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IMPACT OF DEICING SALT ON THE PERFORMANCE OF ASPHALT MIXTURES IN NORTHWEST CHINA: AN INVESTIGATION INTO MECHANICAL PROPERTIES AND INFLUENTIAL FACTORS

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Abstract. Currently, the primary form of high-grade highways is constituted by asphalt concrete pavement. Winter conditions often result in ice and snow accumulation on these pavements, precipitating severe traffic incidents. Statistically, around 15%-30% of such incidents are directly linked to icy and snowy conditions. Hence, when roads are laden with ice and snow, the most cost-effective and efficient countermeasure remains the dispersal of deicing salt onto the road surface. Particularly in China's northwestern region, which experiences low precipitation and consistent droughts, the deicing salts applied during winter aren't diluted or transported away by water flow. Consequently, the soil surrounding the roads retains a higher concentration of deicing salts than other regions, leading to a pronounced impact on the pavement's service life.

This investigation aims to experimentally emulate the impact of this high-salt environment on the mechanical properties of asphalt mixtures, followed by an analysis of the crucial factors that influence the asphalt mixtures' durability.

The current study employs measures such as high-temperature rut testing, Marshall water immersion testing, and freeze-thaw splitting testing to investigate the damage patterns of mechanical properties in asphalt mixtures under varying grading, diverse deicing salt solutions, and differing frequencies of dry-wet cycles. In addition, the study employs grey correlation entropy analysis to ascertain the interdependence among factors influencing the performance of asphalt mixtures.

The findings reveal that after undergoing 0, 5, 10, 15, 20, 25, and 30 dry-wet cycles in solutions of 20% industrial salt (NaCl), 15% urea (CH_4N_2O), and 20% anhydrous ethanol (CH_2CH_3OH), both the high-temperature stability and water stability of asphalt mixtures with AC-13 and AC-16 gradings displayed varying levels of decline. Overall, an enhancement in the fine aggregate percentage in asphalt mixtures can augment the asphalt concrete's resistance to deicing salt erosion. As per the grey correlation entropy analysis, gradation variances exerted the most significant impact on diverse mechanical properties, followed by the type of deicing salt solution, with the least significant impact attributed to the frequency of dry-wet cycles. Thus, judicious selection of road materials and structural design can effectively counter the erosive action of deicing salts, thereby enhancing the service life of the road surface.

Key words: road engineering, asphalt mixture, dry-wet cycle, pavement performance, deicing salt.

Introduction. At present, asphalt concrete pavement predominates high-grade highways, necessitating regular maintenance to mitigate or preclude pavement anomalies [1]. During winter, the manifestation of snow and ice on road surfaces potentially escalates the risk of severe traffic incidents. Statistical data reveal that approximately 15%-30% of traffic accidents are snow and ice-related [2]. Consequently, the most economically efficient strategy for countering snow and ice accumulation continues to be the application of deicing salt [3]. Nonetheless, the prolonged use of deicing salt has been observed to induce substantial alterations in the surrounding ecological environment of the highways [4]. Additionally, this practice has markedly affected the longevity and disease susceptibility of the road infrastructure [5].

Analysis of recent research and publications. To ascertain the effects of deicing salt on asphalt mixtures, pertinent studies have been conducted by various researchers. Juli-Gándara [6] assessed the salt-induced impact on three disparate asphalt mixtures, discovering a higher susceptibility of porous asphalt mixtures to salt degradation. Hassan [7] proposed that freeze-thaw damage inflicted on asphalt mixtures by pure water is less severe compared to when deicing salt is incorporated. Shi's [8] study identified certain deicing salts as prominent culprits of severe asphalt pavement damage, advocating that deicing salt, water, and heat represent essential prerequisites for damage induction. Meanwhile, Wei [9] and Zhou [10] have argued that deicing salt erosion expedites the aging process of asphalt mixtures. Zhou’s [11] work has illustrated that the higher surface tension of deicing salt solutions compared to asphalt allows for easier penetration into the crevices between binder and aggregate, thereby diminishing their interfacial bonding strength. Further, Pan [12] has theorized that deicing salt permeation into the interface between asphalt and aggregate can result in asphalt emulsification, consequently impairing the mixture. Although these studies scrutinize the impact of deicing salt on asphalt mixtures from various viewpoints, they collectively acknowledge that deicing salt can inflict damage of varying magnitudes on asphalt mixtures.

