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COMPARATIVE ANALYSIS OF THE EFFECTIVENESS OF VARIOUS METHODS OF DE-ICING ROADS

ЖОЛДАРДЫ МҰЗДАН ТАЗАРТУДЫҢ ӘРТҮРЛІ ӘДІСТЕРІНІҢ ТИІМДІЛІГІН САЛЫСТЫРМАЛЫ ТАЛДАУ

СРАВНИТЕЛЬНЫЙ АНАЛИЗ ЭФФЕКТИВНОСТИ РАЗЛИЧНЫХ МЕТОДОВ ПРОТИВООБЛЕДЕНИТЕЛЬНОЙ ОБРАБОТКИ ДОРОГ

Abstract. *The winter period poses a serious challenge to the road infrastructure, especially in the harsh climate of Kazakhstan, where frequent snowfalls and extreme frosts create a risk of ice cover on the roads. De-icing road treatment plays a key role in ensuring road safety by reducing the risk of slipping and improving wheel grip on the road surface. The article discusses the main methods of de-icing roads, including chemical, friction, chemical-friction, mechanical and thermal methods. Their features, effectiveness and impact on road safety are described. The results of research on the use of chemical reagents such as NaCl, $CaCl_2$, $mgcl_2$ and biodegradable compounds are highlighted, taking into account their effectiveness at different temperatures and environmental consequences. Innovative technologies such as pavement heating systems are also being considered, which provide a long-term solution to the problem of ice, but are characterized by high costs. The analysis of de-icing treatment methods reveals their advantages and limitations, and also suggests optimal approaches for use in a changing climate. The results of the work can be useful for improving the management of road infrastructure and improving road safety in winter.*

Keywords: *De-icing treatment, road safety, chemical reagents, mechanical methods, thermal heating of roads environmental safety, friction materials, winter infrastructure.*

Аңдатпа. *Қыс мезгілі жол инфрақұрылымы үшін, әсіресе Қазақстанның қатал климаты жағдайында елеулі сын-тегеурін болып табылады, мұнда жиі қар жауады және қатты аяз жолдарда мұз жамылғысының пайда болу қаупін тудырады. Жолдарды мұздан тазарту жол қауіпсіздігін қамтамасыз етуде шешуші рөл атқарады, сырғанау қаупін азайтады және доңғалақтардың тротуармен байланысын жақсартады. Мақалада химиялық, үйкеліс, химиялық-үйкеліс, механикалық және жылу әдістерін қоса алғанда, жолдарды мұздан тазартудың негізгі әдістері қарастырылады. Олардың ерекшеліктері, тиімділігі және жол қауіпсіздігіне әсері сипатталған. NaCl, $CaCl_2$, $MgCl_2$ және биологиялық ыдырайтын қосылыстар сияқты химиялық реагенттерді қолдану бойынша зерттеулердің нәтижелері олардың әртүрлі температурадағы тиімділігі мен экологиялық әсерлерін ескере отырып көрсетіледі. Сондай-ақ, көктайғақтың ұзақ мерзімді шешімін қамтамасыз ететін, бірақ жоғары шығындармен сипатталатын жол жамылғысын жылыту жүйелері сияқты инновациялық технологиялар қарастырылған. Мұздан тазарту әдістерін талдау олардың артықшылықтары мен шектеулерін анықтауға мүмкіндік береді және климаттың өзгеруі жағдайында қолданудың оңтайлы тәсілдерін ұсынады. Жұмыс нәтижелері жол инфрақұрылымын басқаруды жақсарту және қыс мезгілінде жол қауіпсіздігін жақсарту үшін пайдалы болуы мүмкін.*

Түйін сөздер: *Мұздан тазарту, жол қауіпсіздігі, химиялық реагенттер, механикалық әдістер, жолдарды жылумен жылыту, экологиялық қауіпсіздік, үйкеліс материалдары, қысқы инфрақұрылым.*

