The Use of Sustained Release Technology to Reduce Deicing Salt Pollution

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ABSTRACT

The freshwater in North America are becoming increasingly saline due to the excessive production and use of salt, with road deicing salt being a major contributor. Every winter, an astonishing twenty million tons of road salt are applied to public roads in the U.S. for deicing, accounting for over 41% of the nation's total salt consumption. As these salts dissolve, they flow into streams, rivers, and lakes, posing severe threats to the environment, ecosystems, and infrastructure. This research aims to address this issue by reducing reliance on chloride-based deicers and developing a more environmentally friendly deicing system. To achieve this, we designed a core-shell structured capsule that enables the controlled and sustained release of deicing agents precisely when and where needed, and in the required amounts. The core-shell structures allow for the combination of natural deicers, such as beetroot juice, with chloride deicers in a unique manner. Beetroot is encapsulated within a NaCl particle-walled vessel using a rolling coating process, reinforced with a protective outer layer. When the capsule is applied onto icy roads and subjected to external compression (e.g., road traffic), the beet juice stored in the beetroot core is released, partially dissolving the sodium chloride to form a synergistic deicing composition. The structure of the core-shell prototypes was characterized, and their deicing performance was tested in both laboratory and small-scale field conditions. Preliminary data indicates that the method developed in this research effectively de-ices and can reduce salt usage by 35% under mild winter road conditions, offering a more eco-friendly and cost-effective deicing solution.

Introduction

Icy roads are the leading weather-related hazard in the USA [1], responsible for an average of 1,836 deaths and 136,309 injuries per year—more than 3.6 times the toll from all other severe weather hazards combined [2]. These incidents also result in millions of dollars in property damage and economic impacts. Road salting is a widely adopted practice in many regions and is considered highly effective for melting snow and ice on roads during winter or snowy weather conditions [3]. According to a report issued by the American Highway Users Alliance [4], road salt can reduce collisions by up to 85% during the winter season.

The use of salt for ice removal on roads began in the early 1940s in the United States [5], with New Hampshire pioneering the use of granular sodium chloride as early as 1938. By the winter of 1941-1942, a total of 5,000 tons of salt had already been spread on highways across the nation. Since then, the use of road deicing salt has surged dramatically [5]. According to the U.S. Geological Survey [6], the amount of deicing salt used on U.S. roads has increased from one million tons in 1954 to 10 million tons in 1985, and currently stands at approximately twenty-four million tons annually. This equates to around twenty million metric tons (2,200 lbs./metric ton) of salt being utilized for road deicing purposes in the U.S. each year, averaging about 123 lbs. per American. With such a vast amount of salt exposed to the environment, it causes serious damage to water, soil, and infrastructure.

One of the most pressing and concerning issues is that freshwater sources are becoming increasingly saline across North America [7]. Substantial evidence indicates a rapid increase in sodium chloride concentrations in North American freshwater streams, rivers, and lakes caused by road deicing salt over recent decades [8]. Take Lake Michigan as an example. With its expansive surface area of 22,300 square miles and a volume of 1,183 cubic miles, Lake

Michigan stands as the largest freshwater lake in the United States, holding an estimated 1.3 quadrillion gallons of water. Despite its vast size, the impact of road deicing salts on the chloride levels in the lake water is significant. Between the 1800s and 2020, chloride levels in Lake Michigan have risen from 1–2 to more than 15 milligrams per liter [9]. Scientists issue a grave warning that failure to promptly address salt overuse will lead to permanent and irreversible damage to the planet's freshwater resources. Once the salt content of water surpasses the threshold that nature can withstand, the consequences will be severe and irreparable [10].

To address this critical issue, a range of approaches involving both physical and chemical methods have been proposed and tested to reduce the usage of chloride deicers and minimize their impact on freshwater contamination. Among these approaches, the utilization of agricultural byproducts has emerged as a promising, environmentally friendly, and cost-effective method for ice removal on roads [11]. Various agricultural byproducts, including wood chips, corn ballast, coffee grounds, sawdust, wood ash, beet juice, concord grape extract, and glycerin, have been evaluated for their deicing potential, either individually or in combination with road salt [12]. Research indicates that these agricultural byproducts alone may not deliver sufficient deicing performance for practical applications. However, when combined with chemical deicers, they enhance the efficacy of the chemical deicers, enabling them to function effectively even at lower temperatures [13].

