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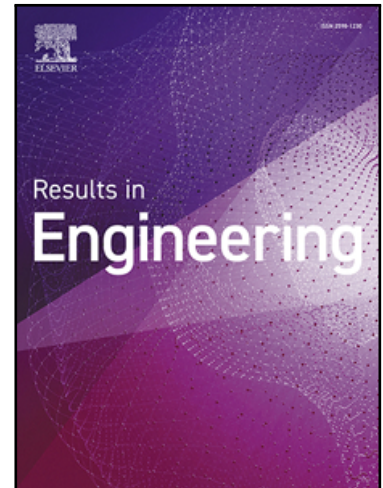
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Airport Traffic Simulator for Anti-icing Runway Winter Products: Chemical Performance by Mechanical Activation

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Abstract

The chemicals products used in airports are essential to keep air traffic flowing safely and smoothly during winter time. However, there is limited reliable information available regarding both their performance and optimal use. It is therefore essential to properly characterize these products and to define their optimum application rates according to the various precipitation parameters (type, intensity, temperature) and other meteorological ones (wind strength, humidity level, etc.), either current and those to come. The mechanical contribution of traffic is often cited as a significant contribution on their efficiency. Mechanical activation plays a critical role in the effectiveness of Runway De-icing Product (RDP) as an anti-icing agent. For instance, if a spreader provides consistent mechanical activation of the product, this can enable airports to avoid spreading again RDP and reducing the risk of runway saturation, saving money and extending the product's effective time. Thus, the development of an Airport Traffic Simulator (ATS) was undertaken to replicate real-world airport runway conditions and their surrounding environment within a

laboratory setting. The evaluation of anti-icing efficiency provides airport maintenance teams with tools to optimize product application costs while maintaining maximum safety. The failure of these tests is determined by the exothermal reaction caused by the ice formation on the circulated surface, which is identified using a thermal camera. The product's efficiency time increases as the temperature rises and the precipitation intensity decreases. This relationship underscores the importance of considering weather conditions when determining the optimal application strategy for RDP. In addition, the ATS crushing of surface contaminant of a RDP has demonstrated that a more frequent mechanical activation significantly enhances the product efficiency as an anti-icing agent. The results obtained in this project serve as a thiving basis for developing a broader analytical framework, thanks to the robust methodology employed, which can be extended to other weather conditions.

Introduction

Inclement and changing winter weather conditions are a major issue in the aerospace industry [1]. Contamination of both aircraft and runways by snow or ice can have critical consequences for air traffic [2, 3], in terms of user safety (passengers and crew members), of environmental impact of chemical usage and of financial implications due to traffic delays or stoppages [4, 5]. It is therefore essential to develop innovative solutions and strategies to enhance safety, minimize environmental incidence, and reduce operational costs in winter conditions.

There are various available tools to airports to remove contaminants from runways [6]:

- Firstly, mechanical methods such as plows and brushes are used to efficiently remove snow from the runway, according to a process established by the airport [7]. However, they

are limited when it comes to ice, as shovels are not always capable of unsticking it from the runway surface.

Consequently, the use of chemical agents becomes crucial. Chemicals weaken its structure and bonding with the concrete / asphalt surface, facilitating its removal [8]. They also provide preventive protection against freezing and frozen precipitations maintaining safe operational condition and ensuring the continuity of air traffic.

The literature has shown that the runway products currently in use are derived from five main molecules. These include aqueous solutions of potassium acetate (KAC), potassium formate (KFO), and glycerol-based hybrids, all in liquid form, as well as solid de-icing agents such as sodium formate (NAFO), sodium acetate (NAAC), and a 50/50 w/w blend of the two [9]. Historically, products based on chloride and urea were used. However, it has been shown that urea, despite its low purchase cost, is harmful to the environment, since its biodegradation into water generates ammonia, which is highly toxic to nearby flora and fauna [10]. Similarly, chloride salts (sodium, magnesium or calcium chloride), used mainly on roads, are unsuitable for airport runways because of its strong corrosion effect for the steel and aluminum alloys used in aircrafts [10]. Thus, 86% of airports in North America use potassium acetate, 41% use sodium formate, and only 14% use sodium acetate [11].

In literature, little research has been carried out on pre-wetted products consisting of a solid Runway Deicing Products (RDP) on which a liquid RDP is applied [12, 13]. Moreover, these products are tested using a method that does not take into account the importance of the contact surface [14]. It therefore seems important to adopt an experimental protocol that appropriately addresses this issue. Indeed, the use of a method that allows solid products

to be used as they are at airports, i.e. pre-wetted with liquid RDP, seems essential to reach a correct interpretation of the results.

Table 1 [9] shows the characteristics of the main product used for de-icing products. Solids stand out as being more robust than RDPs in solution known as liquid. However, liquid RDPs act immediately, whereas solids require prior handling and dissolution into water. It can be seen that solid RDP is longer-acting than liquid, while liquid RDP is quick-acting. A combination of the two (prewet) would give a fast-acting, long-lasting RDP, which is the best possible combination for airports.

Table 1 : Summary of de-icing product characteristics [9]

	Liquid (in solution)	Solid	Pre-wetted (Solid + Liquid)
Adhesion to concrete /asphalt surfaces	Easily adheres	Adhesion varies with particle size	Greater adhesion than solids alone
Efficiency	Acts immediately	Slow acting (Need moisture and mechanical activation)	Synergistic effect. Act faster than solid alone but slower than RDPs in solution alone
Lasting time	Protect for a lower time	Long-lasting effect	Long-lasting effect

RDPs are essential for maintaining safe airport operations during winter conditions, and they come in both solid and liquid forms [15, 16]. These products are primarily used as freezing point depressants, applied directly to runways and taxiways to prevent ice formation and facilitate mechanical removal of snow and ice. Organic de-icing agents, such as formates and acetates, mitigate ice formation by forming hydrogen bonds with water molecules, thereby disrupting their molecular arrangement and delaying crystallization

[17]. This mechanism is particularly advantageous as it not only ensures effective anti-icing performance but also significantly reduces the corrosive effects commonly associated with chloride-based salts [8, 18]. The current RDPs are chosen for their deicing performance and their relatively lower environmental impact [16]. The deicing performance of RDPs is evaluated through various standardized tests that measure ice melting capacity [19], ice penetration [20], and ice undercutting [21]. These tests are designed to simulate real-world conditions and assess the rapidity and endurance of the deicing products [2].

The capability of RDPs to melt ice is meticulously assessed through a variety of methodologies, each designed with the specific aim of accurately quantifying the effectiveness of these products under carefully controlled conditions representative of real-world scenarios. One widely adopted approach in this evaluation process is the ice melting capacity test, which quantitatively measures the mass of ice that a particular deicing product is capable of melting within a one-minute timeframe, thereby providing valuable insights into the speed and efficiency with which the product operates in melting ice [2, 22]. This test is typically carried out in accordance with established standards, such as SAE AS6170, where a predetermined quantity of deicer is methodically applied onto an ice sample, and the subsequent amount of ice that has melted is recorded and analyzed over specified time intervals, which may include 5, 10, and 30 minutes to ensure a thorough assessment [19]. The procedure for conducting this test involves placing a Petri dish containing a sample of ice within a cold room environment, applying the deicing agent to the ice, and then meticulously measuring the remaining ice after a designated period has elapsed to accurately calculate the total amount of ice that has been melted.