Аннотация. *Зимний период представляет собой серьезный вызов для дорожной инфраструктуры, особенно в условиях сурового климата Казахстана, где частые снегопады и экстремальные морозы создают риск образования ледяного покрова на дорогах. Противообледенительная обработка дорог играет ключевую роль в обеспечении безопасности дорожного движения, снижая риск скольжения и улучшая сцепление колес с дорожным покрытием. В статье рассматриваются основные методы противообледенительной обработки дорог, включая химический, фрикционный, химико-фрикционный, механический и тепловой методы. Описываются их особенности, эффективность и влияние на безопасность дорожного движения. Освещаются результаты исследований по применению химических реагентов, таких как NaCl, $CaCl_2$, $MgCl_2$ и биоразлагаемые соединения, с учетом их эффективности при разных температурах и экологических последствий. Также рассматриваются инновационные технологии, такие как системы обогрева дорожного покрытия, которые обеспечивают долгосрочное решение проблемы гололеда, но характеризуются высокими затратами. Анализ методов противообледенительной обработки позволяет выявить их преимущества и ограничения, а также предлагает оптимальные подходы для использования в условиях изменяющегося климата. Результаты работы могут быть полезны для улучшения управления дорожной инфраструктурой и повышения безопасности дорожного движения в зимний период.*

Ключевые слова: *Противообледенительная обработка, безопасность дорожного движения, химические реагенты, механические методы, тепловой обогрев дорог, экологическая безопасность, фрикционные материалы, зимняя инфраструктура.*

Introduction. The winter period presents a complex challenge to the functioning of the road infrastructure, especially in conditions of sharp temperature fluctuations and extreme atmospheric phenomena such as snowfall and frost. One of the critically important factors determining road safety is the formation of ice on road surfaces, which leads to an increase in the coefficient of adhesion and a decrease in the stability of vehicles. Deicing of roads is an integral part of the strategic management of winter conditions and includes a variety of preventive and primary methods -from the use of deicing materials to mechanical and technological solutions. These measures are aimed at minimizing the risks associated with the formation of ice on the road surface, which is critically essential for road safety. The climate of Kazakhstan is characterized by significant temperature fluctuations, especially in winter. In the country's northern regions, winters can be severe, with temperatures reaching -40 °C, as well as frequent snowfalls and severe frosts. This creates unique conditions for the formation of ice and ice on roads, which makes deicing treatment vital to ensure the safety of traffic flows. This article aims to provide a comparative analysis of existing methods of deicing treatment, as well as their scientific validity and practical effectiveness. The impact of these measures on road safety and the condition of the road infrastructure will also be considered. Understanding modern approaches to anti-icing will not only improve road safety but also optimize the operation of the road network in a changing climate, which, in turn, will contribute to the sustainable development of Kazakhstan's transport system.

Methods and Materials. In Kazakhstan, various methods of de-icing roads are used. The most common are the use of anti-icing materials (chemical, chemical-friction, friction), mechanical snow removal, and thermal heating of the pavement (Figure 1).

The friction method of de-icing roads involves the use of abrasive materials such as sand and crushed stone to increase the adhesion of wheels to the road surface in icing conditions. This method is based on mechanical action, which helps to improve grip and reduce the risk of slipping. Sand and gravel are applied to the icy surface of the road, creating an abrasive layer that increases friction between the wheels of cars and the road. This is especially important in low-temperature conditions, when chemical reagents may lose their effectiveness.

The chemical-fractional method of de-icing roads is a combined approach that combines the use of chemical reagents with abrasive materials such as sand and crushed stone. An essential advantage of such mixtures is environmental safety, which, along with an affordable price, makes them quite popular. They have proven themselves only on the positive side; with their help, they

can achieve high-quality results in the shortest possible time. Thanks to a well-thought-out chemical formula, which includes several potent substances, these reagents quickly turn ice and snow into a safe melted mixture, easily removable by mechanical means. The high efficiency of combined reagents is achieved since they most often use substances such as marble or granite crushed stone, sodium formates or potassium acetates, sodium chloride (calcium or magnesium), nitrates, and other compounds in various combinations (Pshembaev, Kovalev, Yaglov, Girinsky, 2020).