Another issue with the traditional salt deicing method is the prevailing overdosing problem [14]. Chloride road salts are usually spread directly onto roadways using specially equipped salt trucks. Once in contact with water or ice, these salts begin to dissolve. Even if the salt concentration on the road is sufficient to prevent icing, these salts will continue to dissolve until they are completely dispersed. This creates a significant amount of waste and pollution. A controlled deicing system is highly desired to address these issues caused by traditional salt deicers.

This paper reports on smart deicing pellets that can significantly reduce chloride usage while achieving a long-lasting deicing effect on icy roads. We designed a core-shell structure that allows for the controlled release of the deicing agent in a precisely controlled manner.

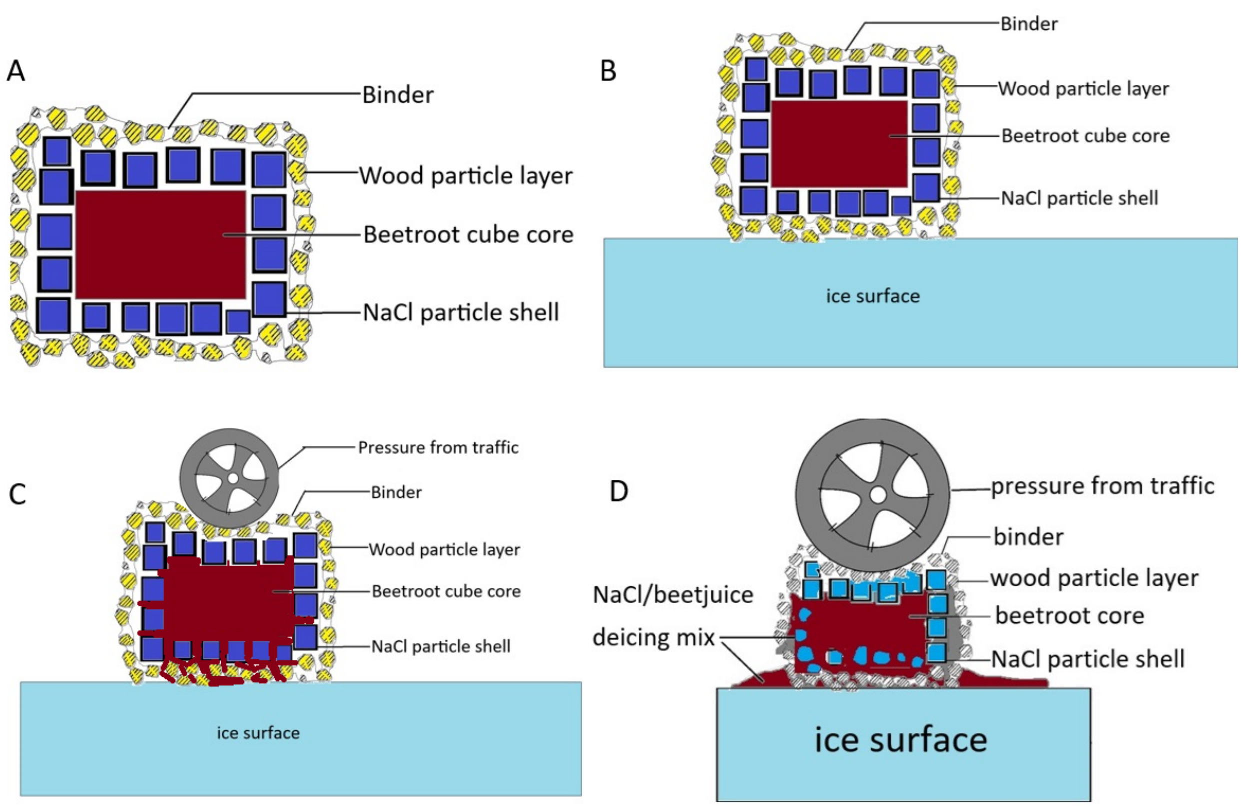

Figure 1. Schematic showing the design of the smart deicing pellets with core-shell structures. A. Design of the core-shell structured deicing pellet. B-D. Schematic showing the mechanism for achieving the controlled release of the deicing agent on the ice surface. B. Schematic illustration of the pellet applied onto the ice surface. C. Road traffic triggers the release process by squeezing the pellet to release the beet juice from the beetroot core. D. The beet juice permeates through the salt particle layer and forms a mixture of sodium chloride and beet juice composition to melt the ice.