In China's northwest region, the prevailing aridity, marked by scant rainfall and incessant drought, dictates the environmental conditions [13]. During winter, the lack of ample water flow restricts the dilution and displacement of the deicing salt dispersed on the roadways [14]. Consequently, this arid environment induces a higher concentration of deicing salt within the road-adjacent soil compared to other regions. Notably, several scholars have scrutinized the effects of deicer on asphalt mixtures under dry-wet cycles. For instance, Zhang et al. [15] explored the impacts of these cycles on asphalt mortar's micro-mechanical properties in coastal regions, noting an increase in the sulfoxide index and large molecule content coupled with a decrease in surface roughness index as cycle times escalated. Guo's [16] application of the pull-off tensile test to asphalt and aggregates exposed to salt immersion cycles revealed a more significant pull-off tensile strength loss following salt immersion than after immersion in pure water. Luo et al.'s [17] findings indicated a rapid decrease in the splitting strength of asphalt pavement after twelve dry-wet cycles in a deicing salt solution. Yu et al.'s [18] evaluation of the rheological properties of asphalt pavement post immersion in a deicing salt solution revealed diminished low-temperature performance and anti-fatigue properties. However, these pertinent studies have not factored in the unique environmental characteristics of China's northwest region, limiting their applicability as references for road design and maintenance in this particular area.

Goal and objectives. Given the distinctive hydrological and climatic conditions of northwest China, the research team established nine monitoring stations across high-grade highways in Gansu Province, China. These stations facilitated the collection of long-term data on precipitation and atmospheric humidity, as well as temperature readings of asphalt pavement [19]. Concurrently, various commonly utilized deicing salts underwent freezing point analysis at diverse concentrations, yielding ice point data [20]. Building upon these data, the study employs three appropriate concentrations of deicing salt solutions to execute dry-wet cycle tests on two types of graded asphalt mixtures, taking into account the climatic and hydrological features of northwest China. The high-temperature rut test is employed to explore the high-temperature stability of asphalt concrete, while the Marshall water immersion test and the freeze-thaw splitting test are utilized to investigate the water stability of the same. Various factors influencing the road performance of asphalt mixtures are assessed via grey correlation entropy analysis, aiming to provide guidance for the selection of optimal road surfaces and application of deicing salts during maintenance in road design.

Research methods. In consideration of the snow-melting capabilities of the deicing salts, and taking into account the distinctive climatic and hydrological conditions of Northwest China, solutions for dry-wet cycles were devised with 15% urea (15% CH_4N_2O), 20% industrial salt (20% NaCl), and 20% absolute ethanol (20% CH_2CH_3OH). Preparations for the dry-wet cycle test involved creating Marshall and rut samples of AC-13 and AC-16 gradations. The full dry-wet cycle process involved:

1) The 24h±0.5h immersion of both gradation samples in the deicing salt solutions, as demonstrated in Figure 1.

2) Post-soaking, the samples underwent a 24h±0.5h air-drying process, as presented in Figure 2.

3) Upon completion of the drying phase, the samples were re-introduced to the deicing salt solutions to initiate the ensuing cycle.

