrance roads to Almaty (from the Kaskelen direction via the upper highway) and to Ust-Kamenogorsk.

One of the main reasons for conducting field tests was the presence of road sections where traditional mechanical methods for removing snow–ice compaction were ineffective. In particular, in a number of locations the pavement was characterized by the presence of a thin but very strong ice layer, the mechanical removal of which led to damage to the asphalt concrete surface when using available equipment. As a result, such sections remained covered with ice, creating a high accident risk.

Under these conditions, it was hypothesized that complete removal of snow–ice compaction could be achieved through the application of liquid chemical deicing reagents. It was assumed that liquid reagents would not only facilitate the melting of ice and effectively disrupt its structure, but would also remain on the pavement surface and perform a preventive function by inhibiting the re-formation of ice. This is particularly relevant for the variable winter climate typical of Kazakhstan, where daytime solar radiation causes partial melting of ice, followed by nighttime refreezing into an even denser and more slippery layer.

The objective of the experimental study was to evaluate the effectiveness of liquid deicing reagents in combating winter slipperiness on the most hazardous road sections, as well as to determine optimal application conditions, including solution concentration, distribution method, and duration of action.

RESULTS AND DISCUSSION

In East Kazakhstan, experimental studies were conducted on two sections of the Almaty–Ust-Kamenogorsk highway. Site No. 1 (Figure 1a), located at the entrance to Ust-Kamenogorsk at km 1820, was investigated on March 2, 2022, from 12:00 to 18:30 under wind speeds of 10–12 m/s and air temperatures of minus 10 to minus 12 °C. The thickness of the snow–ice compaction

on the pavement ranged from 1.5 to 6 cm, with a density of 0.3–0.6 t/m³.

At Site No. 2 (km 1120, Figure 1b), studies were carried out on March 18, 2022, from 12:00 to 19:30 under clear, calm weather conditions with an air temperature of minus 6 to minus 8 °C and relative humidity of 71.8%. The thickness of the snow–ice layer on the pavement ranged from 2 to 11 cm, with a density of 0.1–0.22 t/m³. The average daily traffic volume at both sites was 2 887 vehicles per day.

The transport and operational characteristics of the studied sites differed significantly from each other. At the first site, partial melting of the snow–ice formation was observed on the pavement surface, which considerably deteriorated road conditions and hindered vehicle movement. After the application of the deicing solution, the snow–ice compaction completely melted within 1.0–1.2 hours, as shown in Figure 1b.