Methods

Design Of a Smart Deicing Pellet with Novel Core-Shell Structures

The design of the smart deicing pellets with a novel core-shell structure is schematically shown in Figure 1. Figure 1A presents a drawing of the core-shell structured deicing pellet. First, it has a cubic-shaped, fresh-cut beetroot core. Second, the beetroot cubic core is covered by a salt particle-walled shell. Third, the deicing pellet is further coated with a protective barrier, which could consist of fine wood powders or sand particles. The purpose of this design is to achieve controlled release of the deicing agent (salt and beet juice). The controlled release mechanism is schematically illustrated in Figures 1B-1D. Figure 1B shows that when the core-shell structured deicing pellet is applied onto the ice surface, due to the presence of the protective barrier layer, no immediate deicing occurs at this point because the protective barrier prevents the ice from contacting the salt and beet root core. Figure 1C presents a schematic showing that when the pellet is subjected to external pressure, such as traffic on the road (illustrated in Figure 1C with a wheel on top of the deicing pellet), the beetroot core is compressed and squeezed, releasing the beet juice contained within. As the beet juice permeates through the layer of salt particles, part of the salt dissolves into the beet juice, forming a mixture of sodium chloride and beet juice, as demonstrated in Figure 1D. Under pressure, the outermost barrier layer fractures, allowing the sodium chloride and beet juice mixture to contact the ice, initiating the melting process. Additionally, the presence of the protective layer ensures that the deicing mix penetrates slowly, achieving a long-lasting, slow-release effect. In the experimental section, we will show how the core-shell structured deicing pellets were prepared.

Preparation of the Core-Shell Structured Deicing Pellets

The core-shell capsules were prepared using a rolling coat process. First, freshly cut beetroot cubes, sized between 2-5 mm, were initially poured onto a bed of salt particles. The salt bed was continuously shaken to ensure the beetroot cubes rolled and became completely coated with salt particles. In this process, the beetroot's sugar juice acted as a binder, adhering the salt particles to the surface of the beetroot cubes. Multiple layers of the salt particles were coated onto the beetroot cube. Next, the salt-coated beetroot cubes were transferred to a bed of sand or fine wood powders, which contained 2% cellulose or starch if needed as binder. Using the same rolling procedure, the beetroot cubes were further coated with the sand or wood particles. Finally, the samples were rapidly dried at 75℃ for approximately 2 minutes to ensure the outermost layer was dry. To show the step-by-step making process, a snapshot of each step is taken and presented in Figure 2.

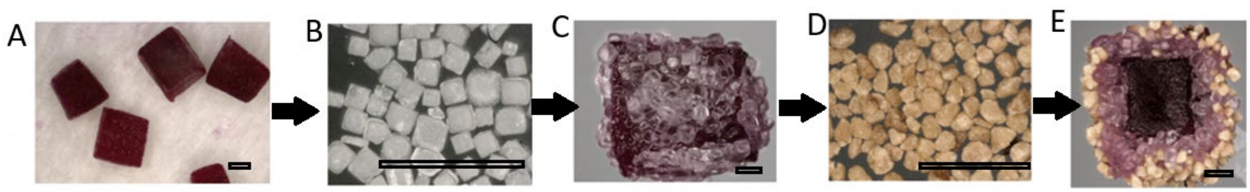

Figure 2. Step-by-step process of making the core-shell structured deicing pellets: A. Cube-shaped beetroot core, B. Sodium chloride particles, C. NaCl particle-covered beetroot cube, D. Fine wood powders, E. Cross-section view of the core-shell structured deicing pellets (bar = 1 mm).