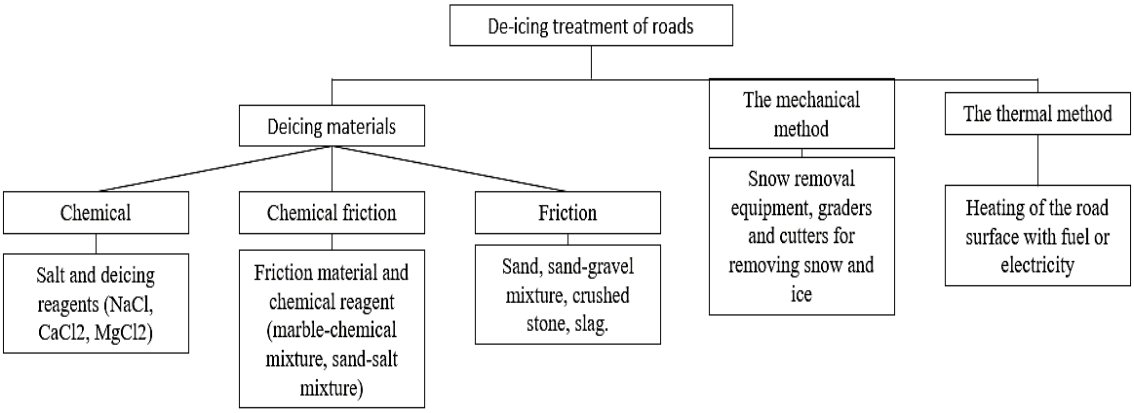

Figure 1. The most common methods of de-icing roads in Kazakhstan
Note – compiled by the authors

Mechanical methods of de-icing roads include a variety of approaches based on physical effects on the ice crust or snow cover. These include using snow plows that remove snow and ice from the road surface and using graders and other specialized devices for grinding and leveling the surface. These methods make it possible to effectively clean roads and improve traffic safety in winter, providing better visibility and wheel grip.

The pavement heating method is a technology aimed at preventing the formation of ice and snow on the road surface using heating systems. Such systems can be electric or water-powered and are laid under the road surface. When turned on, they heat the surface, keeping its temperature above the freezing point. This method can significantly improve road safety in winter, reducing the need for chemicals and mechanical cleaning and providing more comfortable conditions for drivers and pedestrians. However, its application may be limited by high installation and operation costs. According to the conclusion of Chinese researchers, heating systems such as electric heating, pipe heating, and geothermal heating effectively combat ice and snow. However, the cost of transferring energy from the source to the road surface remains high. In addition, repeated loads can damage the cables, leading to failures in the electric heater operation (Xu, Zhou, Feng, Cui, Xie, 2021). Studies have shown that when designing a heating system, methods of removing melted snow and ice from the place of their heating should be taken into account. Thermal insulation layers should be installed at the construction stage of the pavement, as this affects the performance and cost of the system (Kenzhebayeva, Bakbolat, Sultanov, Daulbayev &Mansurov, 2021). The chemical method of de-icing treatment involves using various chemical reagents to prevent the formation of ice and snow on the road surface. The most common reagent is table salt (NaCl), which lowers the freezing point of water. Calcium chloride ($CaCl_2$) is also often used, which is more effective at low temperatures and dissolves quickly, which allows it to act faster. In recent years, the use of biodegradable reagents such as acetic acid, which are less harmful to the environment, has been increasing.

Road salt consists mainly of the active component, sodium chloride, but also contains insoluble particles and impurities, including metallic trace elements, the nature and concentration of which depend on the source of raw materials (Novotny, Murphy, Stefan, 2008). Sodium chloride (NaCl) was first used in the 1930s to accelerate snowmelt. This made it possible to improve the adhesion of vehicles to the road (Denby et al., 2016) and reduce the number of road accidents. Deicing salt has physicochemical properties that allow changing the phase equilibrium of water, which leads to a decrease in the freezing point. At normal atmospheric pressure, clean water freezes at 0°C, turning into ice, which forms on the road surface. However, adding salt to water and dissolving it lowers the freezing point (Durickovic, 2020).

The market's average price of sodium chloride varies from 30 to 70 tenge per kilogram, depending on the delivery method and order volume.

Deicing salt (NaCl) is used in various forms, depending on the condition of the road surface (Barbier, 2019):

• Dry salt: It is used in rainy weather because it is easy to apply and is not washed out by precipitation.

• Brine (saline solution): effective in dry conditions, as it adheres well to the surface but can drain when the road is inclined.

• Moistened salt (a mixture of rock salt and 30% brine): versatile and suitable for different situations. The dry salt provides a mechanical effect, and the brine creates the necessary moisture to start the melting process.

Salt can be used prophylactically (before the appearance of ice) or curatively (after the formation of a slippery surface). Due to its ability to reduce the freezing point of water, road salt prevents the formation of ice or promotes its melting.For a long time, NaCl has been used as the main anti-icing material due to its cost-effectiveness, ease of storage, speed of melting, and ease of use. However, given the recent concerns about its environmental impact, various alternative solutions have been proposed and tested.

According to the results of the study, other inorganic salts ($CaCl_2$, $MgCl_2$, KCl) are more expensive than NaCl and are usually more aggressive to vehicles and road structures such as bridges and overpasses (Benbow, Mark & Merritt, Richard, 2005).