In addition to these traditional methods, calorimetry has also gained attention as a viable technique for measuring the ice-melting capacity of various deicing products. This approach employs a calorimeter to monitor the thermal changes that occur throughout the melting process, thereby facilitating a more precise quantification of the deicer's ice-melting capabilities without necessitating the physical separation of the brine generated from the melted ice from the residual ice [23, 24]. The calorimeter method has been demonstrated to enhance the accuracy of measurements when compared to conventional tests, as it effectively eliminates the potential complications associated with manual handling and mechanical separation, both of which can inadvertently introduce errors into the results [23, 24]. Moreover, the innovative application of infrared thermography has been suggested as a means to evaluate the anti-icing performance of runway deicers, offering both visual and quantitative assessments of their effectiveness in preventing the formation of ice under simulated environmental conditions [25]. Collectively, these diverse methodologies contribute to a thorough and comprehensive evaluation of RDPs, enabling a detailed assessment not only of the immediate ice melting capacity but also of the longer-term anti-icing performance, both of which are absolutely critical for ensuring safe and effective runway operations in challenging winter conditions [13].

Ice penetration test has been recently used to characterize RDP. Recent studies have been conducted to create a dynamic ice penetration model to deepen the understanding of the product [26]. This research centers on developing a dynamic ice penetration model to advance the understanding of runway de-icing product performance. Through ice melting, undercutting, and penetration tests conducted in compliance with aerospace standards, the study seeks to enhance the efficiency of de-icing products, thereby reducing operational

costs and mitigating environmental impacts. The proposed numerical model, validated through rigorous laboratory experiments, reveals that product effectiveness follows a distinct trend over time. Additionally, the research identifies the predominant heat transfer mechanism and introduces a simplified modeling approach that accurately predicts ice penetration rates. These findings provide valuable insights for optimizing de-icing strategies in the aviation industry. Beyond improving de-icing technology, this study establishes a robust foundation for future research aimed at enhancing safety, efficiency, and sustainability in winter operations.

Recent advancements in testing methodologies, such as the use of infrared thermography, have improved the sensitivity and accuracy of these evaluations, allowing for better classification and optimization of RDPs [2, 22, 26].

On the other hand, Ice Penetration (IP) and artificial intelligence have been used to obtaining more efficient RDP [27]. This research aims to tackle environmental challenges associated with deicing agents by leveraging machine learning to improve their efficiency. The study explores the ice-melting mechanisms of various salts and organic solvents, with a particular focus on understanding ice penetration capacity (IPC) as a critical factor for developing eco-friendly deicers. Using advanced analytical tools such as extreme gradient boosting (XGBoost) [28] and Shapley additive explanation (SHAP) [27], the research identifies the primary mechanisms driving ice melting. It highlights the synergistic benefits of combining organic solvents and salts in deicer formulations. The findings propose a promising solution: a propylene glycol (PG) and sodium formate mixture, which offers superior IPC and a significantly lower environmental impact compared to conventional

commercial deicers. This work underscores a clear pathway toward more sustainable and efficient deicing practices.

These chemicals used in airports are essential to keep air traffic flowing smoothly. However, there is limited accurate information available about their performance, optimal application rates, and environmental effects [29]. It is therefore essential to conduct in-depth characterization of these products to optimize their use under varying meteorological conditions. Parameters such as the type and the intensity of precipitation, air temperature, wind speed, and humidity levels must all be considered to determine their effectiveness. Standards do exist to establish minimum requirements for aircraft de-icing and anti-icing to ensure global safety for all individuals involved (airport staff, airline personnel, and passengers) [30]. However, there are currently no lower limits concerning the de-icing and anti-icing performance for airport runways chemical products. This regulatory gap presents an opportunity to address runway safety holistically while considering environmental sustainability and economic performance.

Despite these advancements, there is still a need for further research to refine these methods and ensure they accurately reflect field conditions, as current laboratory tests often use higher application rates than those typically employed in practice [22, 31]. Additionally, the environmental impact of RDPs remains a concern, as their application can affect surrounding ecosystems, necessitating ongoing development of more sustainable formulations [31]. Overall, the main characteristics of current RDPs include their chemical composition, performance under standardized testing conditions, and the ongoing efforts to balance effectiveness with environmental sustainability. Future studies should focus on

integrating real-world data and long-term field trials to enhance the reliability of RDP evaluations, ultimately leading to more informed decision-making in airport practices [22].

In addition to the advancements in testing methodologies, there is an increasing focus on developing more environment-friendly RDP formulations that maintain efficacy while reducing ecological risks [32]. Recent research has explored alternative materials such as bio-based deicers and less corrosive chemical compounds that can effectively melt ice without causing significant nor critical harm to surrounding ecosystems or infrastructure [32]. The transition towards these sustainable options not only addresses environmental concerns but also aligns with regulatory pressures aimed at minimizing harmful runoff from airport operations [32]. Furthermore, integrating predictive modeling techniques could enhance the understanding of how different RDPs perform under varying temperature conditions and application rates, ultimately leading to more tailored and efficient usage strategies that optimize both safety and environmental stewardship in winter maintenance practices [26]. By adopting these innovative approaches, airports can significantly reduce their ecological footprint while ensuring safe and reliable operations during adverse weather conditions.

A representative standardized method is therefore needed to evaluate the performance of RDP in anti-icing mode in the laboratory. To assist in the development of a comprehensive standard defining optimum spreading rates for airport runways, this study focused on the application of pre-wetted solid products. A preliminary test was conducted to observe and to analyse the interaction between chemical products and a freezing drizzle [31]. A concrete block (representative of a runway surface) was treated with a defined quantity of product

(solid and liquid), and was then exposed to a freezing drizzle precipitation. The results revealed that solid products exhibit efficiency limitations under these conditions. Indeed, after discussions with various airports operators and manufacturers confirmed that solid products require mechanical activation, such as crushing, to significantly enhance their performance in protecting critical runway surfaces.

It therefore seems critical to experimentally include and to replicate the mechanical activation of products as occurs in real airports operations, to properly and accurately evaluate their performance. Mechanical activation involves crushing the solid product with the wheel of a vehicle, simulating airport traffic conditions (Figure 1).

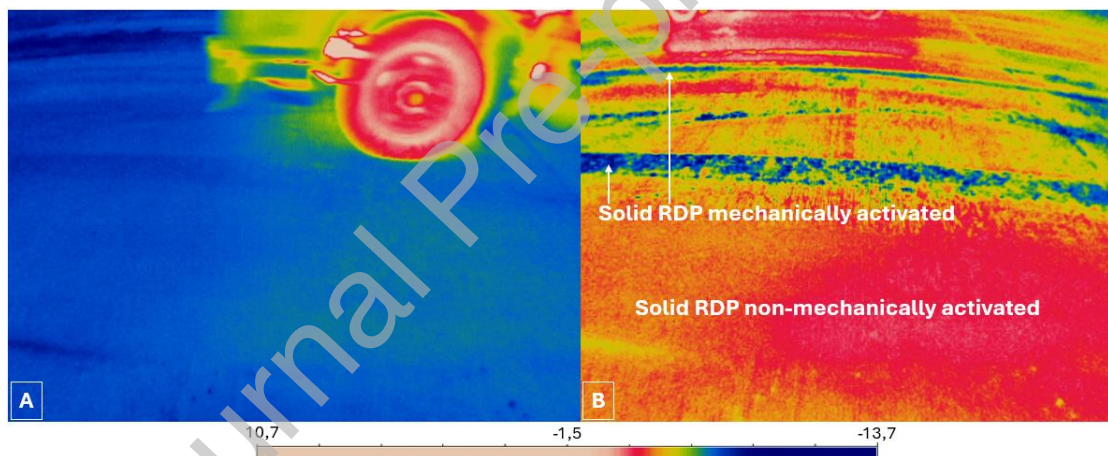


Figure 1 : Thermal image of a test campaign on a Montreal airport runway to evaluate the benefit of a mechanical activation of a RDP. (A) Before the spreading truck passes by. (B) After the spreading truck passes by.