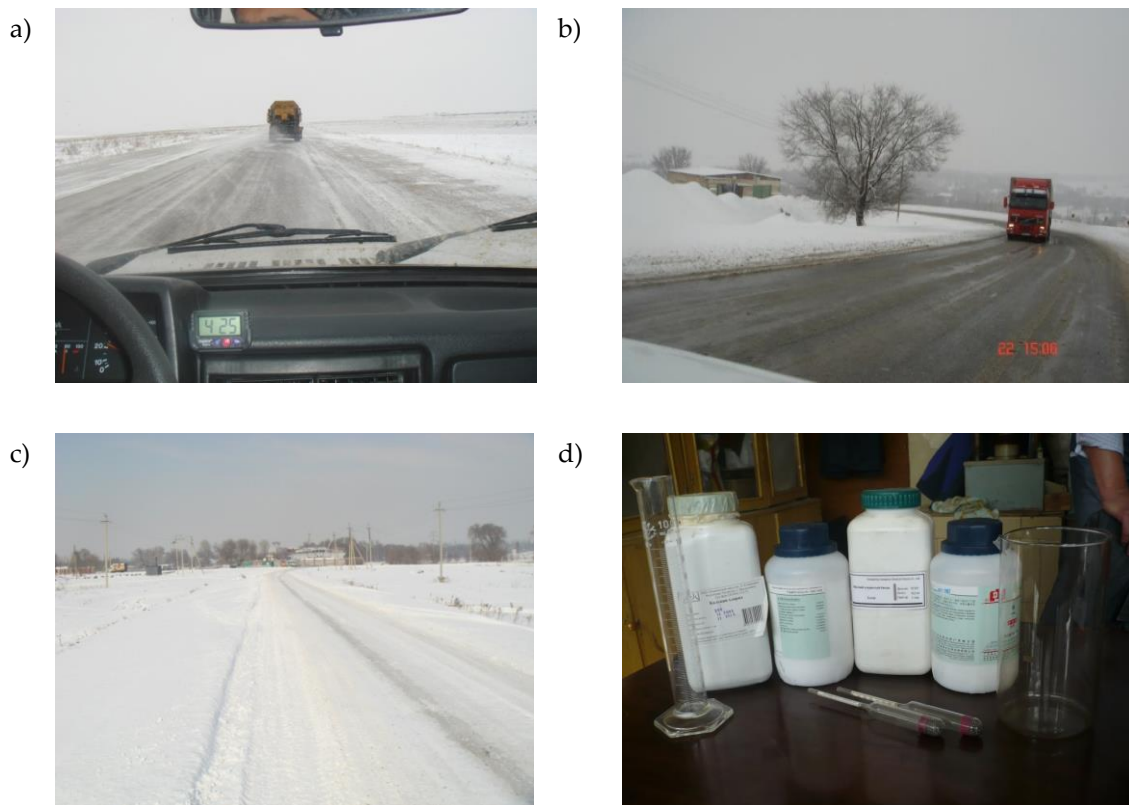


Figure 1. General view of the studied sites: (a) Site No. 1 on the Almaty–Ust-Kamenogorsk highway; (b) Site No. 2 at the same location; (c) entrance road to Almaty (upper highway “Almaty–Kaskelen”); (d) tested deicing reagents and hydrometers used for density determination.

Note – prepared by the authors.

In addition, on some sections of this road, the formation of melted snow crusts and wheel tracks on the surface of the snow–ice layer due to solar radiation was observed (Figure 1), which is typical for roads with high traffic intensity.

Similar studies were conducted on the entrance roads to Almaty. As an experimental site, the entrance to Almaty between Almaty and Kaskelen (upper highway) was selected. Field tests were carried out on February 11, 2022, from 12:00 to 18:00. At Site No. 3, the studies were conducted at air temperatures of minus 5 to minus 8 °C and relative humidity of 86%. The daytime traffic volume at this site did not exceed 560 vehicles per day. The thickness of the dry

snow layer ranged from 2.6 to 8 cm, while its density did not exceed 0.38 t/m³.

Methodology for preparing liquid chemical solutions for field tests. To conduct experimental tests and determine the concentration and distribution rate of liquid reagents, a universal spreader manufactured by Renault was used (Figure 2a). The slipperiness of the pavement was measured using a portable IKSp device (Figure 2b).

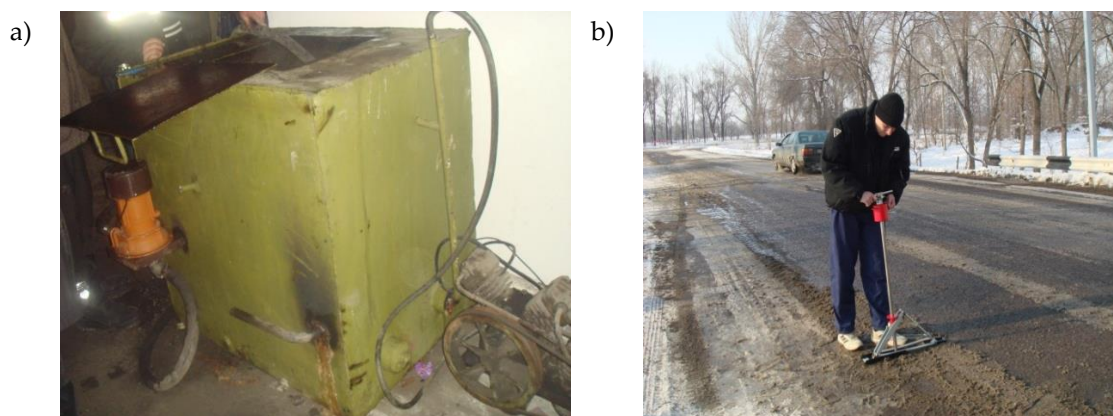


Figure 2. Preparation of liquid deicing reagents for field tests: (a) installation for preparing deicing solution; (b) process of measuring the coefficient of adhesion using the IKSp device.