In 2021, researchers in Poland analyzed the toxicity of sodium chloride (NaCl) to aquatic organisms such as Daphnia magna (daphnia) and Poecilia reticulata (guppy) at various salinity levels. Studies have shown that D. magna is highly sensitive to increased salinity, which suggests that high salt concentrations can significantly affect the survival of these organisms. This study confirms the need to develop more environmentally friendly alternatives, such as biodegradable reagents with less toxicity to aquatic organisms (Frąk, M., Bednarczyk, P., 2021).

Biodegradable reagents for de-icing roads are considered an environmentally friendly alternative to traditional salts. Among such reagents, calcium and magnesium acetates, mixtures based on beet juice, and vegetable additives are distinguished. They minimize the harm to aquatic ecosystems, soil, and vegetation that suffer from the salt runoff of traditional reagents. For example, a mixture of beet juice and salt improves efficiency at low temperatures and reduces the amount of salt needed to treat roads. However, such solutions are expensive, which may limit their widespread use.

Calcium chloride ($CACL_2$) is an effective deicing reagent that is actively used for road treatment in winter. Its main advantage lies in its ability to operate at very low temperatures (up to -51 °C), which makes it more effective compared to traditional sodium chloride, whose efficiency decreases below -12 °C (Nizhny Novgorod State Technical University, 2019). During the dissolution process, calcium chloride releases heat, which accelerates the melting of ice. In addition, it actively attracts moisture from the air, creating a sticky layer that prevents the reagent from being carried away by the wind, especially in conditions of heavy traffic. One of the

environmental advantages is that using $CaCl_2$ reduces the amount of salt needed for road treatment, which reduces the negative impact on the environment. Using a combination of chlorides, including calcium, magnesium, and sodium, with inhibitors minimizes harm to human health, shoes, and tires. Also, it helps to reduce dust on the roads. However, the cost of $CACL_2$ is significantly higher than that of sodium chloride, which limits its use in some cases.This approach is actively discussed and applied in various countries, including Russia, where calcium chloride is used as an independent agent or as part of two-phase reagents. This reduces the cost of maintaining roads and minimizes their environmental footprint.

The average cost of calcium chloride for de-icing roads in Kazakhstan varies depending on the release form and concentrations (usually 94-98%): 500-650 tenge per kilogram.

Magnesium chloride ($MgCl_2$) works effectively at temperatures up to -15°C. Its effectiveness at lower temperatures is significantly lower than $CaCl_2$ but still more effective than NaCl in moderate frosts. This is also supported by a number of experiments and observations, both in Western studies and in studies conducted in regions with a cold climate (Fay, Volkening, Gallaway, & Shi, 2012). The average cost of magnesium chloride depends on the purchase volume and varies between 350-400 tenge per kilogram.

In addition, magnesium chloride helps prevent the formation of ice and dissolves snow faster, creating safer conditions on the roads. It is often used as a solution that adheres easily to the surface and prevents re-freezing. Studies have shown that magnesium chloride, although effective as an anti-icing agent, can cause less damage to concrete surfaces than sodium and calcium chlorides, which are known to contribute to the formation of deposits on concrete during freeze-thaw cycles (Xiang Li et al., 2019). Efforts are also being made to identify and test alternative chemicals for ice control that are more environmentally friendly and less aggressive to infrastructure (Peters & Riemer, 2019). The use of salts as a means of combating ice is a common practice, but it has significant drawbacks.

One of the main ones is the phenomenon of salt erosion, which damages the road surface and structural elements, which leads to a reduction in their service life (Wu et al., 2021).

In 2015, a study was conducted on the effectiveness of deicing chemicals at different temperatures and different melting times (Ružinskas, Andrius & Bulevičius et al., 2016). During the tests, five different materials were studied: NaCl, $CaCl_2$, $MgCl_2$, a mixture of modified sodium chlorides (75%) (SCMC) and calcium (25%), and a mixture of sodium acetate and sodium formate (SASF). In conclusion, according to the intensity of ice melting, $CaCl_2$ and $MgCl_2$ are the most effective.