Fig. 1. The samples immersed in deicing salt solutions

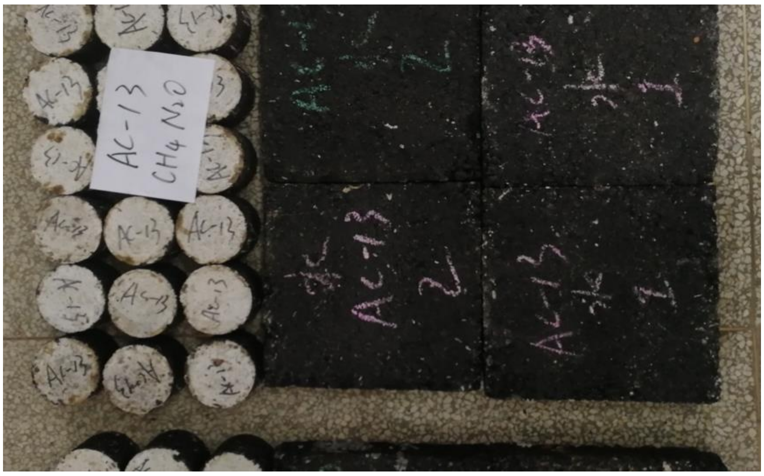

Fig. 2. The samples placed in the air

This methodology denotes a single dry-wet cycle. The experimental procedure encompassed 30 such cycles, with significant indicators assessed at the termination of the 0, 5, 10, 15, 20, 25, and 30 cycles. Given the volatile nature of absolute ethanol, it necessitated the preparation of a fresh anhydrous ethanol solution for each cycle, while the urea and industrial salt solutions were refreshed every three cycles. Upon finalization of the dry-wet cycle, rut samples were subjected to high-temperature rut tests, and Marshall samples evaluated through Marshall water immersion tests and freeze-thaw splitting tests.

Results Analysis Research and Discussion. The alterations in the dynamic stability (DS) and loss rate of the two asphalt mixtures following exposure to dry-wet cycles in three distinct deicing salt solutions are shown in Figure 3.