Note – prepared by the authors

The mixing of the solution used as a deicing material was carried out in a stationary mixing unit (Figure 2a). Its design consisted of an electric pump, a tank for preparing the liquid solution ($V_e = 0.75 \text{ m}^3$), a hose for supplying compressed air, and a compressor. During solution preparation, the water in the tank was preheated to the boiling point ($+100 \text{ }^\circ\text{C}$). This increased the dissolution efficiency of the chemical reagents and significantly reduced their dissolution time (PR RK 218-64-2007, 2008).

Under laboratory conditions, three types of chloride salts were tested: sodium chloride (NaCl), calcium chloride (CaCl_2), and bischofite ($\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$), and their concentrations were determined (Table 2). During field tests, only bischofite ($\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$) and the deicing solution prepared from this reagent were used. The solution was prepared in four concentrations: 5%, 10%, 15%, and 18%. Bischofite was selected as the primary deicing material (Figure 1d).

Table 1. Selection of chemical solution concentrations

Concentration of sodium chloride solution			Concentration of calcium chloride solution			Concentration of bischofite solution		
Solution density, t/m ³	NaCl content in 100 g of solution, g	Freezing temperature, °C	Solution density, t/m ³	NaCl content in 100 g of solution, g	Freezing temperature, °C	Solution density, t/m ³	NaCl content in 100 g of solution, g	Freezing temperature, °C
1	2	3	4	5	6	7	8	9
1.04	5.6	-3.5	1.04	4.8	-2.4	1.04	5.2	-3.56
1.05	7.0	-4.4	1.05	5.9	-3.0	1.05	6.4	-5.25
1.06	8.3	-5.4	1.06	7.1	-3.7	1.06	7.8	-6.40
1.07	9.6	-6.4	1.07	8.3	-4.4	1.07	9.0	-7.38

End of table 1

1	2	3	4	5	6	7	8	9
1.08	11.0	-7.5	1.08	9.4	-5.2	1.08	10.1	-8.28
1.09	12.2	-8.6	1.09	10.5	-6.1	1.09	11.1	-9.10
1.10	13.6	-9.8	1.10	11.5	-7.1	1.10	11.5	-10.00
1.11	14.9	-11.0	1.11	12.6	-8.1	1.11	12.1	-12.90
1.12	16.2	-12.2	1.12	13.7	-9.1	1.12	12.8	-14.20
1.13	17.5	-13.6	1.13	14.7	-10.2	1.13	13.5	-16.10
1.14	18.0	-15.1	1.14	15.8	-11.4	1.14	14.5	-18.70
1.15	20.0	-16.0	1.15	16.8	-12.7	1.15	15.6	-20.30
1.16	21.2	-18.2	1.16	17.8	-14.2	1.16	16.7	-22.10
1.17	22.4	-20.0	1.17	18.9	-15.7	1.17	17.8	-24.50
1.175	23.1	-21.2	1.18	19.9	-17.4	1.18	18.5	-26.80
			1.19	20.9	-19.2	1.19	19.6	-29.20
			1.20	21.9	-21.2	1.20	20.5	-31.20
			1.21	22.8	-23.3	1.21	21.4	-33.40
			1.22	23.8	-25.7	1.22	22.1	-35.50
			1.23	24.7	-28.3			
			1.24	25.7	-31.2			
			1.25	26.6	-34.6			
			1.26	27.5	-38.6			
			1.27	28.4	-43.6			
			1.28	29.4	-50.1			

Note – the dissolution time of chemical reagents depends on the temperature of water heating

Note – compiled by the authors

Table 2. Results of slipperiness measurements at 5-minute intervals

Time, min	Solution concentration, %			
	5	10	15	18
1	2	3	4	5
0	0.09	0.09	0.09	0.09
5	0.10	0.11	0.13	0.14
10	0.12	0.14	0.17	0.19
15	0.14	0.15	0.19	0.21
20	0.15	0.17	0.21	0.23
25	0.17	0.19	0.24	0.25
30	0.19	0.22	0.27	0.28
35	0.21	0.24	0.30	0.34
40	0.22	0.27	0.34	0.37
45	0.24	0.29	0.38	0.40
50	0.27	0.33	0.41	0.44
55	0.29	0.35	0.44	0.48
60	0.31	0.38	0.46	0.52
65	0.34	0.43	0.49	0.56
70	0.36	0.47	0.54	0.61
75	0.39	0.51	0.58	0.63
80	0.41	0.54	0.63	0.68