Table 1. Comparative analysis of chemical reagents

Chemical reagents	Sodium chloride (NaCl)	Calcium Chloride ($CaCl_2$)	Magnesium chloride $MgCl_2$
Temperature range	Up to -10°C	Up to -30°C and below	Up to -15°C
Forms of application	dry salt, in solution as a brine, moistured/humidified salt	dry salt, in solution as a brine, moistured/humidified salt, mixture with other reagents	Solid magnesium chloride, magnesium chloride solution, hybrid mixtures
Reagent distribution time	Before and after ice formation	Before the formation of ice	Before the formation of ice
Melting point	Up to -15°C	-20°C	-20°C
The rate of ice dissolution	Low	High	High
Environmental impact	Most disastrous	The average indicator	The least harmful
Price of 1 kilogram (₸)	30-70	500-650	350-400
Note – compiled by the authors			

Regarding the different melting temperatures, NaCl has shown that ice melts most effectively at temperatures up to -15°C, and $MgCl_2$ is the most effective at higher temperatures. SASF is the most economical material for melting ice.

Russian researchers conducted studies of chemical reagents (sodium chloride NaCl, calcium chloride $CaCl_2$, magnesium chloride $MgCl_2$) from an environmental point of view (Nikishina, Bazarov, 2022). During the study, plants (namely vico-oat mixture) were watered with reagents of various concentrations. After 5 weeks of the study, the results showed that sodium chloride has the most detrimental effect on plant growth, unlike calcium chloride and magnesium chloride. The least negative impact on the soil is manifested in 10% of $MgCl_2$.

Results. During the study, various methods and materials for deicing roads were considered, including mechanical, chemical, and combined approaches. The primary attention was paid to the comparison of chemical reagents, sodium chloride (NaCl), calcium chloride ($CaCl_2$), and magnesium chloride ($MgCl_2$), as well as their environmental effects. Effectiveness of deicing reagents: NaCl has demonstrated good efficiency at temperatures up to -12°C, reducing the freezing point of water and preventing ice formation. However, at lower temperatures, its effectiveness is significantly reduced. $CaCl_2$ has shown high efficiency at very low temperatures (up to -51°C), actively releasing heat during dissolution, which accelerates the melting of ice. This makes it more effective than NaCl in extreme frost conditions. In addition, $CACL_2$ has the ability to attract moisture, which increases its resistance to wind drift. $MgCl_2$ proved to be effective at temperatures up to -15°C, which makes it more suitable for moderate frosts compared to NaCl. However, its effectiveness is also limited at lower temperatures. Studies have shown that $MgCl_2$ can cause less damage to concrete coatings compared to NaCl and $CaCl_2$. Environmental consequences of the use of reagents: The use of NaCl has proven to be the most aggressive for the ecosystem, especially with regard to plant growth. Studies have shown that NaCl has the most significant negative effect on plants, reducing their growth. $CaCl_2$ and $MgCl_2$ demonstrated a less pronounced effect on vegetation, especially at low concentrations. In particular, the 10% $MgCl_2$ solution had minimal effect on plants, which makes it a more environmentally friendly choice. The use of a combination of chlorides such as $CaCl_2$ and $MgCl_2$ with inhibitors can minimize the impact on human health, as well as reduce dust on roads. Application of alternative methods: Combined reagents, such as mixtures of chlorides and biodegradable substances, have shown promising results in reducing environmental impacts and increasing the effectiveness of deicing treatment. Mechanical methods (sand, crushed stone, snow plows) remain effective in improving traction but do not actively melt ice. These methods are instrumental in combination with chemical reagents. Economic efficiency: In terms of economic efficiency, NaCl is the cheapest and most affordable reagent, but its use requires large volumes and may be less effective in extreme climatic conditions. $CACL_2$ and $MgCl_2$, despite their high efficiency at low temperatures, are more expensive, which limits their mass use, especially in regions with mild climates.

Conclusions. The results of the study show that the choice of de-icing materials depends on many factors, including climatic conditions, the cost of reagents, and the environmental consequences of their use.NaCl remains the most economical and affordable option for most regions, but its effectiveness decreases at low temperatures and significantly impacts the ecosystem. $CaCl_2$ and $MgCl_2$ are more effective in extreme frosts and have a smaller environmental footprint than NaCl, but their high cost limits widespread use. To mitigate the impact on the environment, it is recommended that combinations of deicing agents be utilized to advance the development of new environmentally friendly alternatives. Mechanical methods and heating systems can be an effective complement to chemical reagents, especially in conditions where reducing the impact on infrastructure and the environment is required. Thus, in order to increase the effectiveness of the de-icing treatment of roads, it is necessary to consider the balance between economic feasibility, environmental safety, and operational characteristics of various reagents and methods.

Conflict of interest. The authors declare that there is no conflict of interest.

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"Notification of the use of generative AI and technologies using it in the process of writing the manuscript". The authors did not use tools of artificial intelligence services in the preparation of this paper.

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