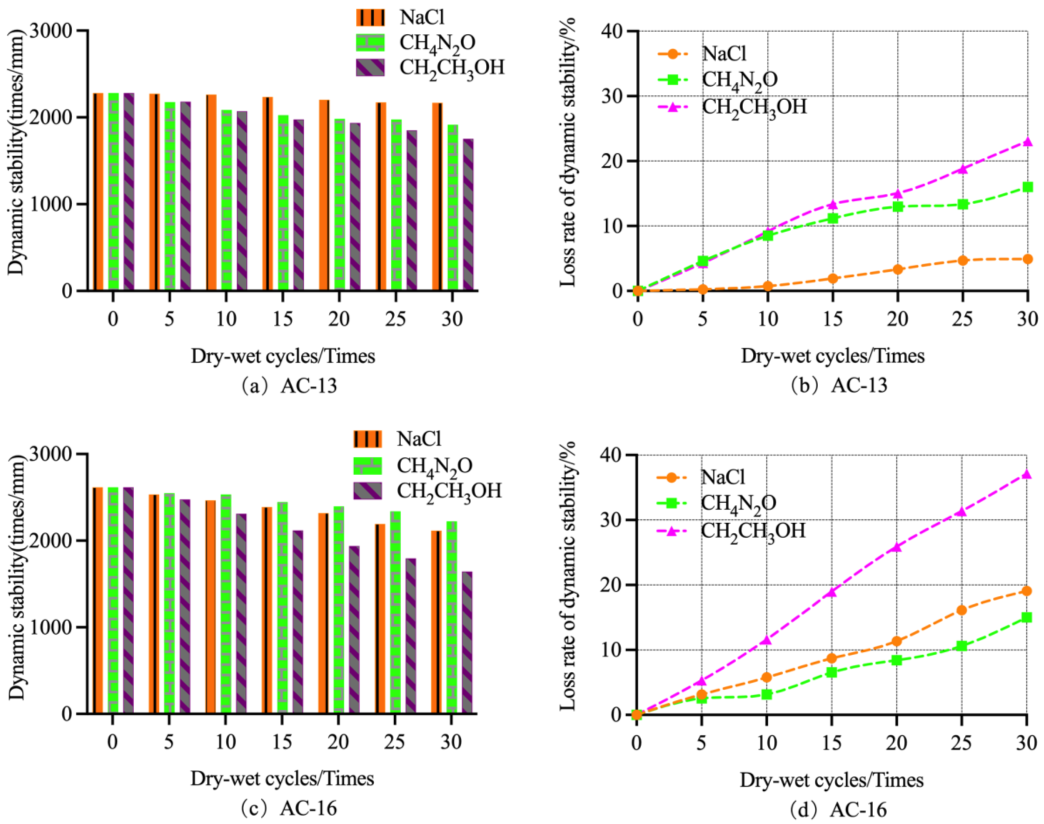

Fig. 3. The alterations in dynamic stability and loss rate after dry-wet cycles

Figures 3(a) and 3(b) demonstrate that, for the AC-13 asphalt mixture, there is an overall downward trend in DS associated with the three different deicing salts as the dry-wet cycles increase. NaCl has the least impact on DS, followed by CH_4N_2O, with CH_2CH_3OH having the most substantial impact. Over the entirety of the dry-wet cycles, DS damage related to NaCl is minimal, at a rate of 4.9%, whereas DS corresponding to CH_4N_2O and CH_2CH_3OH exhibit rates of 16.0% and 23.1%, respectively. Furthermore, within 30 cycles, the lowest dynamic stability values for NaCl, CH_4N_2O, and CH_2CH_3OH are 2168, 1915, and 1754 times/mm, respectively, all surpassing the standard's requirement of 1000 cycles/mm.

From Figures 3(c) and 3(d), it can be deduced that when the gradation of the asphalt mixture is AC-16, the DS corresponding to the three different deicing salts also generally decreases with an increase in dry-wet cycles. Here too, NaCl has the least influence on DS, followed by CH_4N_2O, while CH_2CH_3OH again has the greatest impact. Throughout all the dry-wet cycles, CH_2CH_3OH corresponds to the most pronounced DS damage, at a rate of 37.2%, compared to 19.1% and 15.0%

for NaCl and CH_4N_2O, respectively. Additionally, within 30 cycles, the lowest dynamic stability values for NaCl, CH_4N_2O, and CH_2CH_3OH are 2117, 2223, and 1644 times/mm, respectively, all surpassing the standard's requirement of 1000 cycles/mm.

Upon comparing Figures 3(b) and 3(d), it is evident that the DS decline rate for AC-16 significantly surpasses that for AC-13, suggesting a greater impact of the three salt solutions on AC-16 in terms of DS.

The alterations in the residual stability (MS_0) and loss rate of the two asphalt mixtures following exposure to dry-wet cycles in three distinct deicing salt solutions are shown in Figure 4.