As can be seen in Figure 1, a drop of temperature is observed in the passage of the wheels. The observed endothermic reaction due to the dissolution of the salt into available water indicates that the product has been activated, making it possible to protect the runway more effectively.

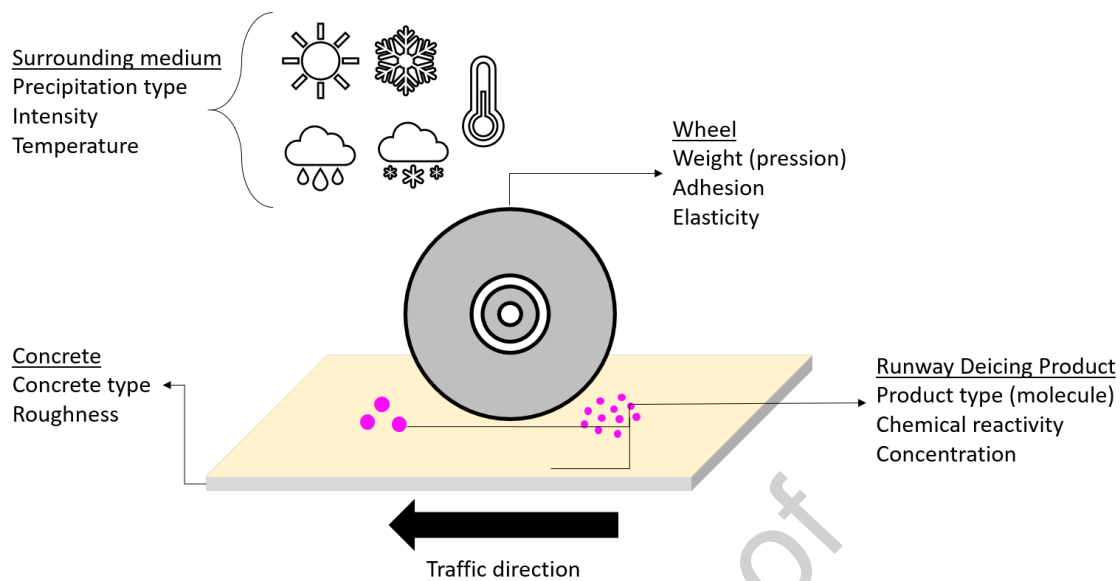


Figure 2 : Diagram of the parameters involved in an RDP being mechanically activated by a wheel on an airport runway

In Figure 2, we can see several parameters involved in an RDP being mechanically activated by a wheel. Indeed, the surrounding medium, the wheel, the RDP and the concrete are involved in this phenomenon. In this study, we worked with airport concrete sample to be sure to have the same parameters as the field one. Also, we worked with known environmental parameters and RDP. We decided to work with a wheel without grooves, to ensure uniform contact with the surface, as grooves create areas where the deicing product is not effectively crushed.

To address this need, the development of an Airport Traffic Simulator (ATS) was undertaken. This innovative tool reproduces airport runway conditions under controlled laboratory settings, allowing the evaluation of solid deicing and anti-icing products.

The ATS enables the testing of products under various types of winter precipitation while controlling critical parameters such as temperature, precipitation intensity, wind strength,

and surface characteristics. This study focused on freezing drizzle at different temperatures and intensities, with particular emphasis on the application of pre-wetted solid products on a simulated runway surface. These parameters were selected based on the SAE ARP5485B standard [33], which governs aircraft deicing and anti-icing protocols. By adopting this methodology, the study offers a pathway to improve the understanding and the application of deicing products for airport runways, ensuring safer, more cost-effective, and environment-friendly winter operations.

This approach is essential to help field operators apply the product under conditions that reflect real-life scenarios. To date, no research has examined the importance of the mechanical activation parameter, despite its critical role for airports when applying anti-icing and de-icing products on runways. This study addresses this gap by analyzing the impact of mechanical activation and proposing a realistic effective time for airport runway environments under various conditions.

1. Methodology

As indicated before, a mechanical activation of the chemicals applied on runways and taxiways is often indicated by airports operators as an improvement of their efficiency. Thus, the design of the Airport Traffic Simulator (ATS) enables us to reproduce both the crushing and the mixing of solid Runway Deicing Product (RDP) necessary for its activation, as also demonstrated during test campaigns on Montreal airport runways in winter 2023 and 2022.

The ATS consists of a steel structure with surrounding protection in which a moving table with a translation maximum speed of around 0.10 km/h is installed and upon which a wheel

with a fixed rotational axis could move, all mounted on a rigid steel frame painted to protect it from corrosion. A scheme of the apparatus and a photo are shown in Figure 3 [31]. A dedicated space is provided for positioning the test sample at the same level of the surface. The wheel incorporated into the assembly, designed to rotate freely as the table/sample moves back and forth. This wheel is solid and smooth, without grooves, to ensure uniform contact with the surface.

To replicate real-world conditions, two compressed-air cylinders are strategically positioned on either side of the wheel. These cylinders apply a controlled load perpendicular to the surface being tested. This applied load can be adjusted up to 2200 kg (89 psi), offering flexibility to simulate various operational scenarios. For the specific series of tests presented here, the load was set at its maximum value, replicating the pressure exerted by the passage of a spreader truck over the sample.

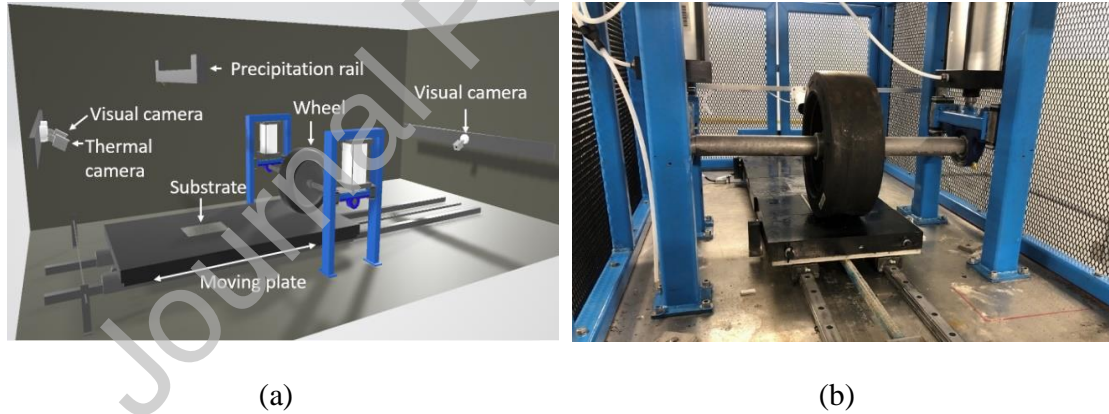


Figure 3 : Diagram (a) and photograph (b) of the Airport Traffic Simulator (ATS)[31]

Two cameras are positioned at opposite ends of the assembly (Figure 3a) to visually validate the experiment, ensuring a comprehensive view of the test process. Additionally,

a thermal camera is employed to monitor and record the temperature distribution across the tested surface during the test, providing critical data for the analysis.