Results and Discussion

Characterization of the Core-Shell Structured Deicing Pellets

The shape and size of the beetroot core, sodium chloride, wood powder, and the final core-shell structure of the deicing pellets were investigated under a digital microscope (OMAX 40X-2500X Digital LED Trinocular Lab Compound Microscope). Figure 2 shows the step-by-step process of making the core-shell structured deicing pellets. Figure 2A presents a microscope image showing the size and shaped of the freshly cut beetroot core. They have cubic shape with the size between 3-5mm. Figure 2B presents the microscope image of the NaCl salt grains. It reveals that the sodium chloride grain has the typical cubic shape with the grain size between 50-200um. Figure 2C shows a beetroot cube core that has been fully coated with the salt grain shell. Figure 2D shows the fine wood powder under microscope. The fine wood particles have irregular round shape with the size between 50-200um. Figure 2E show the cross-section view of the final beetroot-core/salt particle-shell pellet covered with the fine wood powder barrier layer. From the image in Figure 2E, the beetroot cube core, the NaCl particle shell, and the fine wood powder barrier layer can be seen clearly from the image. The microscopy images presented in Figure 2 confirm that the deicing pellet with well defined core-shell structures can be achieved with the rolling coating process. By using this method, about 5lbs of deicing pellet sample were prepared.

The construction of the core-shell structured deicing pellets was further revealed in Figure 3. Figure 3A shows a microscopy image of the core-shell structured deicing pellets observed from top view. It confirms that the deicing pellets are fully covered with the fine wood barrier layer. The deicing pellet sample was carefully cut with a razor knife to expose the inside of the pellets, and its cross-section view image was presented in Figure 3B. It shows that the size of the pellets is about 3mm, the beetroot core is about 1-1.5 mm, and the thickness of the NaCl particles wall is about 0.2-0.5 mm, and the thickness of the fine wood protective layer is less than 0.2mm. The results in Figure 3 confirms that we have successfully prepared the core-shell structures we designed in Figure 1.

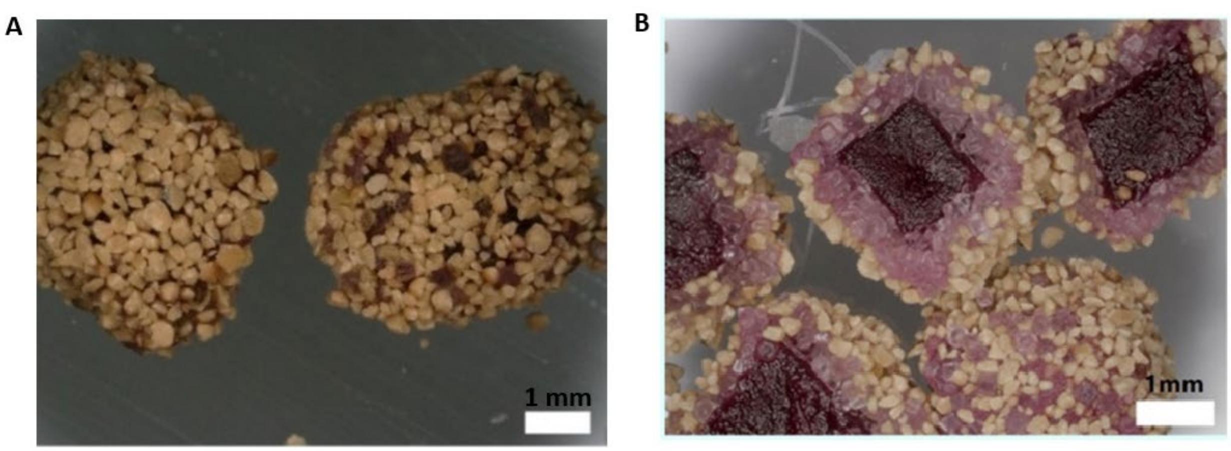

Figure 3. Microscope images of the core-shell structured deicing pellets. A. Top-view, B. Cross-section view (bar = 1mm).

Testing the Controlled Releasing Mechanism

As mentioned in the introduction, the goal of this research is to develop a smart deicing system that enables controlled and sustained release of the deicing agent to reduce waste and pollution. The mechanism to achieve controlled release has been proposed in Figure 1. In this section, we will test to see if the proposed mechanism works or not. To clearly observe the controlled releasing process, the test was conducted in a small glass tube to better showing the controlled releasing process. The test was conducted in a cool environment with an air temperature around -4℃. The test was carried out as the following procedure: one gram of the deicing pellet with core-shell structures was placed in a glass tube containing about 10 grams of fully frozen ice. Due to the presence of the wood particle protective layer, the deicing agents (salt and beet juice) were prevented from contacting the ice, and no deicing was observed, as shown in Figure 4A. After pressing the sample with a pencil, the beetroot core was compressed and squeezed, releasing the beet juice contained within (as shown in Figure 4B, the red color is the natural color of the beet juice), forming a beet juice/NaCl mix that started to melt the ice. Due to the existence of the wood particle protective layer, the beet juice/NaCl mix was slowly released to melt the ice, as seen in Figure 4C the red color of beet juice/NaCl slowly moving to the bottom of the tube. The results in Figure 4 confirm that the mechanism proposed in Figure 1 worked as designed. In the next section, we will test the deicing performance of the samples.