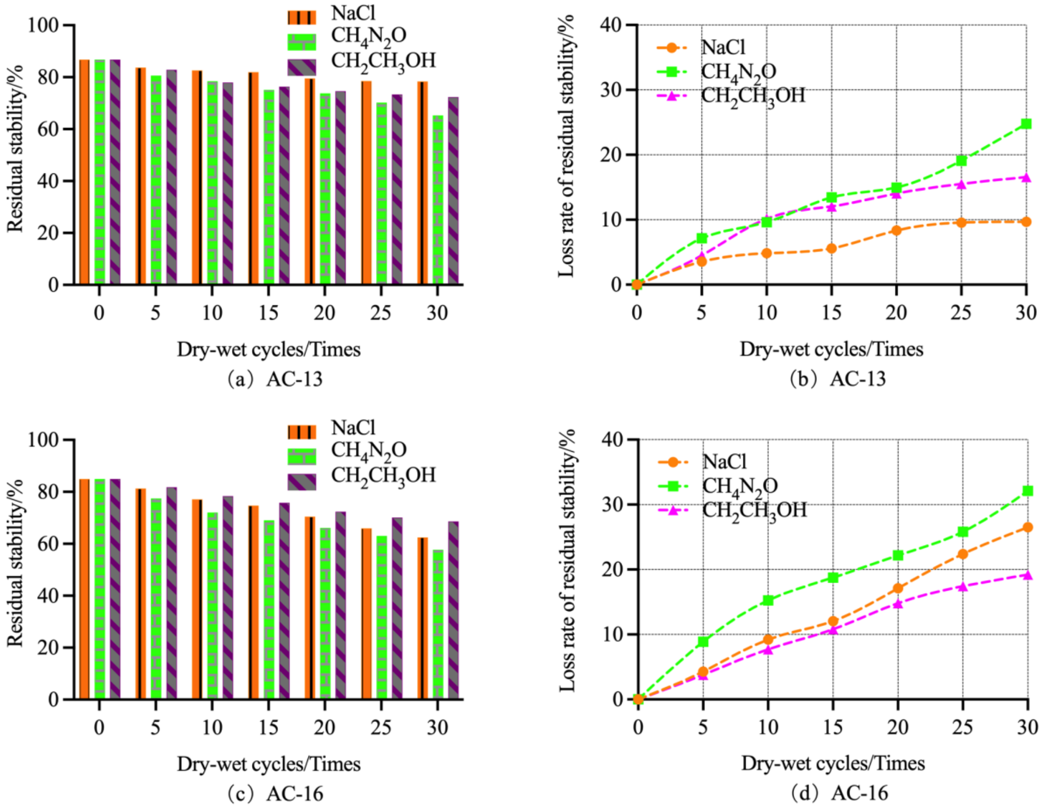

Fig. 4. The alterations in residual stability and loss rate after dry-wet cycles

Upon evaluation of Figure 4(a), it becomes apparent that the MS_0 associated with the three deicing salts undergoes a decline in line with the progressive increase in the number of dry-wet cycles for the AC-13 asphalt mixtures. Further analysis of Figure 4(b) reveals that within a total of 30 dry-wet cycles, NaCl imparts the least effect on MS_0, exhibiting a loss rate less than 10%. The impacts of CH_4N_2O and CH_2CH_3OH on MS_0 show a degree of similarity through the initial 20 cycles, but the 25th and 30th cycles trigger a sudden decline in MS_0 corresponding to CH_4N_2O. The residual stability for CH_4N_2O and CH_2CH_3OH during the 20th cycle is recorded as 73.8% and 74.6% respectively, failing to meet the existing specifications that demand above 75%. Nonetheless, the NaCl-associated MS_0 continues to comply with the current specifications, remaining above 75% throughout the 30 cycles.

From Figure 4(c), similar to the AC-13 mixture, the AC-16 asphalt mixture also demonstrates a downward trend in MS_0 for all three deicing salts as the dry-wet cycles increase. Delving into Figure 4(d), within the 30 dry-wet cycles, CH_2CH_3OH exerts the least effect on MS_0, followed by NaCl, whereas CH_4N_2O imposes the most significant impact. During the initial 20 cycles, the influence of NaCl and CH_2CH_3OH on MS_0 appears comparable, but the 25th and 30th cycles witness a sharp fall in MS_0 corresponding to CH_2CH_3OH. By the 10th, 15th, and 20th cycles, the MS_0 values corresponding to CH_4N_2O, NaCl, and CH_2CH_3OH are 72 %, 74.7%, and 72.4%, respectively, each of which falls short of the current specifications' demand for a figure above 75%.

On comparing Figure 4(b) and Figure 4(d), it is discernible that the rate of MS_0 reduction for AC-16 marginally surpasses that of AC-13, implying a more pronounced impact of the three salt solutions on AC-16 in terms of MS_0.

The alterations in the tensile strength ratio (TSR) and loss rate of the two asphalt mixtures following exposure to dry-wet cycles in three distinct deicing salt solutions are shown in Figure 5.