The ATS device is located within a climatic chamber maintained at controlled temperature, operating under a precipitation rail with a specialized nozzle designed to simulate freezing drizzle conditions. This setup is specifically tailored for anti-icing studies, enabling precise control and reproducibility.

The testing conditions were established based on the experimental protocols detailed in the Global Report Format (GRF) for aircraft anti-icing products [33]. The test conditions for freezing rain are regulated for aircraft fluids. The aim in this study was to replicate these conditions to evaluate the RDPs. So, these tests were conducted out at varying precipitation intensities (5, 8.5 and 13 g/dm²/h) and ambient temperatures (-2°C, -5°C and -10°C) to assess the effectiveness of the products under diverse conditions. According to GRF requirements, the air temperature standard deviation must not exceed ± 0.3 °C, a condition met by the climate chamber used in this work. The temperature of the precipitation in the chamber is monitored at 4°C to ensure that the nozzle does not freeze and that it freezes on contact with a surface. Prior to testing, concrete substrates were preconditioned in the climatic chamber to reach the desired test temperature during a minimum of 8 hours, ensuring consistency and reliability in the results.

Subsequently, 0.5 g of solid RDP, specifically sodium formate (NAFO) (Figure 4 (a)) was carefully deposited onto the surface of the concrete sample. In addition, 0.35 g of potassium acetate (KAC) (Figure 4 (b)) was applied by spraying, replicating the application rates commonly observed in airports operations based on oral exchanges with airports.

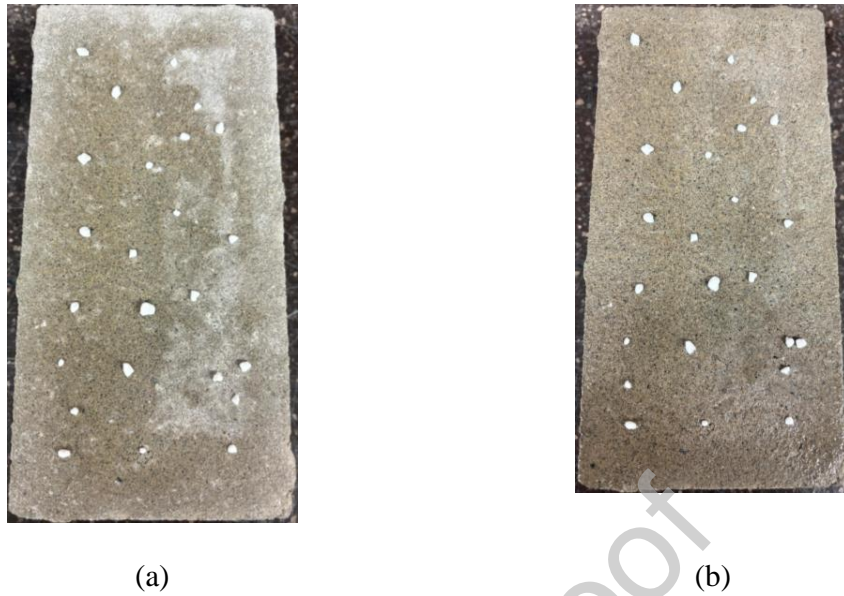


Figure 4: Images of the concrete sample with sodium formate (NAFO) applied (a) and potassium acetate (KAC) sprayed (b) on its surface prior to mechanical activation by the ATS wheel.

Finally, the sample was subjected to the ATS with precipitation until product failure occurred. This failure condition is defined by the formation of ice which is detected through an exothermal reaction (sudden temperature increase) detected by a thermal camera (Optris Pi450i) and its corresponding software (Optris PIX Connect) dedicated to thermal images analyses. The device consisted in an uncooled 382 x 288 pixels frame plane array (FPA) microbolometer detector. It was equipped with a Ge lens with a field of view (FOV) of $18^{\circ} \times 14^{\circ}$. The distance between the camera lens and the target was almost 40 cm. The camera was installed in the climate chamber and switched on at least 30 minutes before the start of measurements, in order to achieve thermal equilibrium of its electronic parts. The camera has a NETD of 60mK with no further specifications provided by the manufacturer. Thermal images were collected in video mode at a frequency of 80 Hz. A visual inspection

was performed after the failure detected by the thermal camera to confirm ice occurrence.

Each test was performed three times to ensure consistency.

2. Results and Discussion

An important aspect of this study was the emphasis on using a thermal camera to determine RDP failure. Relying solely on the human eye, particularly under varying light conditions, may not provide a reliable assessment of whether the concrete surface is ice-contaminated or simply wet. This comparison is illustrated in Figure 5.

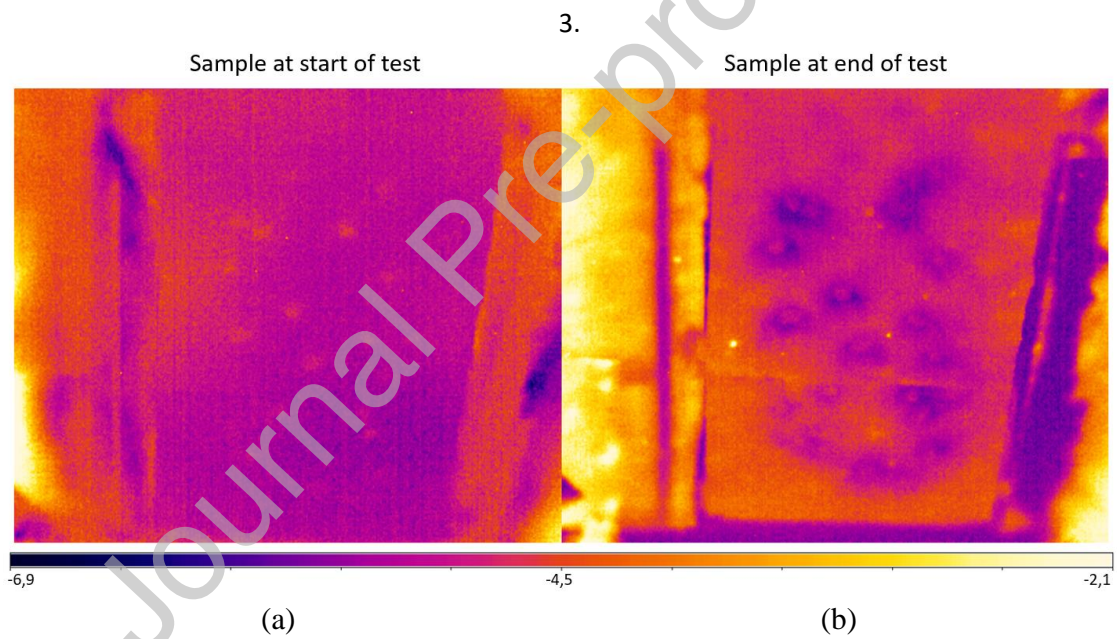




Figure 5 : Thermal images of the concrete sample at the start of the test at -5°C (a) and under a precipitation intensity of $6.5 \text{ g/dm}^2/\text{h}$ (b) along with corresponding visual photographs (c, d) of the block at the end of the NAFO pre-wetted with KAC test.