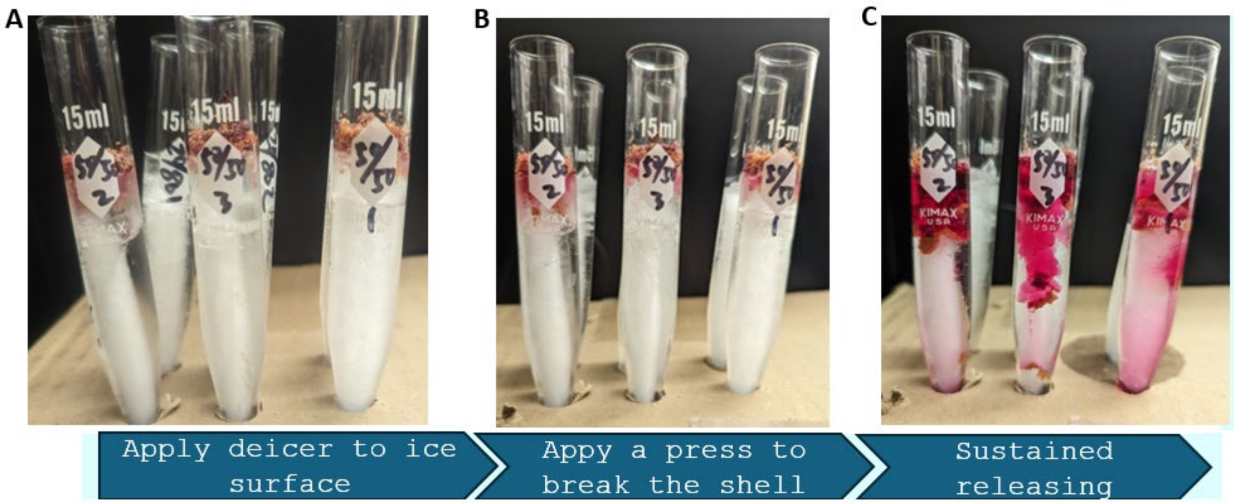

Figure 4. Testing the controlled releasing mechanism. A. Place 1.0g deicer sample in the tube holding about 10g ice. B. Apply a press on the sample surface with a pencil eraser to trigger the releasing process. C. The core-shell structured deicing pellets continuously release deicing mix (the red color is from the nature color of beet juice) to melt the ice.