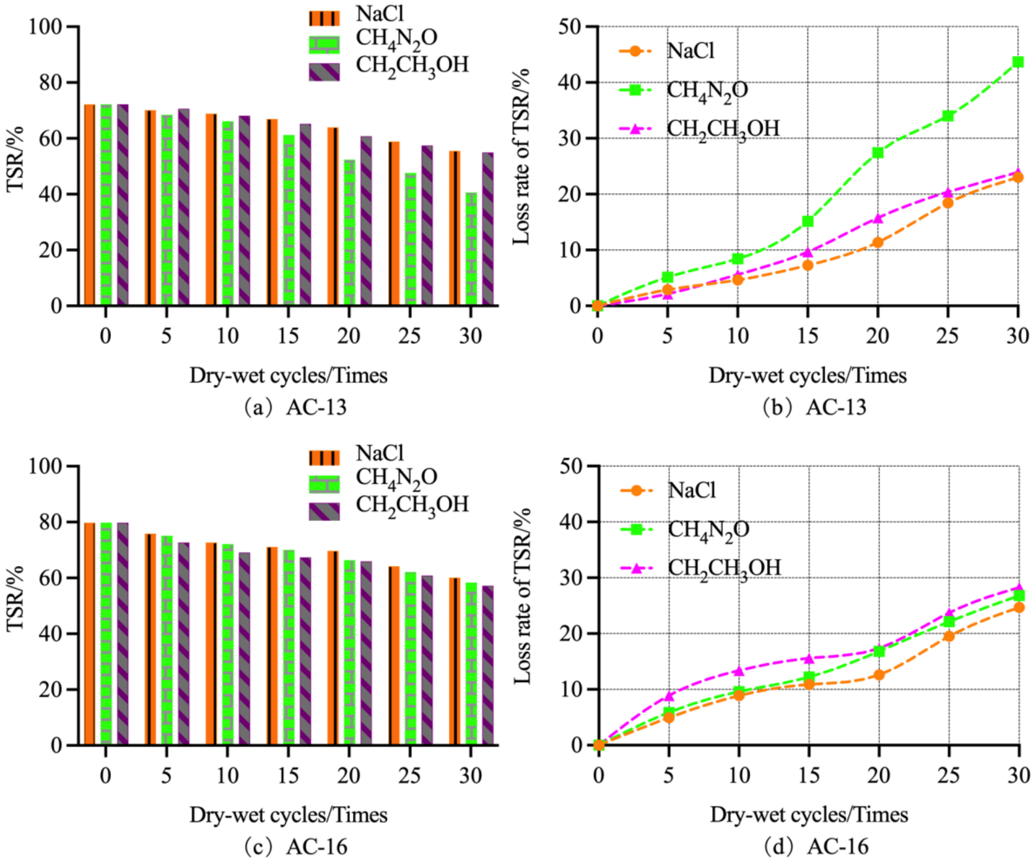

Fig. 5. The alterations in tensile strength ratio and loss rate after dry-wet cycles

As evidenced by Figures 5(a) and 5(b), AC-13 asphalt mixtures present a diminishing trend in TSR in relation to all three deicing salts as the quantity of dry-wet cycles augments. Of these salts, CH_4N_2O exerts a markedly greater influence on TSR compared to the other two, with a less pronounced discrepancy between the effects of CH_2CH_3OH and NaCl on TSR. By the 5th dry-wet cycle, the TSR for CH_4N_2O is 68.5%, and by the 10th cycle, the TSRs for CH_2CH_3OH and NaCl are 68.1% and 68.8%, respectively, failing to achieve the standard's prescribed minimum of 70%.

Referring to Figures 5(c) and 5(d), for AC-16 asphalt mixtures, the TSR shows a similar downward trajectory as the count of dry-wet cycles expands, with no discernible contrast in the impact of the three salts on TSR at equivalent dry-wet cycle numbers. By the 10th cycle, the TSR corresponding to CH_2CH_3OH is 69.1%, and at the 20th cycle, the TSRs for NaCl and CH_4N_2O are 69.7% and 66.4%, respectively, not meeting the required standard of a minimum of 70%.

Upon comparison of Figures 5(b) and 5(d), it emerges that for CH_4N_2O as the deicing salt, the TSR reduction rate for the AC-16 grading outpaces that of AC-13. However, in the case of NaCl or

CH_2CH_3OH being the deicing salts, the TSR decline rate for AC-16 exhibits negligible difference from that of AC-13.