In Figure 5 (a), before the icing, we can slightly distinguish the grains of RDP on the thermal image because of a difference of emissivity between the them and the concrete. When the precipitation work (Figure 5 (b)), the thermal camera reveals the presence colder temperature zones around dissolved salt grains, showing the endothermal reaction due to their dissolution, and then higher temperature zones due to ice, showing and exothermal reaction of its occurrence. This ice formation corresponds with the icing protection time, the failure of the RDP once the concentration in salt is too weak with respect to ambient temperature to remain in the liquid state. This detection is made possible by the distinct temperature contrast between the ice and the surrounding surface, eased by the choice of a color scale. Conversely, the photograph in Figure 5 (c) demonstrates that under certain lighting conditions and viewing angles, the presence of ice may not be perceptible to the

naked eye, even though it is present due to precipitation and the negative surface temperature. In contrast, as illustrated in Figure 5 (d), the ice becomes clearly visible in appropriate lighting or observation. Consequently, the thermal camera proves to be a reliable and effective tool for identifying both RDP time of effectiveness and the onset of ice formation, considered as the RDP time of failure, independently of visible light conditions, with a greater accuracy than visual inspection.

The first series of tests involved maintaining a constant air temperature (-5°C), and a fixed quantity of RDP (0.5g NAFO and 0.35g KAC) while varying the precipitation intensity. The effectiveness time as a function of precipitation intensity is illustrated in Figure 6. As expected, the product's performance decreases as precipitation intensity increases. At a precipitation intensity of $5 \text{ g/dm}^2/\text{h}$, the icing protection time is 32.5 ± 2.5 minutes. When the intensity rises to $8.5 \text{ g/dm}^2/\text{h}$, the protection time reduces significantly to 17.5 ± 2.5 minutes. Further increasing the intensity to $13 \text{ g/dm}^2/\text{h}$ shortens the protection time to 12.5 ± 2.5 minutes. This shows a quasi-linearity in the results. To facilitate interpretation, a line connecting the data points has been added to the graph. These results are significantly different, demonstrating that the process is highly sensitive to variations in precipitation intensity. This trend aligns with our observations under operational conditions.

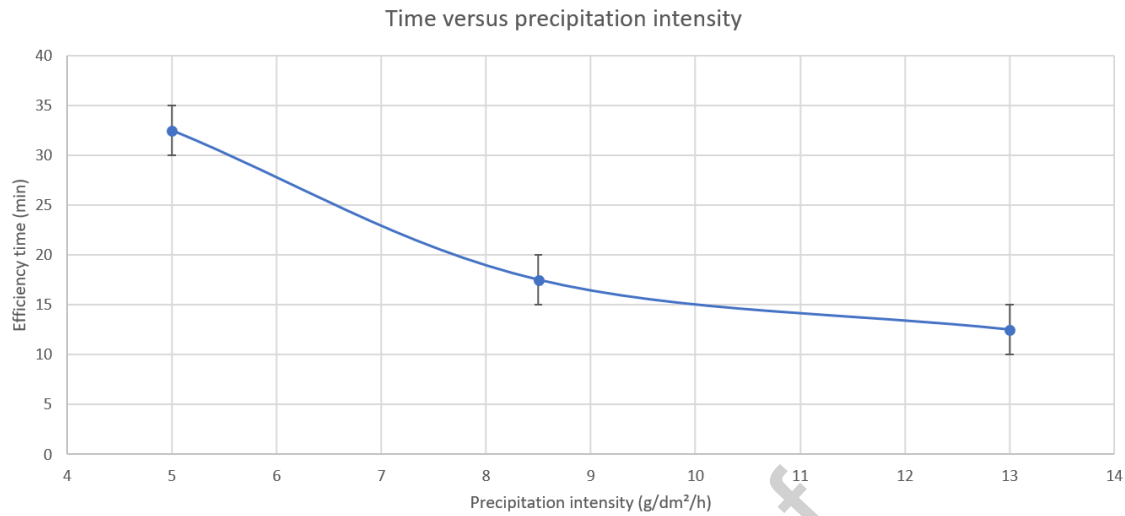


Figure 6 : Efficiency time (min) as a function of precipitation intensity (g/dm²/h) for NAFO pre-wetted with KAC (trend line added for visualization purpose)

The second series of tests focused on maintaining a constant precipitation intensity at 8.5 g/dm²/h and a fixed quantity of RDP of 0.5g NAFO and 0.35g KAC, while varying the test temperature. The temperatures values were determined using the standard governing tests on aircraft anti-icing and deicing fluids [33] and were set at -2°C, -5°C and -10°C. Results are presented in Figure 7.

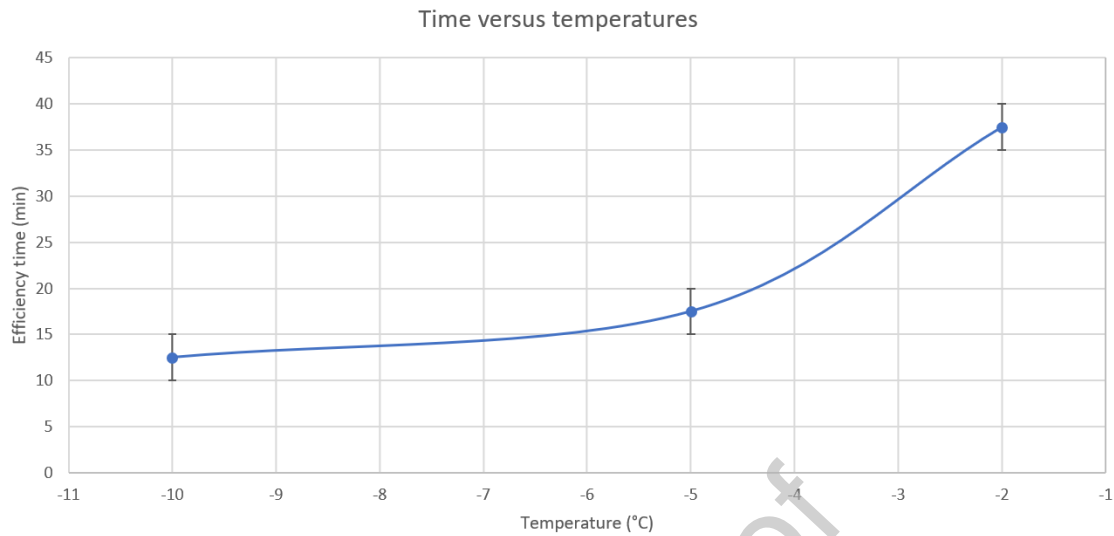


Figure 7 : Temperature (°C) versus time (min) for NAFO pre-wetted with KAC at 8.5 g/dm²/h and a fixed quantity of RDP of 0.5g NAFO and 0.35g KAC (trend line added for visualization purpose)

The lower the temperature, the lower the product's performance; conversely, the higher the temperature, the higher the product's performance.