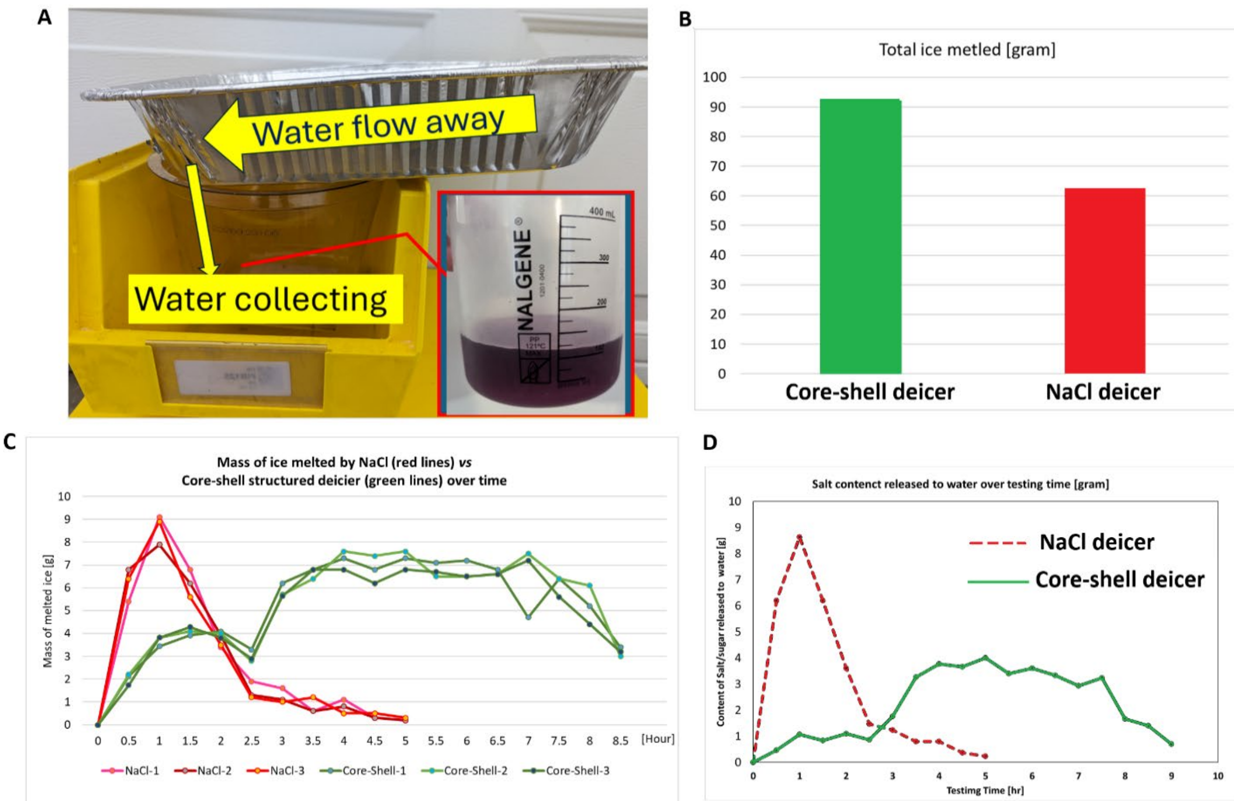

Figure 5. Deicing performance testing setup and results. A. Setup for deicing performance test. B. Bar graph showing the total ice melted by NaCl control deicer (red) and the core-shell structured deicer (green). C. Ice melted by NaCl control deicer (red) and the core-shell structured deicer (green) over time. D. Content of salt/sugar released to water over time.

Testing The Deicing Performance of The Sample

The deicing performance of the deicer was evaluated by measuring how much ice a 50 g deicer sample can melt in 8 hours at -7±1°C. The test was conducted in an aluminum pan (pan-test). In the pan-test, a fully frozen ice sample measuring approximately 8x11x0.5 inches and weighing 500±5 g was placed in an aluminum foil pan tilted at a 15-degree angle to allow the melted water to flow through holes at the bottom edge of the pan, and then collected in a beaker, as shown in Figure 5A. A 50 g sample of deicers was spread uniformly on the surface of the ice. The surface of the ice was pressed with a rubber roller to initiate the releasing process. The resulting melted water was collected in a glass beaker via a funnel. At 30-minute intervals, the melted water was collected in a sealed bottle, and its weight was measured and recorded.

The sodium chloride or sugar content in the water was determined using the dry-weighing method. This involved weighing 1.00 g of the melt water, placing it in a glass dish, and drying it in an oven at 80 degrees Celsius for 1 hour. The weight of the glass dish was then measured and recorded to calculate the concentration of sodium chloride or sugar in the water. In this study, pure NaCl grains (table salt) were used as a control deicer. The setup for the testing and the results are presented in Figure 5.

Figure 5A shows a snapshot of the setup for the deicing performance test. Using this testing setup, the deicing performance of the pellets with core-shell structure and the pure sodium chloride control sample was tested. Figure 5B presents a bar graph showing the total ice melted by the core-shell structured deicer (green bar) and the control