*Grey Correlation Entropy Analysis***.** First proposed by Professor Ju-Long Deng in 1982, Grey Theory is a novel engineering system framework designed to adeptly tackle system issues where information is scant. Over three decades of continued development have seen this theory find applications across various domains. A particular branch of Grey Theory, Grey Correlation Entropy Analysis, allows for a comprehensive assessment of data related to the subject of study in situations of incomplete information, pinpointing the primary and ancillary factors influencing the subject.

The core tenet of Grey Correlation Entropy Analysis is the evaluation of factor relatedness based on the similarity in their geometric shape progression. The similarity in the development trends of factor curves signifies a higher degree of closeness and correlation. Conversely, diverging development trends indicate a lesser degree of correlation and closeness. The process of Grey Correlation Entropy Analysis involves the identification of reference and comparison sequences, sequence initialization, calculation of the difference sequence, determination of the correlation coefficient, and finally, the estimation of the correlation degree.

Utilizing the Grey Correlation Entropy Analysis approach, an examination is conducted to discern the grey correlation between three determinant factors – gradation of the asphalt mixture, type of deicing salt, and the frequency of dry-wet cycles – with the dynamic stability, residual stability, and TSR of the asphalt mixture. This analysis yielded the correlation coefficients between each of these determinant factors and the dynamic stability, residual stability, and TSR respectively, as demonstrated in Table 1.

Table 1 – Results of grey correlation entropy analysis concerning influencing factors

Influencing factor	Gradation	Type of deicing salt	Dry-wet cycles
Dynamic stability	0.7035	0.6568	0.5511
Residual stability	0.6620	0.6341	0.5490
TSR	0.7209	0.6750	0.5648

Table 1 elucidates that the mechanical properties of asphalt mixtures under dry-wet cycles are primarily influenced by the gradation of the mixture. This is followed by the type of deicing salts utilized, with the frequency of dry-wet cycles presenting the least significant impact. This observation suggests that judicious selection of road surface materials can mitigate the erosive effects of deicing salts. Incorporating Liu's research findings on the freezing points of different deicing salts [19], it becomes apparent that the choice of deicing salt type holds diminished significance when the environmental temperature ranges between -5 ℃ and 0 ℃.

Conclusion. Dry-wet cycles were conducted on AC-13 and AC-16 asphalt mixtures using three kinds of deicing salt solutions, and the subsequent alterations in the mixtures' mechanical properties were examined. Data from the high-temperature rut test, the Marshall water immersion test, and the freeze-thaw splitting test were analyzed, leading to the subsequent conclusions:

1. Evaluating from the perspective of high-temperature stability, the detrimental impacts of de-icing salt solutions on AC-13 asphalt mixture can be ordered in a descending sequence as: $CH_2CH_3OH > CH_4N_2O >$ NaCl. Similarly, the adverse effects on AC-16 asphalt mixture due to these de-icing salt solutions follows the decreasing order: $CH_2CH_3OH >$ NaCl $> CH_4N_2O$.

2. Employing the MS_0 for assessing water stability, the ranking of the damaging effect of deicing salt solutions on AC-13 asphalt mixture is: CH_4N_2O > CH_2CH_3OH > NaCl. For AC-16 asphalt mixture, the order is: CH_4N_2O > NaCl > CH_2CH_3OH.

3. With the TSR as an evaluative parameter for water stability, the sequence of damage for AC-13 asphalt mixture by deicing salt solutions is: CH_4N_2O > CH_2CH_3OH > NaCl. For AC-16 asphalt mixture, the sequence is: CH_2CH_3OH > CH_4N_2O > NaCl.

4. In general, increasing the proportion of fine aggregates in asphalt mixtures enhances their resistance against deicing salt erosion.

5. As per the findings from the grey correlation entropy analysis, the gradation of the asphalt mixture is the leading determinant of its mechanical properties, followed by the type of deicing salt solution. Conversely, the number of dry-wet cycles exerts the least influence on these properties.

The scope of this manuscript is primarily focused on the macroscopic analysis of the impact of deicing salts on the mechanical properties of asphalt mixtures. A comprehensive understanding of these effects also necessitates a microscopic investigation, an aspect not included in the current study. Future investigations will leverage computed tomography (CT) image scanning or scanning electron microscopy (SEM) to inspect the microscopic morphological changes in the asphalt mixtures induced by deicing salt erosion.

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ВПЛИВ ПРОТИОЖЕЛЕДНОЇ СОЛІ НА ЕКСПЛУАТАЦІЙНІ ХАРАКТЕРИСТИКИ АСФАЛЬТОБЕТОННИХ СУМІШЕЙ У ПІВНІЧНО-ЗАХІДНОМУ КИТАЇ: ДОСЛІДЖЕННЯ МЕХАНІЧНИХ ВЛАСТИВОСТЕЙ ТА ФАКТОРІВ ВПЛИВУ

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Анотація. На даний час одним з основних матеріалів для влаштування високоякісних автомобільних доріг залишається асфальтобетон. Накопичення льоду та снігу на асфальтобетонних покриттях в зимовий період часто призводять до серйозних дорожньо-транспортних пригод. За статистикою, близько 15-30 % таких інцидентів безпосередньо пов'язані з ожеледицею та снігопадом. Тому, коли дороги вкриті льодом та снігом, найбільш економічно ефективним і дієвим заходом боротьби з ожеледицею залишається розпорошення протиожеледної солі на дорожньому покритті. Особливо в північно-західному регіоні Китаю, де спостерігається низька кількість опадів і постійні засухи, протиожеледні солі, що застосовуються взимку, не розбавляються і не змиваються потоком води. Як наслідок, дорожнього покриття та ґрунт навколо зберігає високу концентрацію протиожеледних солей, ніж в інших регіонах, що призводить до помітного впливу на термін служби дорожнього покриття.

Метою цього дослідження є експериментальне моделювання впливу високосольового середовища на механічні властивості асфальтобетонних сумішей з подальшим аналізом ключових факторів, що впливають на довговічність асфальтобетонних сумішей.

Для досягнення поставленої мети застосовуються такі методи дослідження, як випробування високотемпературної колії, а також випробування за Маршаллом та випробування на розшарування при замерзанні-відтаванні, що дозволяють дослідити закономірності зміни механічних властивостей асфальтобетонних сумішей в умовах різного гранулометричного складу, різних протиожеледних сольових розчинів та різної частоти циклів зволоження і висушування. Крім того, для встановлення взаємозалежності між факторами, що впливають на експлуатаційні характеристики асфальтобетонних сумішей, у дослідженні використано ентропійний аналіз “сірої кореляції”.

Результати показують, що після проходження 0, 5, 10, 15, 20, 25 і 30 циклів висушування та насичення у розчинах 20% технічної солі ($NaCl$), 15% карбаміду (CH_4N_2O) і 20% безводного етанолу (CH_2CH_3OH), високотемпературна стійкість і водостійкість асфальтобетону марок АС-13 і АС-16 знизилися в різній мірі. Загалом, збільшення відсоткового вмісту дрібного заповнювача в асфальтобетоні може підвищити стійкість асфальтобетону до сольової ерозії в ожеледицю. Згідно з аналізом ентропії “сірої кореляції” розглянуто вплив трьох факторів. Найбільший вплив на механічні властивості має різниця в гранулометричному складі, потім тип розчину протиожеледної солі, і найменший - частота циклів насичення та висушування. Таким чином, раціональний підбір складу асфальтобетону підвищує експлуатаційні характеристики при негативні дії протиожеледних солей.

Ключові слова: дорожнє будівництво, асфальтобетонна суміш, цикл поперемінного насичення та висушування, експлуатаційні характеристики покриття, протиожеледна сіль.

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