Note – compiled by the authors

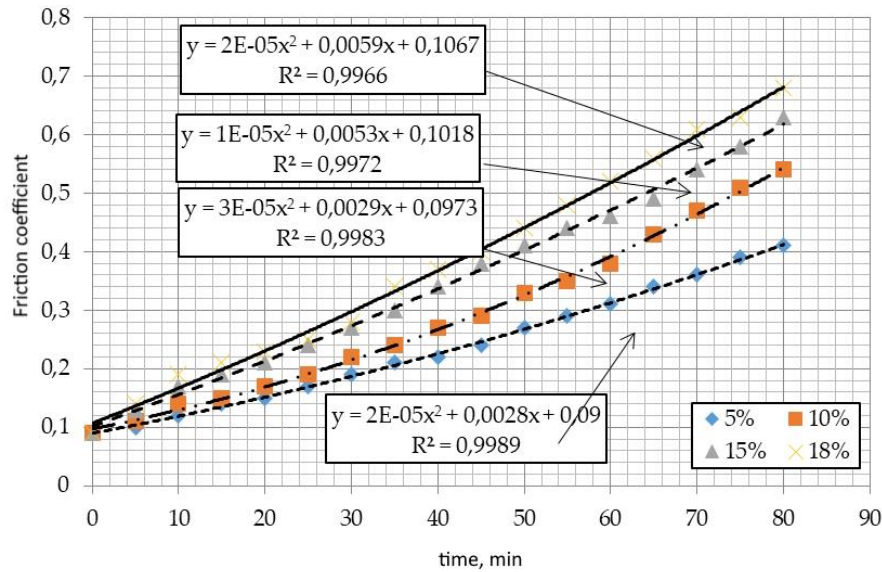


Figure 3. Correlation between the duration of solution action and the coefficient of adhesion of road pavements depending on reagent concentration

Note – prepared by the authors

Figure 3 presents the results of field tests aimed at determining the effective duration of action of a deicing solution based on bischofite. As can be seen from the curves, the effectiveness of the solution increases over time with higher concentrations. At low concentrations, the snow-ice compaction cannot be completely melted; consequently, the coefficient of adhesion does not exceed 0.41. The main reason is that at air temperatures below minus 8 °C, solutions of low concentration (5–7%) are not sufficiently effective.

Regulation of deicing reagent distribution rates and assessment of pavement slipperiness under field conditions. At the experimental sites, chemical reagents were applied using an emergency method, i.e., directly onto the snow-ice layer. The distribution rates were adopted in accordance with calculated data: for solid reagents, the maximum rate was 350 g/m² and the minimum was 90 g/m²; for liquid reagents, the maximum rate was 450 mL/m² and the minimum was 60 mL/m².

As noted above, the distribution of liquid chemical reagents was carried out using a universal spreader manufactured by Renault, provided by the East Kazakhstan branch of JSC “KazAvtoZhol”.

Technology for distributing liquid deicing reagents. In this universal spreader, the distribution of reagents was regulated by: a) an external shutter (Figure 4a); b) an onboard computer controlling the material spreading width (Figure 4b); c) adjusting the operating speed of the vehicle.

Processing of field test results.

Considering the variability of numerous factors affecting the value of the coefficient of adhesion (thickness, density, hardness of snow-ice formations, etc.), it is reasonable to apply a sampling method for its evaluation, even under approximately similar pavement conditions. The sampling method consists of determining generalized characteristics of a population not by measuring all its elements, but by examining only a representative part selected randomly. The applicability of this method is based on the law of large numbers. According to this law, as demonstrated by M.A. Chebyshev’s theorem (Khovanskii, 2013), with a sufficiently large number of observations, the sample mean of a measured parameter approaches its mathematical expectation.



Figure 4. Regulation of chemical reagent distribution rates using (a) the external shutter of the spreader and (b) the onboard computer.

Note – prepared by the authors.

The sample size n (number of measurements) depends on the required confidence level. In engineering practice, a confidence level of $P = 0.95$ is commonly adopted (less frequently 0.997). For a very large population, the required sample size is determined by the expression given in VN RK 6.1-001-2024 (2024).

$$\sigma = \frac{t^2 \cdot \sigma^2}{\Delta^2}, \quad (1)$$

where t is a parameter characterizing the confidence level, i.e., the probability that the deviation does not exceed Δ^2 , which equals $t = 2$ for a confidence level of $P = 0.95$ and $t = 3$ for $P = 0.997$.

Pavement slipperiness is evaluated as follows (VN RK 6.1-001-2024, 2024):

$$K_{ck} = \frac{\varphi_{fact}}{\varphi_{allow}}, \quad (2)$$

where: φ_{fact} is the actual value of the coefficient of adhesion; φ_{allow} is the permissible value of the coefficient of adhesion, equal to $\varphi_{allow} = 0.28$ under winter slipperiness conditions and $\varphi_{allow} = 0.40$ during the dry season.

For a comprehensive evaluation of the performance of bischofite solution ($MgCl_2 \cdot 6H_2O$) (Table 3, column 4), its characteristics were compared with those of traditionally used deicing reagents – sodium chloride NaCl (Table 3, column 2) and calcium chloride $CaCl_2$ (Table 3, column 3). The comparison was carried out under identical laboratory and field conditions, with equal application rates and temperature regimes. The analysis included key indicators such as: solution freezing temperature, duration of action, pavement adhesion coefficient after treatment, braking distance, and residual effect in preventing secondary ice formation.

Table 3. Results of comparative analysis of deicing reagents

Indicator	NaCl (15%)	CaCl ₂ (15%)	MgCl ₂ ·6H ₂ O (15%)
Freezing temperature, °C	-13.6	-10.2	-16.1
Increase in adhesion (after 60 min)	0.38	0.36	0.46
Duration of action, min	up to 90	up to 120	up to 160
Reduction of braking distance, %	12 %	16 %	23 %
Braking distance on ice (at 50 km/h)	28 m	26 m	21,5 m
Residual effect (prevention of secondary icing)	weak	moderate	distinct

Note – compiled by the authors

The bischofite-based deicing reagent ($\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$) has a number of operational advantages that enable its effective use under the climatic conditions of Kazakhstan. Due to its low crystallization temperature (down to -16.1°C at a 15% concentration), the solution remains active even under sustained frost conditions. One of its key advantages is a pronounced residual effect: after application, the reagent remains on the pavement surface for a long time, preventing the re-freezing of ice.

At low concentrations of deicing solution (5–7% and below), their action is insufficient to fully disrupt the structure of the snow–ice layer; as a result, the pavement adhesion coefficient does not exceed 0.41. The main reason is that at air temperatures below -8°C , low-concentration solutions (5–7%) are not effective enough.

CONCLUSIONS

The destruction of the snow–ice structure is strongly influenced by both the concentration of the solution and the duration of the interaction between the snow–ice formation and the chemical reagent. For example, a solution prepared at a 5% concentration increases adhesion from 0.10 to 0.23 within 80 minutes, whereas a 15% solution increases it from 0.10 to 0.41 over the same period. Moreover, this performance indicator depends not only on the solution concentration but also on the density of the snow–ice formation.

After the structure of the snow–ice layer is disrupted, it is necessary to clear the road of melted snow. Typically, the melted snow is in a liquefied state, as shown in Figure 1b.

Field tests demonstrated that, in terms of braking distance reduction, bischofite outperforms traditional NaCl - and CaCl_2 -based reagents by 20–25%. At the same time, it enables an increase in the adhesion coefficient to 0.46 and above, which corresponds to safe operating conditions for roads in winter.

The use of bischofite solutions is recommended under the following conditions:

- Road conditions: compacted snow–ice layer, glazed ice, variable temperatures (thaw–freeze cycles), and high air humidity;
- Road sections: bridges, steep ascents and descents, intersections, accident-prone zones, and high-traffic urban areas;
- Application mode: emergency and preventive treatment of the pavement prior to expected precipitation or a sharp drop in temperature.

CONFLICT OF INTEREST: The authors declare that there is no conflict of interest.

DECLARATION ON THE USE OF ARTIFICIAL INTELLIGENCE TECHNOLOGIES:

The authors did not use artificial intelligence (AI) tools at any stage of preparing this scientific article.

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