NaCl deicer (red bar). It shows that the core-shell structured deicer melted about 92 g of ice, while the NaCl control deicer melted about 63 g of ice. Theoretically, sodium chloride salt is one of the most effective deicing agents and should melt more ice than the core-shell structured deicer, which contains 30% less salt. The reason is that most of the salt dissolved in the water and flowed away with the water. According to the freezing point depression theory [15], to prevent water from freezing at -7±1℃, the salt content should be around 10% which means that the 50g sodium chloride should be able to melt the 500g of ice under idealized conditions. However, the results in Fig. 5B show that 50 g of NaCl melted less than 1/5 of the ice, which is mainly due to the fact that most of the 50 g of NaCl flowed away with the melted water. The data in Figure 5C and Figure 5D support this hypothesis. Figure 5C presents a graph showing how much ice each deicer melted over time. As one can see, pure NaCl is indeed a highly efficient deicer as it works fast and melts three times more ice within the first hour, but its effectiveness drops quickly after 2 hours. In contrast, the deicing pellets with core-shell structure work slowly because it takes time for the beet juice to penetrate through the shells and dissolve the salt. Once the beet juice/salt mix reaches the ice surface, it starts to melt the ice. The deicing pellets continue releasing the juice/salt mix for another 5 hours. This hypothesis is further supported by the data in Figure 5D. The graph in Figure 5D shows the salt/sugar content released into the water during the deicing test. As one can see, most of the sodium chloride was released into the water within the first 2 hours as the pure sodium chloride quickly dissolved and flowed away. In contrast, the core-shell structured deicer slowly released salt/sugar and continued releasing the salt/sugar mix for an additional 5 hours. The results in Figure 5 further confirm that the core-shell structured deicing pellets worked as designed to achieve a sustained release rate over a longer period.

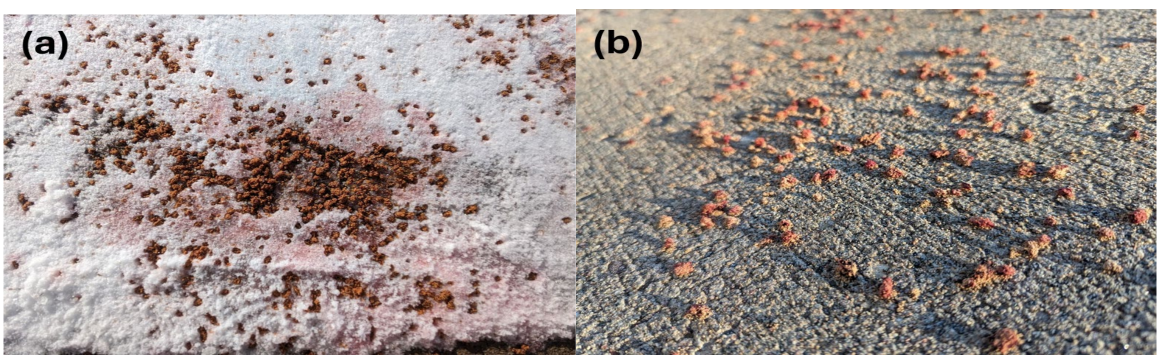

Figure 6. Figure 6A presents a photo showing when the core-shell structured deicing pellets dropped onto ice surface. Figure 6B presents a photo showing after the ice has been melted and the residual of the deicing pellets.

A small area field test was conducted under natural conditions to explore the possibility of recycling the residual of the deicing pellets to further reduce their impact on water and the environment. Figure 6A presents a picture showing the deicing pellets applied onto an icy surface for deicing. Figure 6B presents a picture showing the "leftovers" of the deicing pellets after the ice has melted. The used pellets can be recovered by either vacuuming or sweeping with a broom, as the undissolved salt is still "held" by the barrier layer, as shown in Figure 6B.

Conclusion

With the aim of reducing deicing salt pollution in freshwater, this paper proposes and tests a smart deicing concept with great potential for practical applications. The paper designs a novel core-shell structured capsule in which the deicing agent is embedded at the center to achieve sustained release properties. Furthermore, the core-shell structure designed in this paper allows for the combination of chloride deicer with beet juice, a widely used natural deicer, in a unique way to form a synergized deicing mix, thereby further reducing the required dose of chloride deicer. Additionally, the deicing capsules developed in this paper can be recycled and reused. The core-shell structured deicing capsules can be manufactured in large quantities for real-world applications. Preliminary data show that the method developed in this research effectively deices and can reduce salt pollution by 35% in water under mild winter road conditions, offering a more eco-friendly and cost-effective deicing system. Considering that beetroot is cheap and easily accessible, the core-shell structured deicers developed in this study can be produced on a large scale and have the potential to be used in practical applications.

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