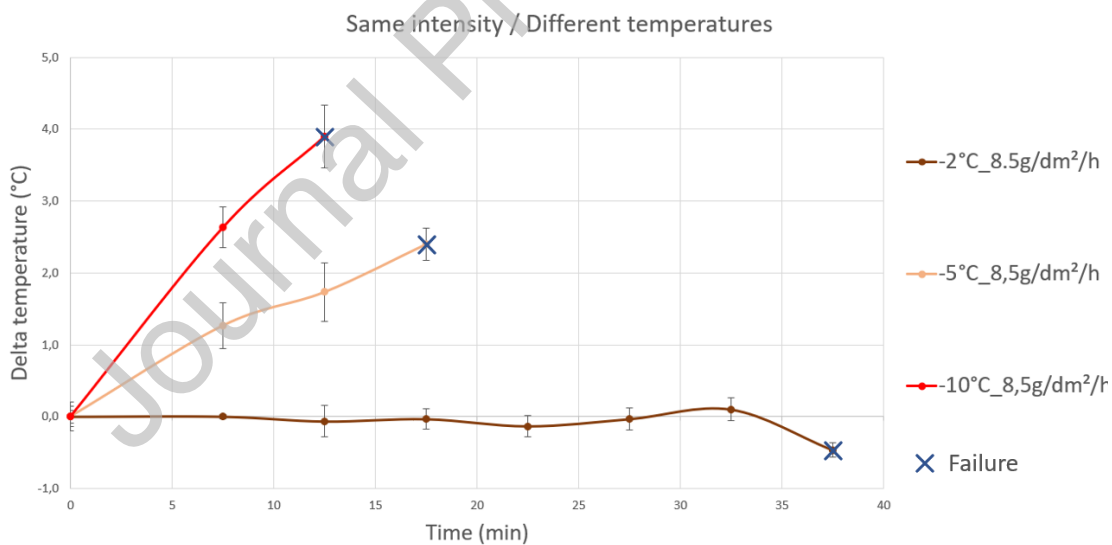
At a temperature of -10°C the icing protection time is 12.5 ± 2.5 minutes. When the temperature rises to -5°C, the protection time increases significantly to 17.5 ± 2.5 minutes. Further increasing the test temperature to -2°C increases the protection time to 37.5 ± 2.5 minutes. This shows a quasi-linearity in the results.

These results are significantly different, demonstrating that the process is highly sensitive to variations in temperature. This trend aligns with observations under operational conditions. To facilitate interpretation, a line connecting the data points has been added to the graph.

It is important to note that the standard deviations in these trends are quite large. This is primarily due to the fact that the concrete sample appears within the thermal camera's field

of view only once every five minutes because of the back and forth movement of the concrete sample below the wheel. It results in a failure time estimation with an error margin equivalent to this interval. Consequently, it is currently only possible to determine the failure time with a precision, of 2 minutes and 30 s. Enhancing the experimental setup by positioning thermal cameras at both the precipitation and wheel levels to continuously track the concrete block would significantly improve measurement accuracy.

As part of the testing process, the temperature variation during the cited test is carefully monitored to ensure the reliability and proper functioning of the apparatus, thereby guaranteeing accurate and reproducible results. Analysing time-dependent evolution of the minimum temperature on the surface of the concrete recorded throughout the tests provides valuable insights. The results for the three temperatures are presented on Figure 8.



(a)

Figure 8: Evolution of minimum temperature (°C) as a function of time (min) during a test with a constant precipitation rate (8.5 g/dm²/h) for NAFO pre-wetted with KAC

To ensure proper analysis and comparison, the data were treated as a difference from the initial temperature. The trials conducted at a precipitation intensity of $8.5 \text{ g/dm}^2/\text{h}$ at different temperatures (Figure 8) have a minimum temperature that increases until failure. This can be explained by the phenomenon detailed in the second phase of the study. Specifically, the deicing product applied onto the samples does not reach its maximum efficiency, as evidenced by the absence of a significant temperature drop during the test. This behavior suggests that the product's action is limited in terms of both its thermal response (temperature variation) and its duration of this variation which is related to the effectiveness under the given conditions. Consequently, the efficiency window of the product is relatively short for these specific samples and tests conditions. The results highlight the critical need to optimize the application rates and compositions of such products to ensure prolonged protection and enhanced thermal management under varying precipitation intensities.

In this context, monitoring the minimum temperature evolution throughout the test provides a valuable tool for characterizing product performance and identifying opportunities for improvement in operational applications.

The study subsequently focused on analysing the evolution of the minimum temperature of the protected concrete sample at a temperature of -5°C and a precipitation rate of $8.5 \text{ g/dm}^2/\text{h}$ representing the best compromise in terms of test conditions. The investigation examined the effect of mechanical activation speed specifically the waiting time between two successive passes under the ATS. In the first scenario, the block passes under the ATS every 5 minutes (blue curve) and in the second scenario, the block passes under the ATS every 2 min 30 s (orange curve). The two scenarios are presented on

Figure 9 and an example of one cycle described with all phases of the process is presented on Figure 10.

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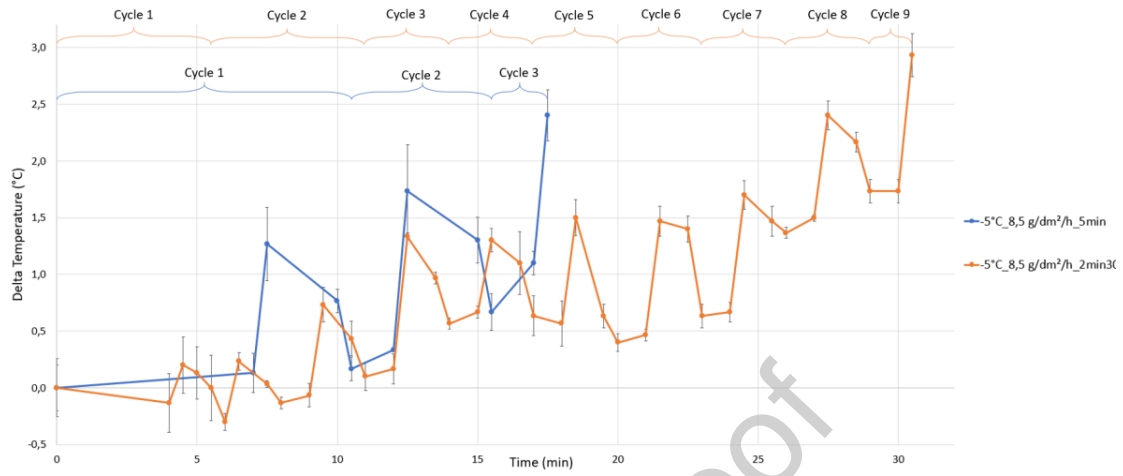


Figure 9: Evolution of minimum temperature (°C) observed according to waiting time for passage under the wheel as a function of time (min) for NAFO pre-wetted with KAC

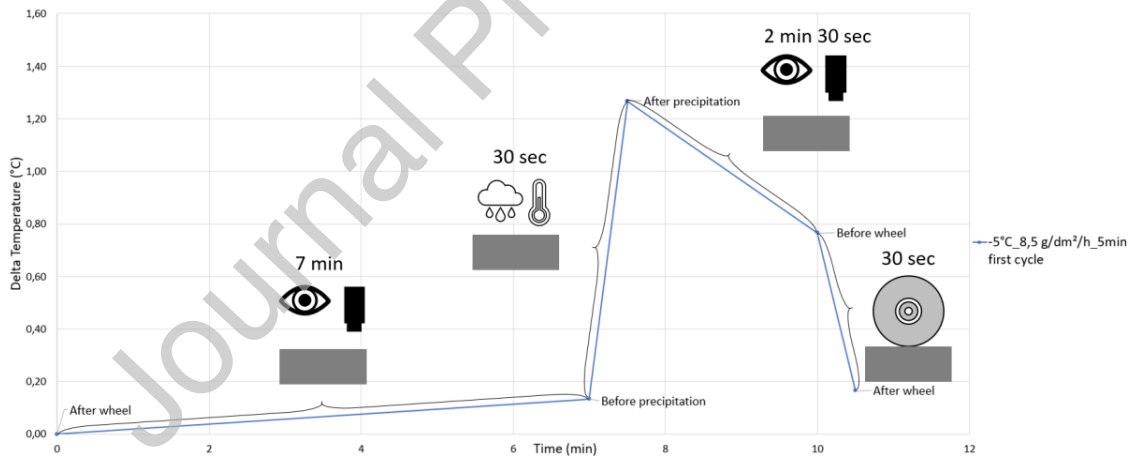


Figure 10: Example of one cycle described with all phases of the process.

The main pattern of each cycle is presented on Figure 11.

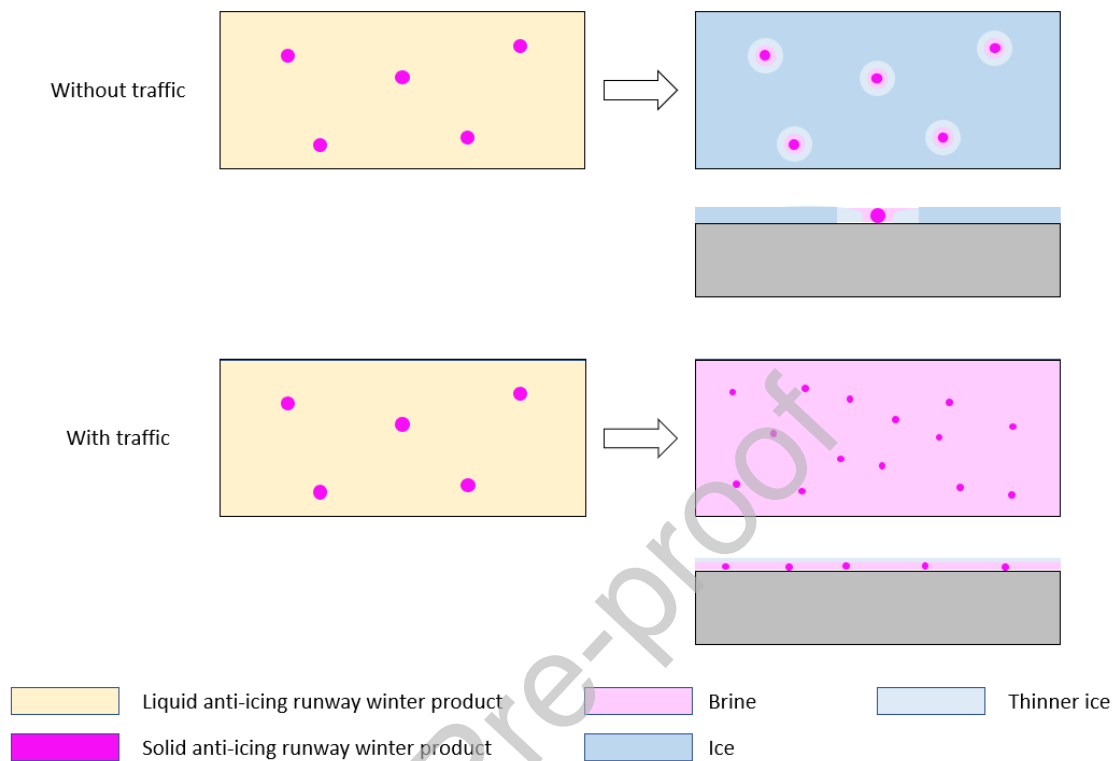


Figure 11 : Representation of the impact of mechanical activation on RDP under anti-icing conditions.

A typical cycle involves several sequential stages (Figure 10). First, the concrete block passes under the ATS, during which a slight decrease in temperature is observed due to the principle of mechano-chemical activation of RDP. This is followed by a waiting period, after which the block is exposed to precipitation, causing a slight increase in temperature of 0.1°C due to the precipitation temperature of 4°C and freezing of the water droplet on contact with the sample. Another waiting period ensues, during which the dilution reaction leads to a gradual temperature decrease. Finally, another passage under the wheel stage ends the sequence.

We can directly observe the impact of mechano-chemical activation on product performance under the same intensity of precipitation and temperature. Indeed, the minimum temperature increases with each pass over the block after precipitation and drops significantly after passing under the ATS. The speed of the moving table is sufficiently slow to ensure that each passage, along with the whole structure being at the test temperature, does not affect the surface temperature, resulting only a mechanical crushing of NAFO with the KAC solution and melted ice.

Furthermore, it is evident that the product's efficiency doubles when the sample is subjected to ATS every 2min30sec. This highlights mechanical activation as a beneficial and critical factor in enhancing the effectiveness of RDP as an anti-icing agent.

By ensuring that a spreader truck mechanically activates the product more frequently (2 min 30 s instead of 5 min), airports can increase the efficiency of RDP without requiring additional applications. This practice reduces the risk of runway saturation, save operational costs, prolongs the effective duration of the applied product and minimizes its dispersion into the environment, thereby contributing to more sustainable deicing operations.

The ATS demonstrates the benefits of mechanical activation on RDP efficiency through mechano-chemical processes. Frequent and consistent mechanical forces maximize the reactivity of RDP with available liquid water, enabling faster ice melting, better distribution, and reduced product use. This process is characterized by the fracturing and reduction of RDP particle sizes, the generation of larger reactive surfaces, and favoring mixing with the ice/brine solutions. These findings provide actionable and quantified

insights for integrating mechanical activation principles into runway deicing and clearance strategies.

On the upper part of Figure 11, it is evident that the absence of mechanical activation leads to significantly greater ice formation primarily due to the lack of disruption of the ice layer integrity, though weakens by the generation of brine and its local debonding from concrete surface. Without mechanical forces, the solid RDP only protect the surface at a fixed point, even the ice finish to form over the solid without any proper protection. While it demonstrates the RDP's efficiency at a single site, the product fails to adequately dissolve and disperse in the brine, limiting its long-term effectiveness. The brine created remains restricted to a small area, and while liquid RDP is initially effective in rapidly melting ice, it lacks longevity, leaving surrounding areas exposed.

In contrast, when mechanical activation is applied, the dynamics of the RDP's performance change drastically. The mechanical pressure eases the dissolution of the solid product more effectively into the brine, and forces the brine distribution evenly across between the ice layer and the runway surface. This results in the formation of a uniform protective layer that spreads over the runway surface. The brine formed in this process undermines the ice structure, making it more brittle and susceptible to weakening under traffic loads. The combined effects of mechanical activation and traffic stresses fragment the ice layer, facilitating its melting, as confirmed by ATS experiments, and eventual removal.

Moreover, the uniform distribution of brine created under mechanical activation enhances the RDP's effectiveness over a larger area and for a longer duration. The continuous exposure of ice to this distributed brine prevents the resurgence of strong ice bonds,

maintaining the protective layer and extending the period during which the runway remains free of contaminants.

In conclusion, we can summarize the RDP efficiency durations as a function of temperature and precipitation intensity (Table 2).

Table 2 : Efficiency duration of NAFO pre-wetted with KAC as a function of temperature and freezing drizzle precipitation intensity

	5 g/dm ² /h	8.5 g/dm ² /h	13 g/dm ² /h
-2 °C		37 min 30 sec ± 2 min 30 sec	
-5 °C	32 min 30 sec ± 2 min 30 sec	17 min 30 sec ± 2 min 30 sec	12 min 30 sec ± 2 min 30 sec
-10 °C		12 min 30 sec ± 2 min 30 sec	

The table shows that the product's efficiency time increases as the temperature rises and the precipitation intensity decreases. This relationship underscores the importance of considering weather conditions (current and to come) when determining the optimal application strategy for RDP. The table, developed using a defined protocol based on ATS and conditions derived from established standards, provides a practical framework for efficient product use.

However, these cells are only a small part of a bigger matrix covering a greater number of winter conditions that could be encountered. With this protocol, RDP can consistently be applied in the same quantity, while the waiting time between applications is adjusted according to prevailing weather conditions. This approach enables airports teams to

optimize their spreading campaigns by aligning product application with environmental demands. Moreover, these durations can inform runway maintenance schedules, establishing safe intervals for aircraft landings and take-offs during winter operations. By correlating efficacy times with operational needs, teams can better balance safety and efficiency.

However, while the protocol and data are promising, further testing is essential to refine these findings. Field tests under varying icing conditions, including snow accumulation and mixed precipitation scenarios, are necessary to establish accurate protection durations. These tests would provide critical insights into the product's performance across diverse environmental challenges and help validate its application strategy.

While the Airport Traffic Simulator (ATS) enables the reproduction of certain operational conditions encountered on chemically treated surfaces, several critical aspects related to mechanical activation remain insufficiently addressed within the current experimental configuration.

First, the effect of mechanical activation induced by wheel passage is inherently localized and confined to the contact trace of the tire. Although splashing or lateral redistribution of the product may occur, such effects fall outside the scope of the present study. In operational settings, it is unlikely that successive vehicle passages will follow identical trajectories. As such, the assumption that repeated passes will proportionally increase the extent of activation may not hold, and the overall efficiency of mechanical activation across a broader surface area remains uncertain.

Furthermore, the experimental apparatus operates at low speeds, which do not reflect the dynamic conditions typically encountered in airport ground operations. Parameters such as vehicle speed, wheel load, contact pressure, and vibrational characteristics may significantly influence the mechanisms of activation (e.g., shearing, film rupture, localized thermal effects), yet these are not currently accounted for in the simulation protocol. As a result, recommendations regarding increased traffic frequency must be interpreted with caution, given the simplification of dynamic inputs.

In summary, while the current protocol offers a solid foundation for optimizing RDP use, additional studies and field validation are crucial to ensuring reliable and safe winter maintenance practices across all operational conditions.

Finally, it should be noted that the granulometry of the chemical product used in the simulation reflects commercially available formulations specifically designed for runway applications. These products are characterized by fine particle sizes, optimized for adherence and uniform distribution, and smaller granules are not considered viable due to operational and safety constraints. Consequently, while granulometry can influence the mechanical interaction with the surface, its variability is limited in practice. The present study therefore relies on fixed, industry-standard granulometry, which aligns with current field usage but inherently restricts the scope for evaluating its effect as an experimental parameter.

The quantity of product applied is also a parameter. However, the quantities of products applied cannot be modified by the equipment available to the ADM research partner, so the study would have lost its practical value.

4. Conclusions

The mechanical activation of a solid deicer is considered as a way to enhance their efficiency during winter operations by operators. Nevertheless, the literature does not really provide elements to support these impressions of efficiency. The ATS was specifically elaborated to provide experimental and objective answers. The crushing of RDP on a contaminated surface has demonstrated that more frequent mechanical activation indeed significantly enhances the product efficiency as an anti-icing agent. In the case presented here, it is advisable for spreading trucks to pass as frequently as possible, as illustrated in Figure 9. Passing under the wheel every 2 minutes 30 seconds maintains runway protection for twice as long compared to passing every 5 minutes. This increased frequency is recommended to reduce both operational costs and the environmental impact on surrounding flora and fauna. Table 2 also highlights the importance of considering future weather data when planning spreading campaigns. Accordingly, it is strongly recommended to monitor conditions closely in order to prepare for timely reapplication. In particular, precipitation intensity and temperature are key factors that must be taken into account.

This innovative laboratory approach addresses a lesser-known operational challenge faced by airports: optimizing the application rate of deicing products on runways. Instead of increasing the quantity of product or introducing additional applications, this method suggests that spreader trucks simply have to pass over the runway again after the initial application, without dispensing additional product. Such a procedure activates the product

more effectively, extending its functional duration and reducing overall product consumption.

In addition, the product's efficiency time increases as the temperature rises and the precipitation intensity decreases. This relationship underscores the importance of considering weather conditions when determining the optimal application strategy for RDP.

Furthermore, this methodology allows RDP to be applied in consistent quantities, with waiting times between applications adjusted to suit weather conditions. This adjustment not only improves the efficiency of spreading campaigns but also aligns product use with operational needs, minimizing waste and reducing environmental impact.

The observed results are influenced by the time elapsed between runway cleaning and subsequent product application. However, for a more robust implementation, it is crucial to develop adaptive tools capable of responding to real-time changes in precipitation and weather conditions. Runways are expansive, and variations in precipitation intensity, type, and temperature across their length are common (e.g., low-intensity freezing drizzle at one end, high-intensity freezing rain at the other). By integrating robust sensors and artificial intelligence into spreader trucks, employees could access real-time data on weather conditions, product efficacy, and reapplication schedules, allowing for more precise and efficient maintenance operations.

To achieve this, additional studies under diverse weather conditions are necessary to build a comprehensive and representative matrix of configurations. The current results represent a foundational precursor to such a matrix. The deployed methodology can be expanded to

include data from various scenarios, such as dry snow, wet snow, freezing rain, and slush. Using advanced tools like Raman spectroscopy [34-37], it will be possible to monitor product concentration and surface temperature accurately. In fact, the inclusion of a Raman probe in the assembly following the block would provide real-time information on the concentration of the product, as well as its solid-liquid transition. To achieve this, the Raman spectrometer will need to be fitted with a grid plate, which will enable different grains to be analyzed simultaneously, thus enabling a representative average to be obtained for the test.

This integrated approach lays the groundwork for smarter, more efficient, and environmentally conscious runway maintenance strategies, ensuring optimal safety and sustainability in winter operations.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: