

Article

Insights into Sea Spray Ice Adhesion from Laboratory Testing

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Abstract

Ice accretion from marine icing events accumulating on structures poses a significant hazard to ship and offshore operations in cold regions, being relevant for offshore activities like oil explorations, offshore wind, and shipping in arctic regions. The adhesion strength of such ice is a critical factor in predicting the build-up of ice loads on structures. While the adhesion strength of freshwater ice has been extensively studied, knowledge about sea spray ice adhesion remains limited. This study intends to bridge this gap by investigating the adhesion strength of sea spray icing under controlled laboratory conditions. In this study, we built a new in situ ice adhesion test setup and grew ice at -7°C to -15°C on quadratic aluminium samples of 3 cm to 12 cm edge length. The results reveal that sea spray ice adhesion strength is in a significantly lower range—5 kPa to 100 kPa—compared to fresh water ice adhesion and shows a low dependency on the temperature during the spray event, but a notable size effect and influence of the brine layer thickness on the adhesion strength. These findings provide critical insights into sea spray icing, enhancing the ability to predict and manage ice loads in marine environments.

Keywords: ice adhesion strength; marine icing; sea spray icing; icing conditions; brine layer



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1. Introduction

Marine icing events pose significant dangers for the shipping industry and off-shore operations in cold regions. The danger is caused by spray ice accretion on structures, which can lead to slippery surfaces, disabled life boats, the capsizing of vessels, or the buildup of critical loads on off-shore structures. The common method to remove icing is thermal and mechanical de-icing, which is either energy-consuming and expensive or dangerous for the crew. The majority of research on sea spray ice focuses on the prediction of icing events, determining the spray generation and ice growth parameters to be implemented in the weather forecasts. After the loss of several vessels in the 1960s, research in spray icing started with cataloguing icing events, and identified the type of vessel, direction in which it was heading, wind speed, and wave height to be important parameters to determine the severity of icing [1–3]. Those findings lead to first icing warnings in operational weather forecasting [4–6]; see ref. [7] for a review. Recent research focuses on the mass and heat balance during icing events to ultimately increase the accuracy of spray icing models.

More detailed icing prediction involves three processes—(i) droplet generation, (ii) droplet movement and trajectories towards a structure, and (iii) droplet freezing. Two types of droplet generation are involved in marine icing events. The first is wave

spray, where droplets are generated from the interaction between waves and structure, creating a burst of upwards-moving water droplets when breaking the waves. The second is wind spray, where droplets are carried by wind from the wave crests or bursting air bubbles [8–11]. The size of the generated droplets varies; for wave spray they are in the range of 10–7000 μm in radius [12,13], while for wind spray the radii vary from 0.5 to 500 μm [14]. Afterwards, the droplets are transported by the wind and eventually impact the structure, where they freeze and form an ice layer. During the freezing process, the brine is expelled from the building ice matrix and becomes entrapped in brine pockets, as well as being pushed to the surface to form a brine layer. These brine pockets and channels form defects in the ice matrix and influence the physical properties of the ice. The size of the brine pockets depends on the speed of freezing and the salinity during the spray event *citepmakkonenSalinityGrowthRate1987b*. The speed of freezing in turn depends on the spray availability (mass flux), as well as the heat balance.

Unlike most adhesion science, ice adhesion research is largely driven by the aim of reducing the adhesion strength [16,17], or delaying ice nucleation and growth [18,19]. The majority of anti-icing research focuses on freshwater adhesion, as this is the dominant form of icing in aviation, power cables, and atmospheric icing. Recently, the interest in saline icing due to its influence on offshore operations in (sub-)arctic regions has increased, but a full examination of the impact of growth conditions on the adhesion strength of ice is missing, as well as adhesion data for high-salinity ice. Zhang et al. [20] tested the saline adhesion strength for temperatures from -50 to -20 $^{\circ}\text{C}$ and salinities of up to 9‰. Mu et al. [21] examined the effect of wind speed 6–15 m/s and temperature -3 to -15 $^{\circ}\text{C}$ on icing and ice adhesion for a liquid water salinity equivalent to about 1 to 20‰, and focused on airfoil blades. These studies show a reduced adhesion strength by one to two orders of magnitude when compared with freshwater ice. This can be partly explained by the formation of a salt-free porous matrix during the freezing of saline ice. As the freezing process is not unlimitedly slow, the brine that is rejected from this matrix increases in salinity and becomes trapped in so-called brine pockets. These pockets act as defects in the ice matrix and decrease the effective solid–solid area at the interface between the ice and the structure. According to Makkonen [22], the decreased interface can not account for the decrease in adhesion that can be observed when comparing saline and freshwater ice. He suggests that a brine layer forms at the interface during the freezing process and further reduces the saline ice adhesion. While the adhesion strength is influenced by various factors, including the nature and purity of the accreted ice, the surface texture, the material properties and roughness of the material on which ice accretes, and environmental conditions such as temperature, humidity and mass transport, the salinity is the leading factor in ice adhesion [23].

We approach the icing problem from a different angle, focusing on the ice–structure interaction in form of the adhesion of spray ice and the impact of growth conditions on the adhesion strength. Understanding the adhesion characteristics of spray ice will provide valuable insights for developing targeted strategies to reduce icing hazards, ultimately improving safety and operational efficiency in cold marine environments. In this work, we present an experimental study on the adhesion of laboratory-grown sea spray ice formed from high-salinity water 32–35 ‰ in a cold laboratory environment. Our study mostly focuses on the effect of three parameters on icing—temperature, accretion rate, and size—that we investigate under controlled settings in the laboratory. To establish a comprehensive understanding of the relationship between growth conditions and ice adhesion, we integrate ice growth observations with in situ temperature measurements obtained through infrared (IR) imaging. Additionally, we employ specialized adhesion testing module within the experimental setup, enabling us to quantify the adhesion strength

under varying conditions. To better understand the difference in growth conditions and parameters, and their impact on ice adhesion, we performed X-ray micro-tomographic imaging to obtain the 3D microstructure of the sea spray ice [24]. This multifaceted approach not only enhances our understanding of ice adhesion mechanisms but also provides critical insights that could inform the development of more effective anti-icing strategies for offshore structures in saline environments.

2. Theoretical Framework

Saline spray ice is a porous material, for which the fractions of ice, brine, and air change with temperature, resulting in properties that are distinct from those of pure ice. This section outlines the theoretical framework and analytical methods to estimate these volume fractions based on the equilibrium thermodynamics of the ice–brine mixture. It involves liquidus equations between brine salinity and temperature, and an established relationship between temperature, brine salinity, and the density of brine and ice, and observations of ice salinity. Additionally, equations for the expulsion of brine during internal freezing are given, which are relevant for ice salinity and the analysis of ice adhesion. Ice adhesion strength is quantified using force–displacement data, with adhesion calculated from the maximum force and theoretical contact area.

2.1. Ice Adhesion

$$\sigma = \frac{F_{\max}}{A}. \quad (1)$$

The adhesion strength σ is calculated based on Equation (1), where $F_{\max}$ is gained from a force displacement diagram that is recorded with the force transducer. A is the sample plate surface normal to the air and sea spray flow. The sample plates have an edge length L of 3–12 cm, but the corners are rounded with the radius $r = 0.02$ cm, resulting in $A = L^2 - (4 - \pi)r^2$. We can neglect the corner correction with a relative area increase of less than 10^{-4} for our sample holders. However, as we shall see below, the contribution of the lateral surfaces in the thickness direction of the sample plate (by edge overgrowth) can play a significant role. We observed that the lateral edges and the lower edge were often covered with overgrowing ice, which will be discussed in detail in Section 5.3. These three edge surfaces contribute an additional of $3DL$ to the effective plate surface, where D is the thickness of the sample plates. Hence, the surface needs to be corrected to

$$A_e = A(1 + \frac{3D}{L}). \quad (2)$$

In the following, we will first analyse the strength based on A , and the edge overgrowth effect will be considered later. Hence, the adhesion values provided are upper bounds.

The contribution of gravitational forces, in addition to the loading force, is given by the following:

$$F_g = M_i g, \quad (3)$$

where M_i is the mass of the ice sample, and $g = 9.819 \text{ m s}^{-2}$ is the gravitational acceleration. This force ranges from approximately 0.02 to 4.5 N, significantly smaller than the contribution of $F_{\max}$.

2.2. Brine Salinity and Volume Fraction

The salinity of an ice sample S_i is defined as the fraction of the salt mass and the total mass of the ice sample, with m_{pi} , m_s , and m_{pw} being the masses of pure ice, salt, and pure water in the spray ice matrix, respectively.

$$S_i = \frac{m_s}{m_{pi} + m_s + m_{pw}}. \quad (4)$$

Similarly, the salinity of brine S_b is defined as the fraction of the salt mass and the total brine mass:

$$S_b = \frac{m_s}{m_s + m_{pw}}. \quad (5)$$

In thermodynamic equilibrium, the temperature T_f and salinity S_b of brine are related by a liquidus relationship, defining the temperature at which the brine begins to freeze at a given salinity. We use the following relationship for the aqueous NaCl solutions proposed by Maus [25]:

$$T_f = -0.05818 S_b (1 + 6.5067 \times 10^{-4} S_b + 5.6015 \times 10^{-6} S_b^2 - 9.2265 \times 10^{-9} S_b^3) \quad (6)$$

for the tabulated values above 18 and up to 235‰ and

$$T_f = -0.06286 S_b (1 - 0.03223 S_b^{1/2} + 0.005009 S_b - 0.0001549 S_b^{3/2}) \quad (7)$$

for the tabulated data between 1 and 50‰. T_f is given in °C. While the latter equation is more accurate for low salinities and natural seawater, the difference between these equations in the range 18 and 50‰ is less than 0.006 °C. To estimate S_b from T_f the following inversion is used:

$$S_b = 0.001609412 x^9 - 0.03466275 x^8 + 0.3053039 x^7 - 1.415099 x^6 + 3.79249 x^5 - 6.459237 x^4 + 5.802355 x^3 + 14.847938 x^2 + 0.05434995 x + 0 \quad (8)$$

where $x = \frac{1}{\sqrt{-T_f}}$. This equation is valid down to a temperature of -21.6 °C (brine salinity 235‰), where the transition from brine into solid salt starts. Equation (8) is mostly used in the present work (Note that there is no standard for the freezing temperature of brine. Based on the discussion of available datasets by [25], the relative accuracy of Equation (8) is probably better than 0.5%).

During the cooling of an ice brine mixture, more ice successively forms, rejects the solute, and increases the brine concentration S_b to remain in thermodynamic equilibrium with the lower T_f . Considering that the ice has a volume V and the brine occupies a volume V_b , the brine volume fraction v_b is then given as follows:

$$v_b = V_b/V = \frac{1}{1 + \left(\frac{S_b}{S_i} - 1\right) \frac{\rho_b}{\rho_i}}, \quad (9)$$

where ρ_b and ρ_i are the brine and pure ice densities, S_i is the bulk ice salinity, and S_b is the brine salinity.

2.3. Densities of Ice and Brine

The average density of a porous medium composed of multiple constituents is calculated as the weighted sum of the individual densities (ρ), each multiplied by its respective

volume fraction. For spray ice, these are the volume fraction of brine (v_b), of air (v_a), and of pure ice ($v_i = 1 - v_b - v_a$), leading to the bulk ice density ρ .

$$\rho = \rho_i(1 - v_b - v_a) + \rho_b v_b + \rho_a v_a \approx \rho_i(1 - v_b - v_a) + (\rho_w + \beta S_b)v_b \quad (10)$$

where ρ_i is the density of pure ice. In the right hand expression, the air density ρ_a has been neglected and ρ_b of brine was approximated as

$$\rho_b = \rho_w + \beta S_b \quad (11)$$

based on the density of pure water ρ_w and an effective haline contraction coefficient $\beta = d\rho_b/dS_b$. The brine volume fraction v_b in this study was determined using Equation (9) based on the observed salinity of ice S_i and the temperature T_f (and the corresponding equilibrium salinity of the brine S_b). Standard measurements of v_a , based on volume and weight, would be highly uncertain for our small samples e.g., [26]. However, the micro-CT data discussed below provided high-precision measurements of air volume fraction and ice density.

For the calculations in this paper, we use $\rho_i = 0.917 \text{ g cm}^{-3}$, with $\rho_w = 1 \text{ g cm}^{-3}$ and $\beta = 0.8 \text{ g cm}^{-3}$ per weight fraction salt. Bulk ice density is computed for some micro-CT examples (see Section 4.4 below); however, in all computations based on ρ (brine layer thickness, effective ice thickness), we use a constant $\rho = 0.94 \text{ g cm}^{-3}$, which corresponds to a sample with 1% air volume and 15% brine volume fraction at -10°C .

2.4. Expulsion of Brine

The cooling and internal freezing of the saline ice implies a process known as expulsion. This is related to the density change during internal freezing and the phase change of brine, and was first quantitatively described by Cox and Weeks [27] in connection with the storage and cooling of sea ice samples. Expulsion implies that some brine is pushed out of a sample and may be lost in that way, decreasing the salinity of the sample. Makkonen [22] has discussed the significance of this process for the adhesion of saline ice. His derivation is based on the ice bulk salinity change when cooling a sample from T_1 to T_2 , that has been derived by Cox and Weeks [27] as follows:

$$\frac{S_i(T_2)}{S_i(T_1)} = \left(\frac{S_b(T_2)}{S_b(T_1)} \right)^{\left(1 - \frac{\rho_w}{\rho_i}\right)} \left(\frac{\rho_w + \beta S_b(T_2)}{\rho_w + \beta S_b(T_1)} \right) \exp\left(\frac{\beta}{\rho_i} (S_b(T_1) - S_b(T_2)) \right). \quad (12)$$

where $S_i(T_1, T_2)$ denotes ice bulk salinity and $S_b(T_1, T_2)$ brine salinity depending on temperature. To derive this equation, the density ρ_i of pure ice was assumed to be constant (neglecting its temperature dependence) and the density ρ_b was approximated by Equation (11).

Equation (12) may be rewritten in terms of the salinity change as follows:

$$S_i(T_2) - S_i(T_1) = S_i(T_1) \left(\left(\frac{S_b(T_2)}{S_b(T_1)} \right)^{\left(1 - \frac{\rho_w}{\rho_i}\right)} \left(\frac{\rho_w + \beta S_b(T_2)}{\rho_w + \beta S_b(T_1)} \right) \exp\left(\frac{\beta}{\rho_i} (S_b(T_1) - S_b(T_2)) \right) - 1 \right). \quad (13)$$

Makkonen [22] assumed that the expelled brine creates a liquid brine layer on the surface of the ice, which may reduce adhesion if the surface corresponds to a ice–substrate interface. To derive that brine layer thickness, Makkonen [22] assumed that brine is equally

expelled to all surfaces during the cooling of an ice cube from temperature T_1 to temperature T_2 . The mass of expelled salt m_s may be written as

$$m_s(T_2) = M(S_i(T_1) - S_i(T_2)), \quad (14)$$

where S_i is the salinity of the ice and M_i the mass of the ice sample (including brine and ice). The mass of expelled brine m_b during cooling from T_1 to T_2 is then given by

$$m_b(T_2) = \frac{m_s(T_2)}{S_b(T_2)}, \quad (15)$$

where S_b is the salinity of the brine. Assuming the expelled brine forms a liquid layer on the ice surface with an area A , its thickness d_b can be expressed as

$$d_b(T_2) = \frac{1}{\rho_b(T_2)} \frac{m_b(T_2)}{A} \quad (16)$$

Using $\rho = M/V$ for the bulk ice density and neglecting the change in the latter with temperature, one can combine Equations (11), (14) and (15) to derive the following:

$$d_b(T_2) = \frac{V}{A} \frac{\rho}{(\rho_w + \beta S_b(T_2)) S_b(T_2)} (S_i(T_1) - S_i(T_2)), \quad (17)$$

where ρ is the bulk ice density, V is the volume, and A is the surface area of the ice. The brine layer thickness d_b may then be computed from Equations (13) and (17) if the initial and final temperatures T_1 and T_2 and the initial salinity $S_i(T_1)$ are known. The problem is that the initial freezing temperature T_1 is unknown. To solve this discrepancy, Makkonen [22] proposed the use of an analogy involving the salinity of columnar sea ice [15], which yields a relationship between S_b and S_i of the form

$$S_i = k^* S_b \quad (18)$$

with interfacial distribution coefficient k^* at the ice water interface. Using a value of $k^* = 0.26$, one can express the initial freezing condition as follows:

$$S_b(T_1) = \frac{S_i(T_1)}{0.26}. \quad (19)$$

The physical interpretation is that the spray ice freezes in such a way that its liquid fraction at its outer freezing interface is $k^* \approx 0.26$, and that the temperature T_1 corresponds to a brine salinity concentrated to S_i/k^* . Note that k^* can be viewed as the critical liquid fraction at which saline ice begins to expel brine, which subsequently forms a brine layer on its surface.

Combining Equations (13), (17), and (19), the following equation can be derived for the brine layer thickness d_b :

$$d_b(T) = \frac{V}{A} \frac{\rho}{\rho_b(T)} \frac{S_i}{S_b(T)} \left(1 - \left(\frac{k^* S_b(T)}{S_i} \right)^{\left(1 - \frac{\rho_w}{\rho_i} \right)} \frac{\rho_w + \beta S_b(T)}{\rho_w + \beta S_i/k^*} \exp \left(\frac{\beta}{\rho_i} (S_i/k^* - S_b(T)) \right) \right). \quad (20)$$

where S_i is now the initial ice salinity, S_i/k^* is the initial brine salinity, and T notes the final temperature.

In addition to the thermodynamic properties, the thickness of the brine layer depends on the specific surface A/V of the ice volume considered. For a cube, this is calculated by Makkonen [22] as follows:

$$\frac{V}{A} = \frac{L}{6}. \quad (21)$$

For a cuboid, corresponding to our case of ice growth to thickness H on square plates with side length L , one has the following:

$$\frac{V}{A} = \frac{L}{4 + 2L/H} = \frac{1}{4/L + 2/H}. \quad (22)$$

An argument can be made for the brine being rejected away from the cooling surface (here assumed to be the impinging air), under the assumption that all brine is rejected to all surfaces except the surface exposed to the cooling source. The specific surface is given by

$$\frac{V}{A} = \frac{L}{4 + L/H} = \frac{1}{4/L + 1/H}. \quad (23)$$

Thus, the brine layer thickness would increase with a decrease in the specific surface.

Figure 1 shows the relation between the brine layer thickness, the temperature T_2 , and the ice salinity based on a cuboid $9 \times 9 \times 1.5$ cm sample and $k^* = 0.26$. The brine layer thickness starts to grow at the temperature corresponding to $S_b = S_i/0.26$, which is thus salinity-dependent. With this assumption, there is no brine layer growth at higher temperatures. The brine layer thickness grows rapidly with decreasing temperature while brine is expelled from the sample. When the temperature drops further, the brine layer partly refreezes. At some point, the refreezing effect exceeds the expulsion, which explains the maximum brine layer thickness shown in the graphs. This maximum brine layer thickness is only slightly dependent on ice salinity. However, as discussed below, it strongly depends on the thickness of the ice layer that is formed.

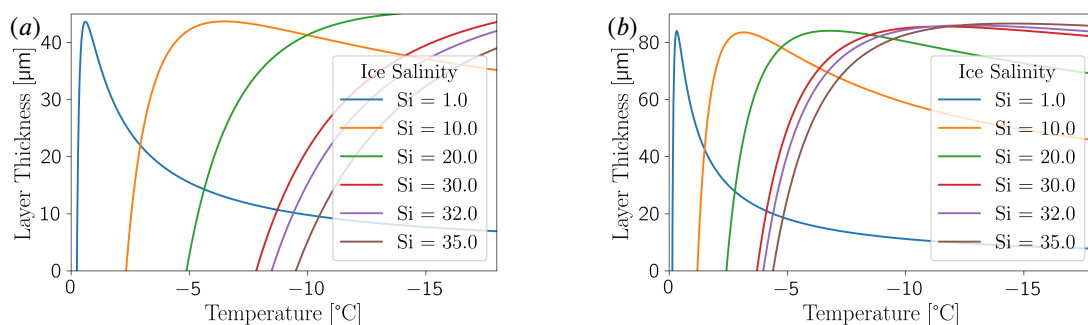


Figure 1. Theoretical brine layer thickness on the surface of a $9 \times 9 \times 1.5$ cm ice sample as a function of temperature. Typically, sea water salinity is around 32‰. These plots are based on the description of Makkonen [22] with (a) $k^* = 0.26$ and (b) $k^* = 0.5$.

3. Experimental Methods

A controlled laboratory setting is used to investigate the adhesion of sea spray ice to aluminium plates of varying sizes under subzero temperatures. Using a saline water tank and directed airflow to simulate sea spray, the setup enables in situ ice growth and adhesion testing. Complementary measurements include temperature monitoring, ice characterization, micro-CT-based microstructure analysis, and salinity profiling to elucidate factors influencing ice adhesion strength.

3.1. Ice Tank Setup

The experimental setup in the present study consists of a tank filled with saline water located in a cold room, as presented in Figure 2. The tank ($120 \times 80 \times 120$ cm) is filled with ≈ 800 L of water containing 32‰ NaCl. The decision to use NaCl instead of artificial seawater was made to avoid the crystallization of sodium sulphate in the samples to

simplify the microstructure determinations using μ -CT. As the water level and salinity fluctuate due to spray experiments and evaporation, both are monitored and adjusted to maintain water levels between 82 and 84 cm and salinity between 32 and 35‰. The spray flux is created by two “Aktobis Turboluefter WDH-AB1” fans that are able to move up to 4500 m³ of air per hour. The fans are placed on the front wall of the water tank and directed, with an angle of approximately 45°, onto the surface of the water. They are identical and feature air intake on the left side, resulting in a reduced air intake for the right fan. Therefore, an asymmetric wind distribution is generated in the tank, with slightly stronger airflow on the left side than on the right. As described below, this leads to a range in accretion rates on the mounted plates, depending on the position (see Section 3.3).

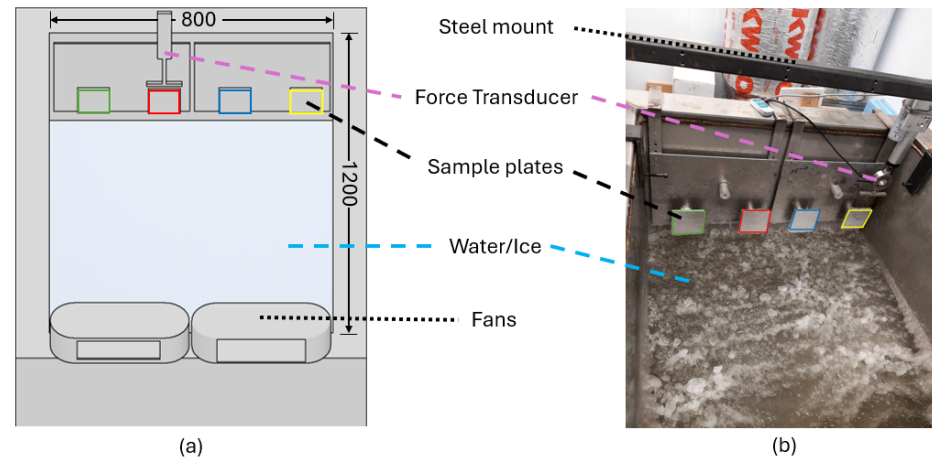


Figure 2. The experimental setup as (a) a schematic looking onto 9 × 9 cm sample plates and (b) a picture at the end of a spray icing experiment with the mounted steel bracket and force transducer. The sample positions S1, S2, S3 and S4 are highlighted in green, red, blue and yellow; the annotations are in mm.

The sample plates used to grow the ice are 1 cm thick, square-shaped, and made from laboratory-grade aluminium without any surface treatment. Plates with an edge length of 3, 6, 9, and 12 cm were used. The corners had a radius of 0.2 cm. When mounted, the centre positions of the samples remained consistent across different sizes, as shown in Table 1. The plates were centrally spaced 20 cm apart and located 16 to 18 cm over the maximum water level.

Table 1. Position of the samples in the tank and average ice thickness h_{ice} , unit in cm. x describes the distance between the centre of the sample and the left tank wall and z the distance from the bottom of the tank to the centre of the sample when looking in the spray direction. The sample position has an influence on the ice growth due to the spray rates being non-uniform. The resulting average ice thickness h_{ice} at each sample position is presented, along with the standard error.

Position	x	z	h_{ice}
Sample 1	10	100	1.21 ± 0.47
Sample 2	30	100	0.98 ± 0.21
Sample 3	50	100	0.66 ± 0.06
Sample 4	70	100	0.39 ± 0.15
Water min	—	82	
Water max	—	84	

Experiments are started when the water temperature is close to the freezing point. During a spray experiment, the airflow generates a wavy water surface, at which water droplets are disrupted and accelerated towards the back wall of the tank. These droplets

impinge on the back wall, as well as on the sampling plates mounted in front of the back wall using a bracket and aluminium cylinders with a radius of 2.5 cm and a length of 5 cm to separate the ice growing on them from the ice growing on the back wall. With an increase in the duration of the spray experiment, the ice layer on the plates and wall grows, the water in the tank cools down further, and an ice layer extending from the leeward side of the tank begins to form on the water. Usually, an experimental spray session lasts for 1.5 to 2 h of spray and results in ice layers of up to 3 cm thick. The asymmetric wind distribution leads to most of the spray reaching the samples on the left (positions 1 and 2) of the tank, while less spray impinges on the plates on the right side, especially the sample close to the tank wall (positions 3 and 4). This effect influences the resulting ice thickness, as will be discussed below.

3.2. Temperature Measurement

For the experiments, several temperatures are of direct interest. First, the water needs to be at freezing point at the start of the experiment. This is tested using an external thermometer. During the experiments, the room temperature was monitored using the room control to provide a clear indication as to whether the experimental conditions are stable.

Additional measurements were performed to obtain a detailed temperature profile by means of an Infratec Pir uc 605 IR-camera. This camera was pre-calibrated for the temperature range of interest and produces similar temperature results to external temperature measurements. For the IR temperature to reflect the actual surface temperatures, an emissivity correction with $\epsilon_w = 0.95$ and $\epsilon_i = 0.97$ and calibration using a known water temperature equivalent to the freezing point of the NaCl-solution at the start of the experiments was performed. The temperatures of the sample surfaces, water, and the surroundings were determined from the images by defining areas of interest on the sample positions (green, red, blue, yellow) the water (black) and over the tank for the surrounding temperature (gray). Figure 3a–d provide examples of the IR images before the start of the experiments at -10°C for (a), (b), and (d), and -15°C for (c). The IR imaging can be used to create a time series of the temperature during the experiment, as shown in the example in Figure 3e. The average temperature during the spray experiment, the setup of the adhesion test, and the adhesion test is referred to as average surface temperature (T_{IR}). It should be noted that the the temperature profiles represent the evolution of the surface temperature measured at the front of the ice during buildup at four sample positions. These profiles naturally vary over time and with different sample positions. For the purpose of correlating these with the ice adhesion, the temperature used corresponds to the final surface temperature, measured just before the adhesion test and after the ice equilibrated with the surrounding environment and completed the brine expulsion.

In addition, temperature sensors from Thermochron iButton (DS1922L-F5) were mounted on the back of the sample plate to provide additional temperature measurement. They were enclosed in small plastic bags to increase their resistance to water and placed just under the aluminium cylinder; the sample plate was mounted in the centre of this cylinder. These sensors record the temperature on the backside of the plates and were not used in the present study.

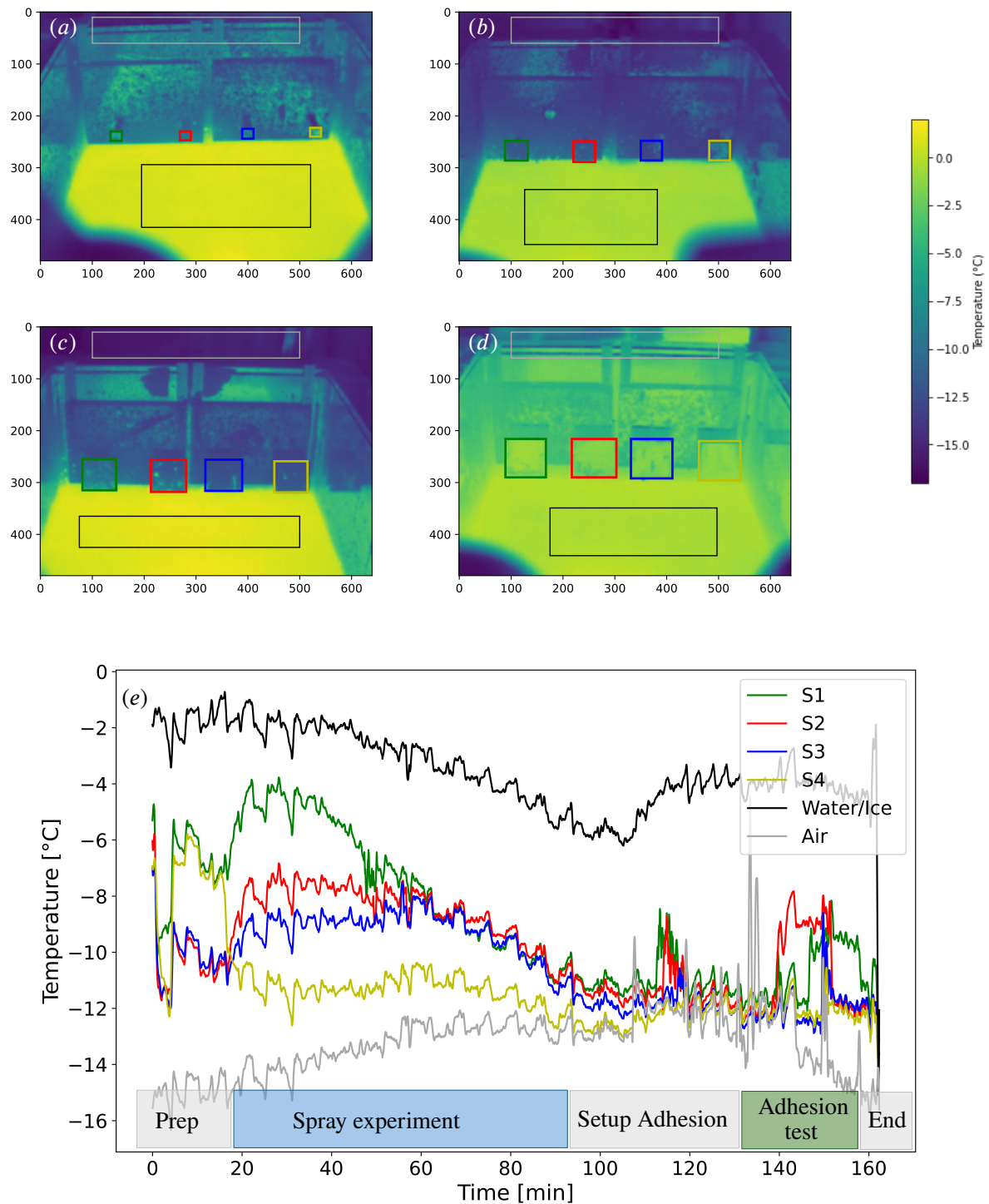


Figure 3. Overview of infrared imaging used to characterize temperature distributions and evolution during the spray-ice experiments. (a–d) show initial infrared images of 3 cm, 6 cm, 9 cm, and 12 cm sample plates, respectively, recorded before spray onset. (a,b,d) are from experiments at -10°C , (c) from an experiment at -15°C . The surface temperatures during ice growth were averaged over color-coded areas (green, red, blue, yellow) corresponding to the Plate positions. (e) presents a time series from a separate experiment at -15°C , illustrating the full thermal response during spraying. Spray began at minute 18, causing an immediate temperature increase, and ended around minute 110. Subsequent ice thickness measurements and adhesion test preparations partially obscured the camera's view of the marked regions. S1 to S4 present the sample positions corresponding to the color-coded areas.

3.3. Ice Measurements

During spray experiments, the thickness of the growing ice sample was measured roughly every 30 min and before the adhesion test with a caliper. For 3 cm samples, thickness was measured only once, in the centre of the sample, while for 6 cm samples it was measured on the top and bottom of the sample plate. For 9 and 12 cm samples, measurements were performed on the top, centre, and bottom of the sample plate. An example of the development of the thickness during growth is provided in Figure 4. The thickness increases faster at the lower end of the samples, and overall ice growth slows down toward the end of spray experiment. In this work, we refer to the measurement taken at the end of experiments as “thickness” and assume a uniform thickness increase takes place from top to bottom to represent the average thickness of a sample. Depending on position, the final average ice thicknesses ranged between 0.15 and 2.5 cm. The averages were between 0.4 and 1.2 cm for the four positions, as can be seen in Table 1.

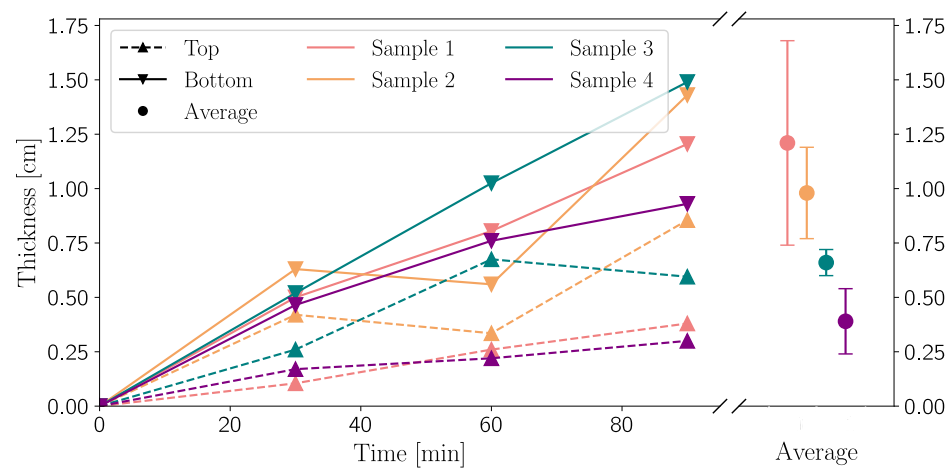


Figure 4. Time series of the thickness development during a 10 °C experiment on a 9 × 9 cm sample holder. The thickness was measured in 30 min time-steps at the top and bottom of the samples growing in positions 1–4. The ice thickness increases from the top (dotted line) to the bottom (solid line) of the same sample and depends on the position within the tank. On the right side, the average ice thickness for each position for all experiments, as presented in Table 1, is visualised.

After adhesion tests, the samples were weighed unless they had come into contact with water or were broken into pieces, making weighing difficult. In such cases, samples were assigned a calculated weight based on a density of 0.94 g cm^{-3} and the sample thickness. The weighed samples were then cut for microstructure analysis using micro-CT and stored at the experimental temperature until imaging. After micro-CT imaging, the samples were thawed for salinity measurements using a Mettler–Toledo 5Go salinometer. The salinity was determined by measuring the electrical conductivity and converting it into salinity values. Both the dimensions and the weight of the growing ice samples are important for the adhesion of spray ice. The weight has a direct influence on the adhesion strength, as it contributes to the adhesion strength with gravitational forces.

To obtain a quick indication of the growth characteristics of the ice sample, we defined the effective thickness as the weight (w) of the sample after the experiment divided by the front surface area (A) and the theoretical density $\rho_{theo} = 0.94 \text{ g cm}^{-3}$ of spray ice with a salinity of 35‰. This assumes that a generalised wedge shape that does not depict the real sample geometry. The insights from the effective thickness are described in Section 4.1.

3.4. Ice Adhesion Test

The adhesion of the grown spray ice was tested in situ, without moving the samples after the spray experiment. To do so, a vertical shear testing setup consisting of a steel frame, force transducer, and load cell was mounted on the tank. The steel frame was clamped with two screws on each side to the tank so that it stood on top of the samples. The force transducer, a GLIDEFORCE LACTP-12V-20 with a TS.116.R8 load cell, was mounted with two screws above the sample positions and needed to be aligned with the sample before each experiment to obtain an accurate measurement of the shear force.

During the adhesion test, the linear actuator moved with a constant speed of 14 mm/s and the load cell recorded the force applied to the ice; this process is presented in Figure 5a. A representative force–displacement curve is shown in Figure 5b, with variations shown in Figure A1 in the Appendix A. The adhesion strength (σ) is the quotient of the maximum force (F_{max}) during the experiment and the front surface area (A) of the sample plate. The effect of ice growing around the edges of the sample plate, as shown in both Figure 5a,c, is neglected, which implies an overestimate of σ . This aspect will be discussed in detail in Section 5.3.

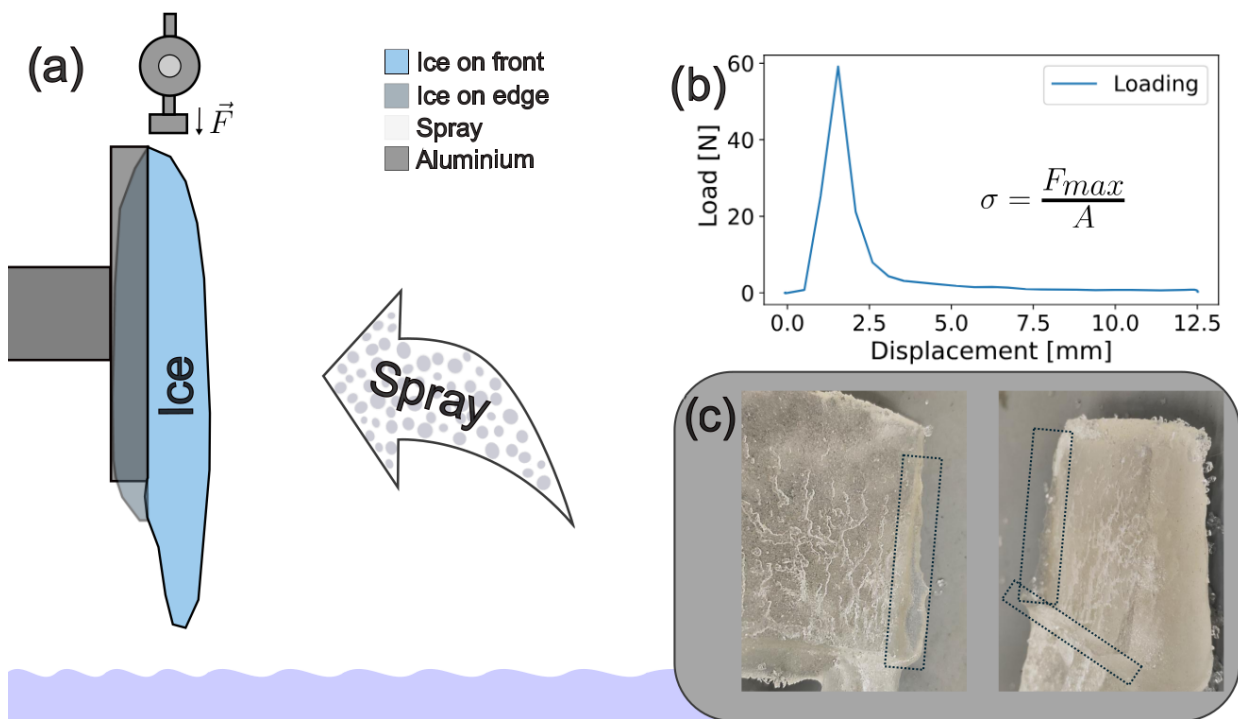


Figure 5. Schematic and results of the spray ice adhesion test, illustrating the experimental setup (a), a typical force–displacement curve during ice detachment (b), and the detached ice samples (c). (a) Ice forms on the plate from sprayed water, covering the front surface and parts of the edges; some of the brine might form icicles but the extent and shape of icicle formation vary depending on spray conditions. A force transducer applies a load to detach the ice while a load cell records the force response. (b) Representative force–displacement curve showing the increase in force as the ice is pushed, followed by a sharp drop upon detachment. (c) Detached ice samples (6 cm wide) formed at $-7\text{ }^{\circ}\text{C}$, showing edge overgrowth, as highlighted by dotted frames.

As described above, the spray setup allows us to vary the ice growth conditions by changing the air temperature, wind speed, and the water level in the tank. Here, we focus on the variation in air temperature, using -7 , -10 and $-15\text{ }^{\circ}\text{C}$ as the set room temperature (T_R) to generate sea spray on square aluminium surfaces with edge lengths of 3, 6, 9, and 12 cm. This temperature range falls within the conditions reported for marine icing events, as described by, for example, Samuelsen and Graversen [28], and encompasses regimes of

light, moderate, and heavy icing for water temperatures at near-freezing temperatures [6]. Table 2 shows the number of adhesion tests performed for each combination of temperature and sample dimension.

Table 2. Number of successful adhesion tests for each combination of temperature and each sample edge length.

Edge Length [cm]	Temperature [°C]		
	−7	−10	−15
3	0	7	7
6	6	12	10
9	7	10	15
12	8	4	10

Ice generally detached in one piece; however, a few 3×3 cm samples did shatter and were excluded in the subsequent analysis. For the remaining samples, except one grown at -7 °C, no fracturing or compaction was observed during the measurement. This is attributed to the significantly lower ice adhesion strength relative to the cohesive strength of the ice. The largest number of tests was performed at -15 °C with 9 cm samples, because this was the combination used to initially test the adhesion setup. The number of tests at -7 °C is the lowest because the still-quite-wet ice samples tended to fall off the sample plate before adhesion tests could be conducted. The combination of -10 °C and the longest edge length of 12 cm also caused samples to fall off, so adhesion measurements were challenging.

3.5. X-Ray Micro-Tomographic Scanning

An X-ray micro-tomographic scanning of spray ice was performed within a few hours after the sea spray experiment and at a final temperature between -7 and -15 °C. Imaging, segmentation, and analysis followed the procedures applied to sea ice [29] and saline ice layers on concrete [30]. Scanning was conducted at the Norwegian Centre for X-ray Diffraction (RECX), Scattering and Imaging at NTNU, with an XT H 225 ST micro-CT system from Nikon Metrology NV. Image acquisition settings were slightly dependent on sample volume, with a current source in the range 90–110 μ A and an acceleration voltage of 400–450 kV using a Wolfram target. Scans were performed with 3142 rotations per 360° and an exposure time of 708.00 ms, with a scan duration of about 40 min. The field of view (2000×2000 pixels) was 54×54 and 85×85 mm, corresponding to a pixel size of 27 and 42.5 μ m. Specimens were scanned in an alumina sample holder, with top and bottom temperatures controlled by a self-assembled cooling system based on thermoelectric assemblies (www.lairdtech.com accessed on 1 March 2019, now Tark Thermal Solutions)), with a precision of 0.5 °C. Nikon Metrology XT Software was used for the reconstruction of the data sets. Data were stored as 16-bit grey value stacks and segmented with GeoDict [31] into the constituents of air, brine and ice. Air porosity was segmented as described in Maus et al. [29]. The segmentation of brine and ice was more challenging due to the much smaller absorption contrast. We set the histogram threshold between brine and ice to match the theoretical brine porosity that is expected from temperature and salinity. As the smallest pores remained undetected, our median pore sizes are overestimates and only represent pores larger than 27 (42.5) μ m. The GeoDict PoroDict package was used to quantify the fractions of open and closed brine and air pores. The size of the pores and ice structures was determined using a sphere fitting algorithm to determine the fraction of the pore or ice space that belongs to a certain diameter interval. The results from this analysis are the median brine pore size D_b and the median air pore size D_a , further distinguishing between open and closed pores (subscripts op and cl). The pixel size of 27 μ m (42.5 μ m

for the largest sample presented here) was considered as the uncertainty of all presented microstructure measures. More details are provided in [24].

4. Results

4.1. Ice Growth

Initial ice accretion occurred on all plate sizes for all temperatures for the variety of spray conditions inside the ice tank. The ice growth typically followed a linear behaviour, as shown in Figure 4, with differences in ice growth at different positions. For some samples at the highest temperature $-7\text{ }^{\circ}\text{C}$, especially those with a small area ($3 \times 3\text{ cm}$), the ice growth stopped early in sample position 4, resulting in samples that were too small for adhesion tests. For all plate sizes (edge length of 3 to 12 cm), the ice thickness increased from the upper part of the plates to the lower part of the plates.

The effective thickness was plotted with the measured average ice thickness in Figure 6. The ratio of the effective thickness to the measured thickness can help in interpreting the ice growth. Samples where the effective thickness is larger than the measured thickness are interpreted as having icicles or overgrowing ice on the edges. Samples with a lower effective thickness do not have impactful icicles or edge icing and the porosity impacts the effective thickness. Samples growing on plates of minimum 6 cm length frequently developed icicles from out-flowing brine, as shown in Figure 7. The 3 cm samples did not commonly develop icicles. Thus, the higher effective thickness in Figure 6 for 3 cm samples will be dominated by the edge overgrowth and should, with full edge coverage, lead to a two times higher effective thickness than the measured thickness, while the weight of the icicles will be the dominant reason for the larger effective thickness for larger sample dimensions. In the microstructure analysis below, we show that the 3 cm samples also differentiate themselves from the larger samples through the absence of large drainage channels and pores, which are observed for samples with side lengths larger than 6 cm. For a more detailed discussion, see ref. [24].

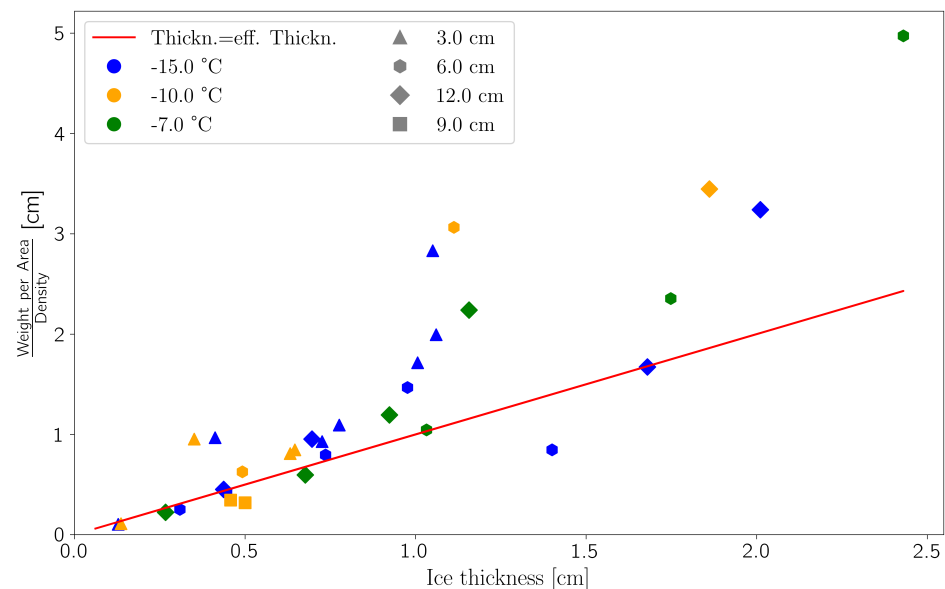


Figure 6. Comparison of effective ice thickness and measured ice thickness. The red line indicates where the measured ice thickness is equal to the effective thickness. Values above this line indicate the growth of icicles and ice formation on edges (the latter affect is more pronounced for smaller sample sizes).

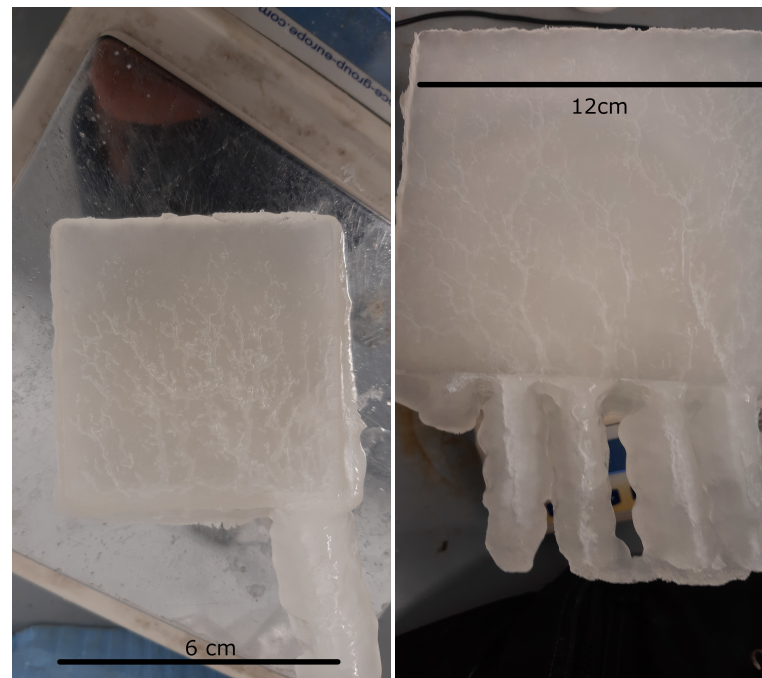


Figure 7. Photo of samples with visible brine channels and drainage features after the adhesion test. The picture is reused from [32].

4.2. Adhesion Strength of Spray Ice

The average adhesion strengths in groups of different edge lengths and temperatures are listed in Table 3. The overall mean adhesion strength of all samples is 15.8 ± 20.7 kPa. The mean values of runs grouped by temperature, temperature, and size, as well as size, only range between 2.7 and 30.7 kPa. Treating samples that could not be tested due to their falling off as a 0 kPa adhesion strength, leads to a reduced average adhesion strength, as presented in the *-marked column in Table 3. We proceed with the recorded values, potentially overestimating the adhesion strength. The variation in the adhesion strength with temperature (T_R) and different sample dimensions is shown in Figure 8a. With an increase in temperature, the adhesion strength decreases, and this effect is stronger for smaller sample sizes. Furthermore, the plot shows a difference between the smallest 3×3 cm samples and the other sizes.

In the following, we present the adhesion results, based on growth conditions such as temperature, spray rate, and salinity, as well as sample geometries, to identify their influence on the adhesion strength of sea spray ice.

Table 3. Overview of the adhesion strength of sea spray ice samples. The mean value and standard deviation (std) are presented for (from top to bottom): all samples, samples grouped by temperature, samples grouped by both temperature and size (represented by edge length), and samples grouped by size only, alongside the number of samples belonging in the category. The columns marked with * present the data, including samples that fell off before the adhesion test could be conducted with an adhesion strength of 0 kPa. For the combination -7°C and 3 cm edge length, all eight samples were unable to be tested.

Temperature [°C]	Edge Length [cm]	Count	Adhesion Strength [kPa]		Count *	Adhesion Strength * [kPa]	
			$\bar{x}$	std		$\bar{x}$	std
all	all	93	15.80	20.70	106	13.90	20.10
−15	all	33	25.00	26.50	38	21.70	26.10
−10	all	43	12.00	16.90	44	11.70	16.80
−7	all	17	7.60	5.00	24	5.40	5.40

Table 3. Cont.

Temperature [°C]	Edge Length [cm]	Count	Adhesion Strength [kPa]		Count *	Adhesion Strength * [kPa]	
			$\bar{x}$	std		$\bar{x}$	std
−15	3	7	63.00	22.50	8	55.10	30.50
−15	6	12	14.20	21.30	12	14.20	21.30
−15	9	10	16.90	13.10	10	16.90	13.10
−15	12	4	11.30	3.90	8	5.60	6.50
−10	3	7	28.70	29.10	8	25.10	28.80
−10	6	10	17.00	17.70	10	17.00	17.70
−10	9	16	4.70	6.20	16	4.70	6.20
−10	12	10	7.00	4.30	10	7.00	4.30
−7	6	6	9.00	6.80	8	6.70	7.10
−7	9	3	4.20	2.70	8	1.60	2.60
−7	12	8	7.80	3.80	8	7.80	3.80
all	3	14	45.90	30.70	16	40.10	32.60
all	6	28	14.10	17.50	30	13.10	17.30
all	9	29	8.90	10.50	34	7.60	10.20
all	12	22	8.10	4.20	26	6.80	4.80

4.2.1. Influence of Growth Conditions

First we present the influence of the temperature on the adhesion strength. Figure 8b represents the measurements at −15 °C and contains the widest range of measured adhesion values. Figure 8c shows a smaller variation, with the majority of the measured adhesion strength −10 °C being lower than 20 kPa. This set of data points is the biggest, because it includes the tests that were conducted to test the setup. In the experiments at −7 °C, all recorded adhesion values were below 20 kPa, as presented in Figure 8d. Hence, the majority of samples, independent of the temperature, showed an adhesion strength of below 20 kPa, while some higher adhesion strength values were observed at lower temperatures. The temperatures used here are the set room temperature (T_R) in the lab, corresponding to the temperature at which the adhesion of the ice was tested and the samples were stored. However, T_{IR} during the growth experiment was generally higher and may vary between samples of the same spray experiment based on the amount of spray that reaches the sample. The T_{IR} is influenced by the spray rate, the measured water temperature (T_w) and T_R , but is also susceptible to malfunction in the cold lab, leading to an increase in the lab temperature by some degrees.

The adhesion in the dependence of the T_{IR} during a spray icing run is shown in Figure 9a. A dependence of adhesion strength on the average temperature during ice growth is not apparent.

In Figure 9b, we show the adhesion strength as a function of the salinity of the samples after CT imaging. The measured salinities range from 15 to 32.5‰ in the same range as previously observed in the field [1] and laboratory [15,33,34]. Within this range, no clear dependence of adhesion strength is observed. It is important to note that this salinity refers to the value after adhesion measurements and CT imaging, not the water salinity (ranging from 32 to 35‰) or the initial ice salinity. The dependence of adhesion strength on the brine volume fraction is shown in Figure 9c. Low adhesion is recorded over the full range of brine volume fractions, with no clear dependence present. Some 3 × 3 cm samples show a higher adhesion strength, and this occurs over a wide range of brine volume fractions, from 13 to 21%.

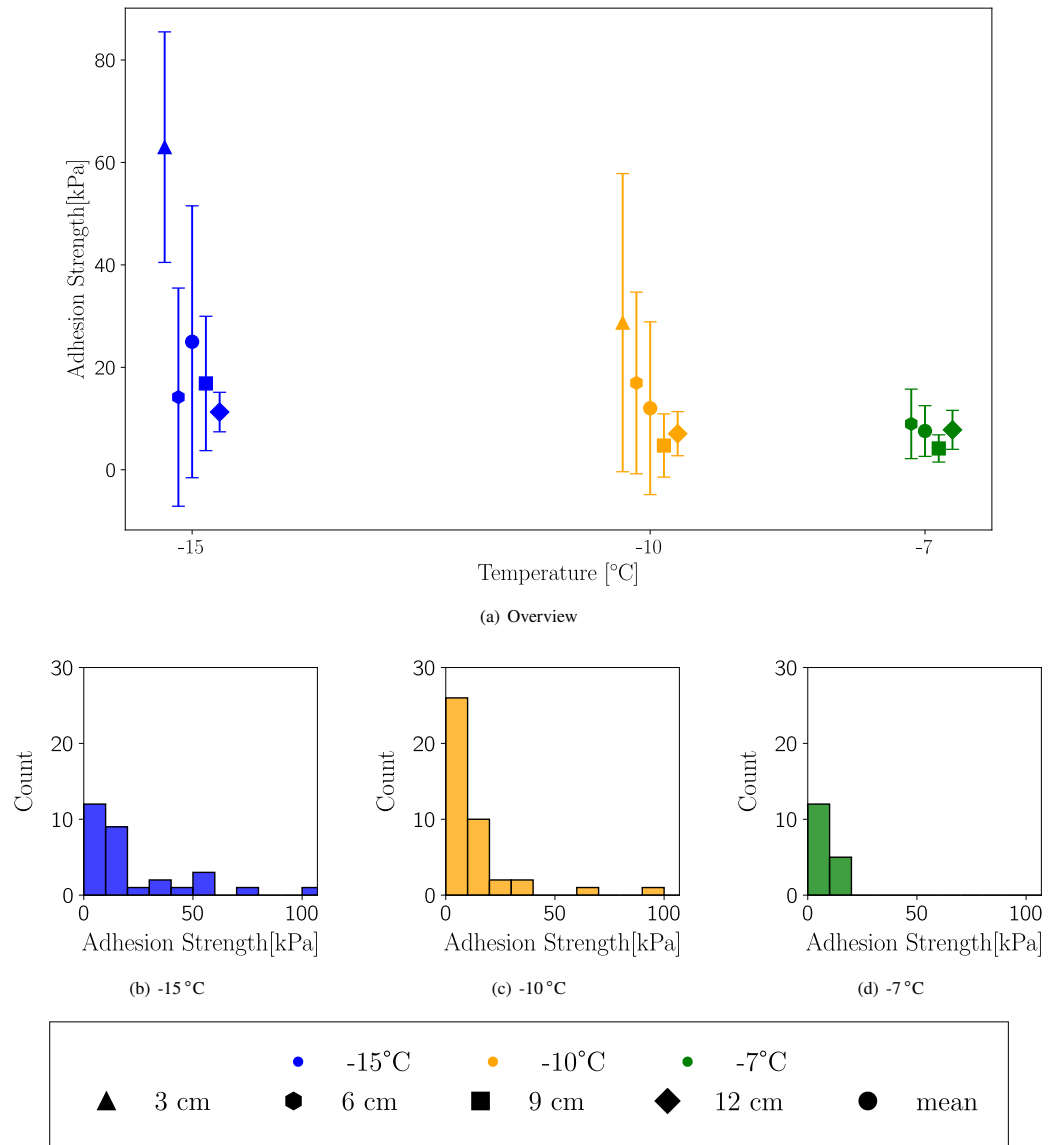


Figure 8. Overview of adhesion strength as a function of temperature. (a) Average adhesion strength with standard error for each sample dimension, as well as the overall average for all samples (●). (b–d) Histograms showing the distribution of measured adhesion strength at (b) −15 °C, (c) −10 °C, and (d) −7 °C. For all temperatures, the majority of samples exhibit a low adhesion strength, below 20 kPa.

Based on Equation (20), the theoretical brine layer thickness can be calculated for the samples using the average thickness, the salinity of the water, and T_R [22]. For −10 °C samples, a small brine layer between 0.5 and 7 μm should have formed and the brine layer for −15 °C can be in the range of 2 to 17 μm . While the scatter is large, at these two temperatures the adhesion strength appears to decrease with increasing brine layer thickness. The calculated brine layer thickness is negative for −7 °C, resulting from the approximation $S_b(T_2) = S_w/0.26$, which predicts an initial temperature for brine expulsion and the onset of brine layer formation that is below the final temperature of the experiment. A negative brine layer thickness should thus be interpreted as the lack of a brine layer. However, a liquid layer remaining on the aluminium surface was observed at all temperatures after the adhesion tests. This contrast indicates an imperfection in the brine layer prediction, most likely related to Equation (19).

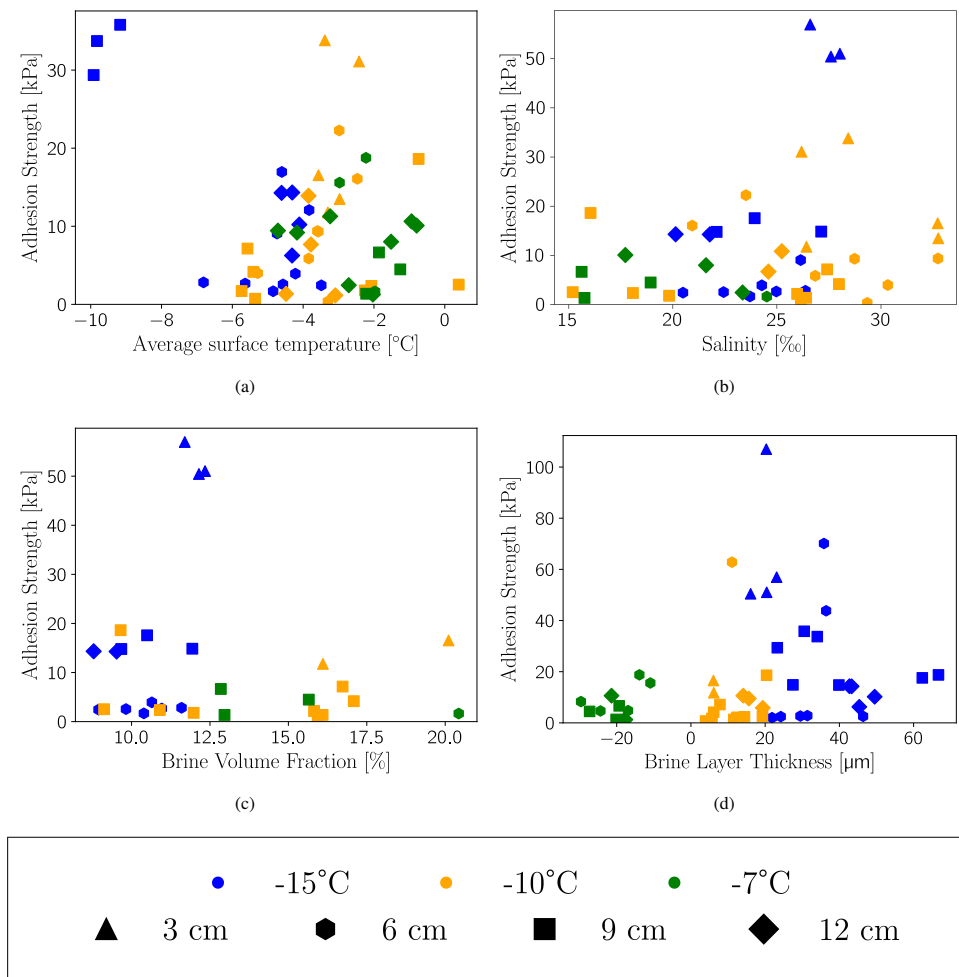


Figure 9. Adhesion strength plotted against (a) the average surface temperature during spray experiments, (b) the salinity of the sample after CT measurements, (c) the brine volume fraction calculated based on the set room temperature, and (d) the brine layer thickness computed using salinity, sample dimensions, and $k^* = 0.26$.

4.2.2. Influence of the Sample Dimensions

In Figure 8a, the adhesion strength is presented, along with the average values for samples of the same size. Especially the smallest 3 cm samples show a different behaviour than the rest. To get a clearer display of the adhesion strength we refer to the Appendix A in which we present the adhesion results in double logarithmic plots (Figure A2). It is noticeable that the majority of high adhesion strength values are measured for small edge length's of the samples. Instead of just improving the readability of the data the double logarithmic representation can also be used to find power law correlations in the data using linear regression in double logarithmic space.

Figure 10b,c show the adhesion strength versus the ice weight and the dependency of the adhesion strength on the ice thickness. Samples that have a low thickness have a low growth rate, while samples with high thicknesses have faster growth rates, leading to eventual icicle formation. The high adhesion values do not occur at low or high sample thicknesses but are located in the medium range of samples, with thicknesses between 0.7 cm and 1.7 cm. As shown in Figure 10c, with increasing weight, the adhesion strength and its variance decrease. The outlined data points are based on weight calculations from the measured thickness with a density of 0.94 g cm^{-3} for spray ice samples.

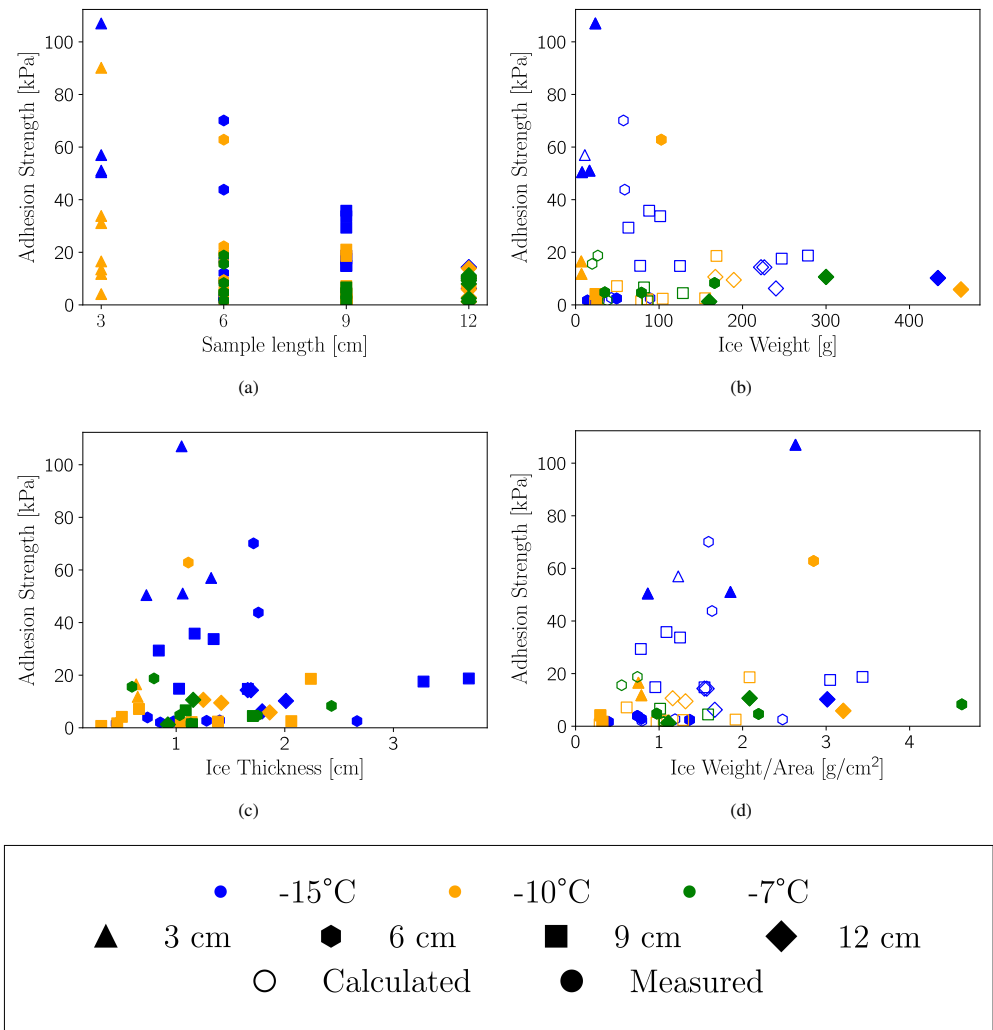


Figure 10. Adhesion strength in relation to sample dimensions. Adhesion strength over (a) the sample edge length, (b) the weight of the sample from measurements (filled shapes), as well as that calculated based on the thickness (outlines), (c) the average ice thickness in cm, and (d) the ice weight per area, representing the thickness.

4.2.3. Thickness and Weight per Area

Figure 10c shows that low adhesion was observed for all ice thicknesses; however, in the range of 0.7–1.7 cm ice thickness there were higher adhesion values. Through all datasets, the double logarithmic correlation between adhesion strength and thickness is positive and the exponent is below 1, so the adhesion strength increases with the ice thickness, but at a decreasing rate. Without the smallest samples, this is statistically significant.

In Figure 10b a negative correlation between high adhesion strength and lightweight samples seems apparent; however, the only statistically significant group is the group without the smallest sample dimension of 3 cm, with a positive correlation between weight and adhesion strength. This contrast to the first impression can be explained with the additional higher adhesion values in Figure 10c, indicating that the small samples have a stronger effect than the overall influence of the weight. This can be further seen when using the weight per area instead of the absolute weight value, which shows a positive correlation that is statistically relevant for every subgroup of the data. This is in alignment with the expectation, as the weight per area multiplied by the density of ice provides the apparent thickness.

4.2.4. Brine Layer Thickness

Figure 9d shows negative brine layer thickness, which of course is physically impossible, and would either describe the ice as growing without a brine layer or not growing at all at -7°C . Thus, it is worth looking into the positive values only; they are presented in Figure 11a. The brine layer for samples growing in -10°C is small. For -15°C samples, a significantly increased brine layer thickness was observed; however, this does not show a clear relationship with the adhesion strength. The overall correlation for this group without the lowest temperature is positive, indicating an increase in adhesion strength with increasing brine layer thickness. This is contrary to the expected of a decreased adhesion strength with increased brine layer. While the double logarithmic model fails to explain the majority of points, it inhibits statistical significance.

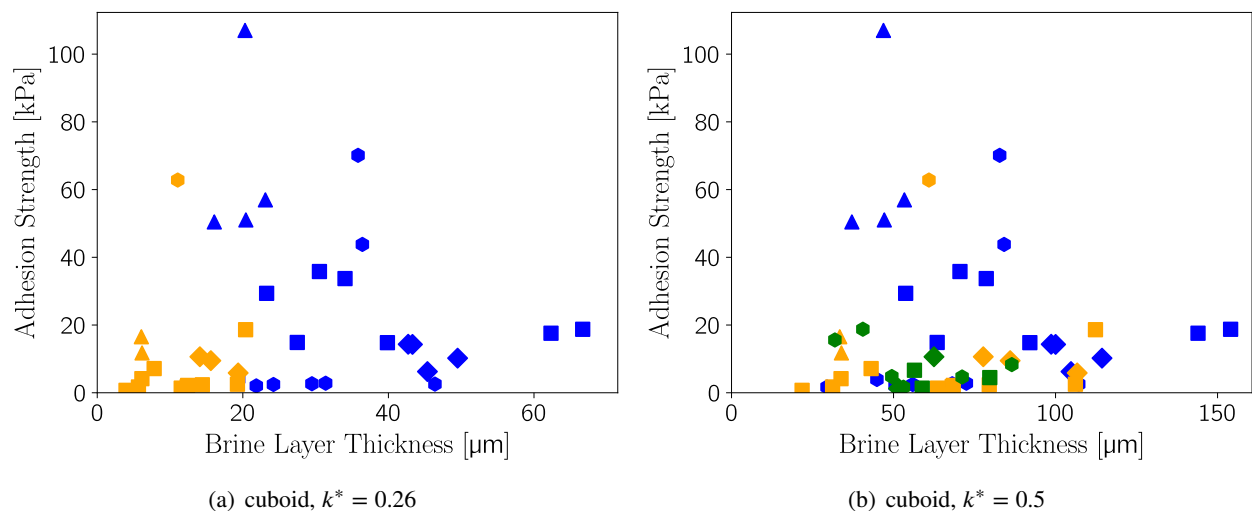


Figure 11. Adhesion over brine layer thickness for (a) the interfacial distribution coefficient $k^* = 0.26$ without the -7°C samples and (b) $k^* = 0.5$ including all samples. In both cases, a decrease in adhesion strength with brine layer thickness can be observed; a higher k^* leads to larger brine layers for the experimental conditions of each sample.

By setting the interfacial distribution coefficient to higher values, the calculated brine layer becomes positive for all temperatures. We chose to calculate $k^* = 0.5$ here, as microstructure analysis suggests a liquid fraction higher than that reported for sea ice, which, in turn, could be temperature-dependent. The resulting relation between adhesion strength and brine layer is shown in Figure 11b and indicates a positive correlation between the brine layer thickness and the adhesion strength for all datasets. The relation increases with increasing brine layer thickness if the smallest samples are excluded. This indicates that there might be different dominant processes for samples of different sizes.

4.3. Correlation Coefficients with the Adhesion Strength

The pairwise pearson correlation coefficients of the physical and experimental properties, along with the adhesion strength and a comparison, are presented in Figure 12. the correlation from linear regression between these parameters and the adhesion strength are additionally presented in Table A1. We determined the correlation between both the original data and data transformed to the log-log space. There are some high correlations with high statistical significance that can be explained by the calculation of the correlated values, this includes edge overgrowth and edge length, brine layer thicknesses and temperature, brine layer thickness and brine volume, salinity and brine volume, and brine volume and temperature. The moderate negative correlations between salinity and edge length

indicate that larger samples have a lower salinity, which can be related to brine channels forming in larger samples, as presented in Section 4.4.

The largest influence on the ice adhesion strength was the sample size, with a negative correlation (linear: $r = -0.44$ $p < 0.001$, doublelogarithmic: $r = -0.38$). We also calculated the correlation between strength and the correction factor $(1 + 3D/L)$ for the edge overgrowth; see Equations (2) and (27). A slightly stronger correlation was obtained (l: $r = 0.55$ $p < 0.001$, dl: $r = 0.42$ $p < 0.001$). Also, the temperature (measured as deviation from freezing temperature ΔT) and the weight per area correlated significantly with adhesion strength. The calculated brine layers showed only a weak and a mostly positive correlation with adhesion strength that, given the high p values, is not significant.

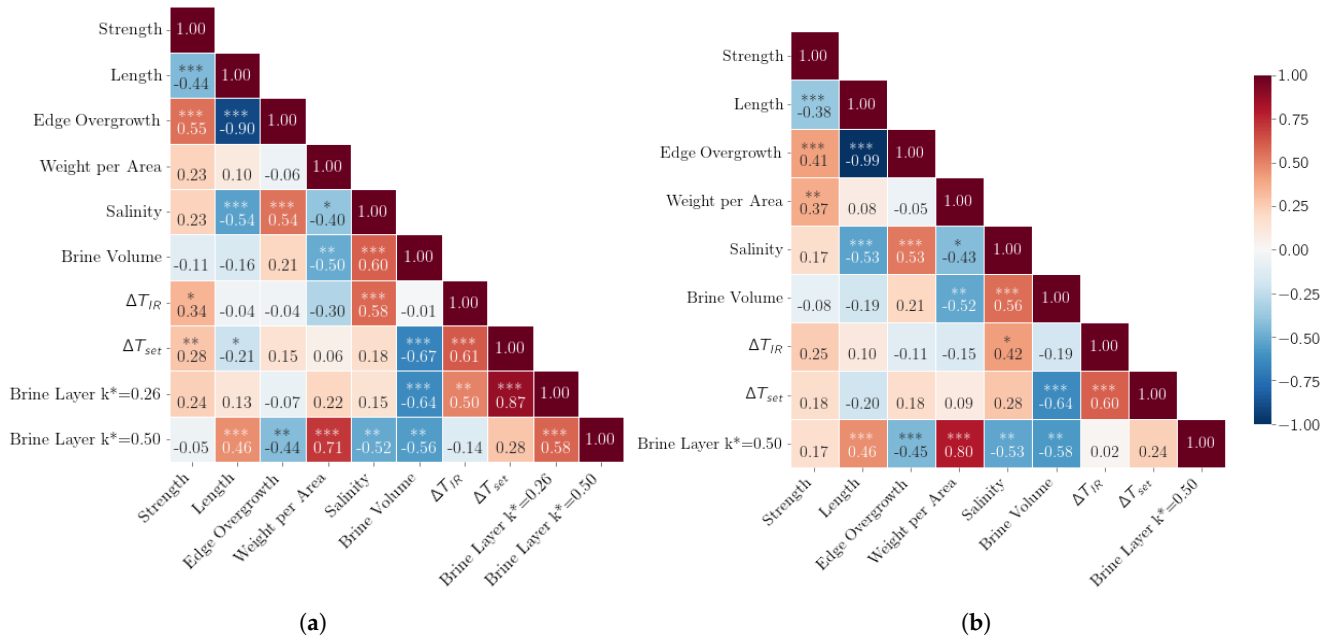


Figure 12. Correlation between ice adhesion strength and experimental parameters for (a) the recorded data and (b) double logarithmic transformed data (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). The parameters of edge overgrowth, weight per area, brine volume and the brine layers are calculated parameters.

Additionally, we performed both linear regression and regression in the log-log space between the strength and the parameters. The linear regression shows the slope m and an intercept a , while double logarithmic linear regression enables us to determine the exponent m and scaling factor a in a power law of the form

$$\sigma = aP^m \quad (24)$$

to quantify the dependence of adhesion strength σ and property P . The regression analysis was performed for two subgroups of data: the set Full includes the entire dataset but is biased by the lack of adhesion data at -7 °C for the smallest sample dimension; the set LARGE excludes the smallest sample dimension, allowing for comparability across the largest samples at all temperatures. The full information is presented in Table A1. Excluding the smallest sample dimension introduces a statistically significant positive correlation between adhesion strength and brine layer thickness, which is counterintuitive to the influence a brine layer is expected have on ice adhesion.

4.4. X-ray Micro-Tomographic Imaging

Three-dimensional measurements by X-ray micro-tomography were used to study differences in microstructure between the different sample sizes, their porosity, and their density. Figure 13 compares 3D views of the microstructure of samples from experiments at -10°C , with brine pores in green, air pores in red, and ice being invisible. In addition to the three samples sizes on which adhesion experiments were obtained (3, 6 and 12 cm), we also show part of the spray ice grown behind the mounted samples on a large (30 cm in height, 60 cm wide) alumina plate. Table 4 summarises the porosity and microstructure characteristics. We distinguished between open-air porosity $\phi_{a,op}$, closed-air porosity $\phi_{a,cl}$, and open-brine porosity $\phi_{b,op}$, closed-brine porosity $\phi_{b,cl}$, and corresponding median (by volume) pore diameters. Note that the open pore diameters are based on a porosimetry algorithm [29] and represent the pore diameter at which 50 percent of the open pore space may be reached from outside the sample. They are a measure of the throats or bottlenecks of the pore space.

The results may be summarised as follows. Median brine pore diameters, closed $D_{b,cl}$ and open $D_{b,op}$, are below $100\text{ }\mu\text{m}$, and cannot be determined with high precision due to the limited image resolution of 27 and $42.5\text{ }\mu\text{m}$. However, the results were similar for other saline ice types [29,30,35]. Closed-air pore diameters $D_{a,cl}$ were similar to brine pores but larger in some cases. The most striking feature was the open-air pores that had, with the exception of the smallest samples, a median diameter of almost a mm. These pores can be interpreted as drained brine channels. Their fraction increased from less than 1 % in the 3 cm sample to almost 8 % in the largest sample. For the 3 cm samples, fewer drainage pores were observed, and their diameter was also smaller. The 3 cm ice samples also lost less salt.

Table 4. Summary of 3D sample statistics, properties in columns from left to right: air temperature T_a , ice salinity S_i , open (*op*) and closed (*cl*) air porosity ϕ_a , brine porosity ϕ_b , median air pore diameter D_a , median brine pore width D_b , salinity difference ΔS of seawater (with salinity of $\approx 34\text{‰}$) and sea spray ice, and the resulting bulk ice density ρ .

Plate Size	Thickness cm	T_a $^{\circ}\text{C}$	S_i ‰	$\phi_{a,op}$ %	$\phi_{a,cl}$ %	$\phi_{b,op}$ %	$\phi_{b,cl}$ %	$D_{a,op}$ μm	$D_{a,cl}$ μm	$D_{b,op}$ μm	$D_{b,cl}$ μm	ΔS	ρ gm^{-3}
3 cm	1.3–1.7	−10	26.2	0.5	0.44	14.0	1.8	146	54	41	67	7.8	0.94
6 cm	1.8–2.0	−10	23.2	0.9	0.44	12.5	1.6	820	171	41	86	10.8	0.93
12 cm	1.5–2.1	−10	22.6	1.3	0.72	8.4	5.3	801	50	43	51	11.4	0.93
Large	3.0–4.5	−10	16.2	7.9	0.06	5.6	4.0	849	210	70	90	17.8	0.86

Figure 13 shows that the largest air pore fractions were seen at and close to the ice–alumina interface (front right surface). Further into the sample, and also at the interface, one can observe drainage air pores with a diameter of the order of a mm. These were most dominant for the large plate (a), and were almost absent in the $3 \times 3\text{ cm}$ sample along the growth direction (d). At some locations, one can also find brine pores of a similar diameter, but these do not run vertically through the samples. Note that the interface cannot be well-resolved with the present spatial resolution, and we may have missed the brine layer in the smallest sample. Figure 14 shows selected horizontal 2D views of the 3D images in Figure 13, illustrating the brine and air pore pattern in the drainage direction. If one comes closer to the ice–alumina interface, (drained) air channels dominate over brine channels, and one finds little brine in the vicinity of the drained air channels. This indicates that the surrounding brine formed a wide pore prior to drainage. Although we cannot know if the brine drained prior to or after the adhesion test, it is clear that these drainage pattern

are the pathways of brine from the spray. Figure 14a shows two prominent features of undrained wide brine channels (in green) with a high surrounding solid fraction (in white), which may illustrate their state prior to drainage. The 2D image also shows that, in the 3 cm sample (d), large channels have not developed yet. It seems that the air pores were also surrounded by regions of low brine concentration.

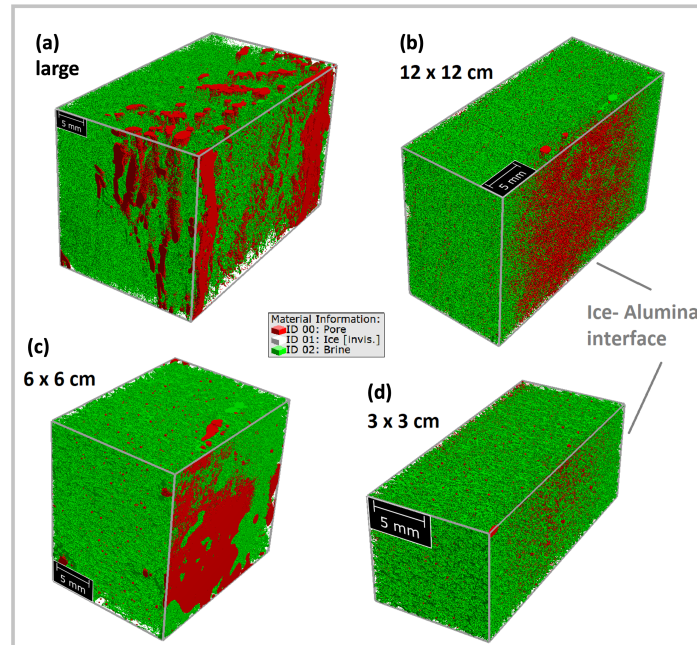


Figure 13. Three-dimensional views of the microstructure of saline spray ice grown on four accretion plate sizes: (a) the large plate behind the mounted sample plates, (b) 12×12 cm, (c) 6×6 cm, and (d) 3×3 cm. Brine pores are green, air pores are red, and ice is invisible. The growth direction is from the front right surface (close to the ice–alumina interface) to the back left surface. Note the different scale bars for the samples.

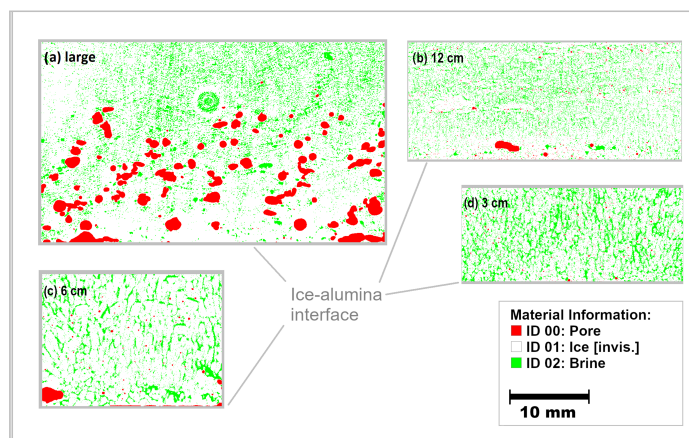


Figure 14. Selected horizontal sections of the 3D images shown in Figure 13. Brine pores are green, air pores are red, and ice is invisible. The growth direction is from bottom (close to ice–alumina interface) to top. Note that different scales of the samples in Figure 13 were adjusted and the single scale bar is valid for all samples.

5. Discussion

We presented observations of the adhesion strength and icing characteristics of saline spray ice under a variety of growth conditions. Our results demonstrate that sea spray ice exhibits a low adhesion strength that shows a complex dependence on growth conditions.

We found a dependence on test temperature, similar to the results documented for freshwater ice. While a dependence on brine volume fraction and salinity has not been found, adhesion strength seems to be primarily dependent on geometrical factors like ice thickness and edge length. Below, we suggest that this dependence may involve several processes: (i) a deterministic size effect where adhesion strength is controlled toughness [36]; (ii) a thickness-based size effect relating to tensile and bending forces, (iii) a size effect related to the overgrowth of ice on the lateral surfaces; (iv) the expulsion of brine to the sample surface, which also depends on sample geometry (as can be seen from Equation (23)).

5.1. General Results

The obtained average adhesion strengths of 15.8 ± 20.7 kPa for sea spray ice samples are significantly lower than the reported adhesion strength, ranging from 0.11 to 4.5 MPa for freshwater ice on aluminium tested via shear test at a similar T_{RS} of -9 and -15 °C [37]. These tests included a variety of different treatments of the aluminium surface. For example, an inter-laboratory study reported 326 ± 30 kPa on polished aluminium in -10 °C as the lowest bulk water ice adhesion strength, and 285 ± 49 kPa for the same system at -18 °C, while precipitation ice had a higher adhesion of 734 ± 75 kPa (-10 °C) and 340 ± 44 kPa (-18 °C). Bulk freshwater adhesion tests performed with the presented setup were in the range of 126 to 210 kPa [32], showing a lower measured adhesion strength than other setups. However the obtained adhesion strength for saline spray ice is, on average, one order of magnitude lower than the lowest freshwater strength groups when considering ice type and treatment.

A decrease in adhesion strength for saline ice compared to fresh water ice has been reported before [20–22,38].

Makkonen [22] observed that even small amounts of salinity significantly reduce ice adhesion, with values as low as 10–30 kPa for saline ice compared to 100–350 kPa for freshwater ice in the temperature range down to -20 °C. Similarly, Zhang et al. [20] found adhesion strengths ranging from 52 to 400 kPa on aircraft tires, notably lower than those for freshwater ice (1 MPa), confirming that low salinity levels cause a substantial reduction. Luo et al. [38] further demonstrated that ice adhesion drops below 20 kPa on low-energy surfaces at moderate salinities, highlighting the strong sensitivity of adhesion strength to salinity. These studies were performed on salinities that are, except for the study by Luo et al. [38], much lower than the salinities we observed in the sea spray samples (15–33‰) on different surfaces with different adhesion measurement methods, making an exact comparison difficult. However they show that the significantly lower observed adhesion is related to the salinity of the samples.

5.2. Properties Affecting Adhesion Strength

We investigated the effect of several properties and experimental conditions on the adhesion strength. Salinity and brine volume are the properties that are known to have a strong impact on the mechanical properties of sea ice [39–41] and other saline ice types [30]. However, for both, we could not find a significant impact on adhesion strength. This aligns with other reports on the influence of the salinity on the adhesion strength. Several authors report a strong decrease in adhesion strength already for salinities as low as 1‰ [20–22]. Our samples were all more saline than this value. We considered whether this lack of correlation may be related to the delay between adhesion tests and salinity measurements, caused by the CT-Imaging, which might allow for brine drainage from the sample and a corresponding salinity reduction. However, our analysis shows that the brine loss in sample plates of 3 to 12 cm edge length, shown by the drained brine pores, was less than 1%. Hence, we do not expect a bias of the correlation due to brine drainage after the adhesion test.

A third property related to the thermodynamics of spray ice is the brine layer thickness, representing the measure of brine expelled to the surface of the ice. This brine layer was proposed by Makkonen [22] as a key property controlling low adhesion in saline ice, and its effect was recently highlighted by Chatterjee et al. [42]. However, our results here were also contrary to this. Either we found no correlation of strength with brine layer thickness or an increase in strength with expelled brine. We also found a significant correlation for the test temperature, although this was quite weak for the large data subset that is not biased by the size–temperature correlation ($R^2 = 0.1$). Hence, the property with the strongest impact on the adhesion of freshwater ice also appears to play no major role.

Instead of the thermodynamic properties of temperature, brine volume, salinity, and brine layer thickness, several geometrical parameters appeared to have the strongest effect on our ice adhesion results. This overall behaviour, which is summarised in Table 5, thus deserves further discussion.

Table 5. Properties affecting the adhesion strength.

Property	Relationship Strength, This Study	Other Studies
Temperature	+	Makkonen [22]
Edge length	++	Golovin et al. [36]
Sample thickness	++	Wang et al. [43], Rønneberg et al. [44], Rośkowicz et al. [45]
Brine layer thickness	+	Makkonen [22], Chatterjee et al. [42]
Geometry, edge overgrowth	+++	

5.3. Size Effects

5.3.1. Sample Length and Crack Propagation

A well known size effect from fracture mechanics is a decrease in nominal strength with size—see Dempsey [46] for a discussion of sea ice. Recently, Golovin et al. [36] showed that such a size effect may be relevant to the adhesion strength of ice. They stated that when the length of the ice–substrate interface exceeds a critical value L_c , the ice removal force tends to plateau, and interfacial fracture becomes governed by crack propagation. This critical length is influenced by several factors, including interfacial toughness. The lower the toughness, the shorter the critical length. Under these conditions, the measured ice adhesion strength decreases with increasing specimen size once the critical threshold is surpassed and strength is governed by the following equation, [36,46]:

$$\sigma \propto (1 + L/L_c)^{-1/2}. \quad (25)$$

In our study, the interfacial toughness between seawater ice and aluminium was not directly measured, and it is unknown. On the one hand, we may expect the interfacial toughness to be higher than that of the low-toughness coatings reported [36]. However, an effective interfacial toughness linked to brine at the interface could provide an argument for low values. Our correlation indicates that the strongest size effect exponent occurs at small sample size, decreasing towards larger samples, which is a different behaviour that one would expect from Linear Elastic Fracture Mechanics. Such a behaviour is more consistent with the edge overgrowth effect discussed below. Overall, and based on these considerations, as well as the force–time evolution, we rate it as unlikely that crack propagation was a dominant mechanism in our experiments.

5.3.2. Sample Thickness

The correlation between adhesion strength and thickness or effective thickness, represented by weight per area, is weak in linear space. A larger and statistically significant correlation can be found in double logarithmic space. Thickness effects were reported for peeling and shear strength experiments and may be described by the following Equation [45]:

$$\sigma \propto H^q. \quad (26)$$

e.g., an exponent of $q = 0.75$ may be expected when bending moments play a role. Indeed, experiments have shown that shear adhesion tests yield a lower adhesion when the force is applied farther away from the interface [43,44]. In our experiments, with increasing thickness, the force was applied, in relative units, closer to the interface, which would involve less tensile and may explain the increase in strength with thickness. However, we did not control or monitor the exact positioning of the force application with respect to the interface. We found exponents ranging from 0.72 to 0.83 in the double logarithmic linear regression (Table A1).

As discussed in Section 5.4, there is another effect represented by the thickness, where thicker samples form at a higher growth rate. More rapid growth normally implies a smaller crystal size, which, in turn, may be expected to increase the strength. However, that aspect is not fully understood for sea ice [41,47,48] and requires further investigation.

5.3.3. Edge Overgrowth

There is a size effect related to the geometry of our sample that we only became aware of at the end of our study. For many samples, we found an overgrowth of the sample plate on three of the four edges (at the upper edge, no overgrowth was observed due to the general downflow of brine). This overgrowth then leads to a size effect of the form

$$\sigma \propto (1 + 3d_e/L), \quad (27)$$

where d_e is the overgrowth thickness. In our experiments, we have not obtained detailed observations of the edge overgrowth thickness d_e , but it was found to reach the thickness of the aluminium sample holder plate ($D = 1$ cm). Equation (27) is therefore consistent with a stronger size effect at a smaller sample size L , which is indeed the type of size effect we observed. Therefore, it seems reasonable to use the sample holder thickness $D = 1$ cm for d_e in Equation (27). This provides an adhesion strength that is lower by 25 to 37.5% when comparing the 6–12 cm samples to the 3 cm samples. The edge overgrowth may thus roughly explain half of the observed size effect. Indeed, it shows the largest correlation with the adhesion strength ($r = 0.547$ and $p < 0.001$).

We also considered the possibility that the overgrowth thickness increases with ice thickness (e.g., in the form $d_e = aH$ for $d_e < D$). The effect of edge overgrowth on adhesion strength should therefore be strongest for the smallest L . However, the regression does not show a stronger thickness or weight/area effect on adhesion when including the 3 cm samples (see Table A1).

5.3.4. Brine Layer Thickness—Mixed Size Effects

Having identified three types of size effects that would lead to an increase in the adhesion strength with ice thickness and edge length, we can ask how these interact with the brine layer thickness. To illustrate this, we combine Equations (16), (22), and (23), and write them in the following form:

$$d_b \propto (4/L + n_b/H)^{-1}, \quad (28)$$

where $n_b = 1, 2$ depends on whether brine is assumed to also be expelled to the spray surface or not. This equation shows that the brine layer increases with both L and H . The geometric size effects that enter the brine layer model through the surface to volume ratio will thus overshadow the effect of brine layer thickness on strength, as the theoretical brine layer thickness depends on temperature, salinity, sample thickness, and edge length.

5.4. Brine Layer, Brine Drainage, and Microstructure

The geometric size effects discussed in the previous section are considered the most likely explanation as to why our results do not show a strong correlation between ice adhesion and the estimated brine layer thickness, as predicted by the theory of Makkonen [22]. Another aspect of our investigation into brine layer thickness is that, using the standard setting of $k^* = 0.26$ from Makkonen [15,22], we can obtain a negative brine layer thickness for the highest temperatures, while $k^* = 0.5$ would yield a positive brine layer for all temperatures. More recently, slightly different values for k^* have been suggested, with Makkonen [49] proposing $k^* = 0.30$ based on a theoretical analysis of dendritic growth, and Horjen [50] arguing for $k^* = 0.34$ based on an analysis of different datasets of spray ice salinity. Overall, dendritic growth models that were suggested [49,51], as well as observations [24,50], indicate that k^* is uncertain, with a plausible range between 0.2 and 0.6. Currently, no validated theory on k^* exists, and it is an open question as to whether a constant value is justified at all. An (unknown) dependence of k^* on growth conditions may also bias the relationship between adhesion strength and a modelled brine layer thickness.

In addition to the uncertainties in brine layer modelling and the size effects, we anticipate that the possible effect of brine layer on adhesion strength is affected by other processes. The brine layer thickness (Equation (20)) is an estimate based on the assumption that all brine expelled from the ice matrix due to internal freezing and phase change builds the brine layer on the surface of the sample. However, our microstructure analysis indicates that the brine layer build-up is more complicated than that view. For thicker ice samples, as well as larger sample plates, Figures 13 and 14 show the development of the internal brine channel network and the outflow icicles with the brine channels. This process means that less brine is available for the brine layer at the ice–aluminium interface, which in turn should increase the adhesion strength. The increase in the volume of large drainage pores with sample dimensions, as shown in Table 4, indicates that the drainage of brine from spray ice is governed by the sample dimension. Such an effect is known for its natural convection in porous media controlled by a critical Rayleigh Number e.g., [52], and has been described for sea ice [25,40,53,54]. For example, for the 3 cm samples, fewer drainage pores with a smaller diameter were observed, and these samples also lost less salt. This brine drainage effect adds to the expulsion size effect, as described in Equation (28), where the brine layer increases with both L and H . As a result, one would expect an increase in adhesion strength with ice thickness, which is consistent with our observations.

Furthermore, recent analyses of sea ice [29] and thin ice samples on concrete [30] have shown that the cooling and internal freezing of ice samples forms disconnected brine inclusions, from which no brine is expelled. The lower the temperature, the higher the fraction of disconnected pores. Another complication may relate to the ice growth conditions, as it is generally known that the crystal size of ice decreases with growth velocity and freezing temperature for fresh ice [55,56] and sea ice [57,58], and one would also expect this for sea spray ice. Crystal size will influence the entrapment and expulsion of brine and the micromechanical properties of ice [30]. In addition, crystal orientation can impact the formation of the brine layer, such as the directional freezing of salt water, which may lead to anisotropic permeability, as documented for columnar sea ice [59,60].

In the present experiments, the spatial resolution and ice–brine contrast was insufficient to resolve such crystal structure details.

Last but not least, we note that a continuous brine layer at the ice–substrate interface would lead to very low adhesion. However, in our experiments the adhesion strength was typically reduced by a factor of ten compared to freshwater ice. It thus appears likely that the brine expulsion leads to an interfacial regime with low ice concentration, rather than a distinct brine layer. Details of this regime are currently not known, but may be crucial in establishing the relationship between brine content and adhesion strength. We conclude that a concise theory of brine entrapment, expulsion, and redistribution in sea spray ice does currently not exist and will likely require a better understanding of the microstructural details described above. For now, our observations of brine on the ice–substrate interface (after adhesion tests) are qualitative. The formulation of a comprehensive brine redistribution model requires more micro-CT data and a higher spatial resolution than we were able to obtain so far. We are currently working on imagery of the ice–brine interface with a resolution of an order of magnitude higher than that in Figures 13 and 14.

5.5. Practical Implications of the Size Effect

The inherent size effects of the experimental setup that we observed in our study have implications for the understanding of ice adhesion on real-world structures subjected to marine icing. First, our study showed that ice growth around minor 3D structures can dominate the variability in the adhesion strength, with small geometric features (like screws and bolts) becoming more important than thermodynamic growth conditions (like temperature, spray, and accretion rates). Second, while our largest samples were sufficiently large to resemble the adhesion on large surfaces without such geometric constraints, the samples' overall size range strongly reflects the edge effect. Hence, we were unable to derive an LEFM size-effect law e.g., [36], Equation (25), for the spray ice in our experiments. However, we expect that this law could become relevant for larger surfaces on ships and offshore structures.

Another important result of our study is the role of microstructure, particularly the occurrence of brine drainage channels and the formation of icicles for sample sizes larger than 3 cm. We only know this transition, related to internal convection in the sea spray ice, approximately. It depends on the geometry and surface orientation of sea spray ice, which deserve further study. We regard it as likely that the process of desalination by internal convection affects the ice adhesion. In principle, this adds another size effect to the adhesion problem.

Hence, what we can propose on the basis of our study are now five ways in which size can affect adhesion strength: (i) geometric effects through the increased surface size due to small obstacles; (ii) increasing brine layer thickness with thicker ice; (iii) brine drainage from the sample, increasing with size and over time, and potentially decreasing the adhesion (although brine channels at the ice–material interface may also act in an opposite way); (iv) size effects arising from sample length due to fracture mechanics; and (v) size effects due to sample thickness and corresponding bending forces. All these effects may have played a role in our experiments, and contributed to a typical standard deviation of 100% in the adhesion strength when considering all samples. However, a closer look in Table 3 shows that the standard deviation decreases from above 100% for the 6 cm samples to 50% for a 12 cm side length. This finding of an increase in the variability and uncertainty of mechanical properties with decreasing sample size is well known from studies of sea ice [39,41,46]. This aspect may guide future experiments studying the different size effects

explicitly; in principle, they may all be present in many practical situations where sea spray ice is forming or has to be removed.

5.6. Limitations of the Results

The spray generation, achieved using fans, allowed us to study a range of spray accretion rates in one experiment, as the spray flux to the sample holders was position-dependent. However, with the laboratory spray icing setup, we could not cover the full range of natural spray icing events, e.g., the results represent non-cyclic wet icing conditions with water droplets that have a shorter airborne trajectory than those in the field. Puolakka [61] showed that for small droplet sizes (50–200 μm), a significant undercooling can be reached within 50 cm trajectories. Neither the droplet size, nor the undercooling were quantified in our experimental setup. While droplet sizes will have an influence on the supercooling, both aspects, as well as the spray rates, can affect the transition from wet to dry icing conditions. The difference in ice growth between thin and thick samples likely shares some characteristics of this transition, but we did not focus on this aspect, as the generated spray resembles wind spray rather than wave spray.

Despite taking precautions, such as de-icing the cooling fans before the experiments, the cold lab cannot maintain the room temperature at exactly the desired set room temperature (T_R) due to the introduction of warm spray, a humidity increase, and latent heat release during tank ice formation. This results in temperature fluctuations during the experiment that affect the ice growth rate and structure, as well as brine drainage and redistribution. Other temperature conditions are also beyond our control. The sample holder temperature at the start of the spray ice growth was higher than the set room temperature due to the proximity of the samples to the water surface. The temperature during the adhesion test, however, was lower than that during ice growth, as stopping the fans also stops the release of latent heat from spray ice. In our experiments, the time between spray stop and adhesion test was 20–30 min, which may be insufficient to achieve full thermal equilibration of the ice samples.

As discussed above, the brine layer model in the current state does not account for microstructure details like internal drainage channels and brine entrapment in disconnected inclusions. However, the calculations indicate that brine expulsion is an interesting approach to understand and model the connection between ice adhesion and the salinity and the freezing process of saline spray ice. A more detailed analysis should focus on the role of microstructure and thermodynamics on the redistribution of brine. Sample dimension and brine drainage from the spray ice interior and its surface are likely to play another important role.

The information from micro-CT imaging supports the conclusion that the loss of salt from sea spray ice—that is, the decrease in its salinity from the initial seawater value to down to half it in our experiments—is strongly related to the existence of brine channels. These have diameters of the order of a millimetre and their concentration increases towards the interface on which the spray is accreting; see Figures 13 and 14. While these findings indicate that the brine transport through these channels could play a major role in brine accumulation at the interface, and hence the adhesion strength, the results so far are qualitative. To understand the redistribution of brine, one would have to develop a 3D model of porous sea spray ice that accounts for thermodynamics and fluid flow. However, for sea ice, at present, only crude approximations of such models exist [25,53,54,62].

Adhesion tests of very thin ice (a few mm) were difficult in our setup. While we were able to measure low adhesion in the range 1 to 10 kPa, the setup contains potential sources of error. For example, the alignment of the stamp can influence the measured adhesion strength [44]. The variable distances between the stamp and the ice–Al interface can

change the fracture from a shear to a bending mode, as we discussed in connection with the thickness dependence. We tried to align the ice and stamp position for each sample, but were unable to determine the variability or uncertainty introduced by the upper ice shape. We also recall that, in our experiments, samples tended to fall off when temperatures were too high, but why this only occurred for ice samples with smallest edge length of 3 cm remains unexplained. One would expect the opposite due to the larger specific contact area with edges included. The differences in heat transfer (air flow and mounting of samples) could play a role, as well as the increased brine loss in larger samples.

While our experiments represent wind spray, rather than the sea spray generated through the interaction of waves with ships, we obtained similar growth rates to those observed under natural icing conditions [1,33,63]. Our laboratory setup differs from the more commonly used experiments in icing wind tunnels, e.g., [15], or spray generation with a nozzle, e.g., [8,34]. The latter approaches can control more parameters, e.g., they have independent settings for the air and water temperatures, as was recently demonstrated in a large set of experiments by [64]. However, in the latter study, the droplet diameters were limited by the pump and nozzle system. In general, both approaches have their limitations, and we suggest that future studies should aim for experiments that enable the generation of true wave impact spray, as is possible with larger ice tank facilities, e.g., [65,66].

6. Conclusions

In this paper, the icing characteristics and the adhesion strength of high-saline spray ice under a variety of growth conditions were explored. The adhesion strength of saline ice, as determined in our experiments, depends on the temperature, sample dimension, and geometry, as well as the redistribution of brine and the internal ice microstructure. These properties and processes interact in a complex manner that we currently do not fully understand. The main conclusions are summarised as follows:

- The adhesion strength of the spray ice that is formed from the sea spray of seawater is one to two orders of magnitude lower than that of freshwater adhesion.
- Depending on sample dimension and temperature, the adhesion strength of sea spray ice varied from a few to 100 kPa.
- For growth and standard thermodynamic variables, we found an impact of test temperature on ice adhesion, but little effect of bulk salinity and bulk brine volume.
- The geometry of samples had, for our size range, the strongest influence on the ice adhesion strength. A combination of size effects, including the sample edge length, overgrowth on these edges, and the sample thickness, all play a role.
- Brine can be found on the interface of the samples after the adhesion tests, and this brine layer is expected to decrease ice adhesion. However, the brine layer thickness estimated after Makkonen [22] shows a slight positive correlation with adhesion strength. Our analysis shows that this behaviour may be related to other size effects.
- Ice microstructure and the internal redistribution of brine, as revealed by micro-CT imaging of sea spray ice samples, play an important role in the ice adhesion strength. These processes and their impact on microstructure and brine evolution at the ice-adhesion interface, are key to obtaining a fundamental understanding of the adhesion of saline ice.

Overall, due to the many processes that contribute to the adhesion strength, we were unable to isolate and quantify their individual effect. However, our findings suggest that within the tested parameter space, the influence of temperature and salinity is secondary compared to microstructural and interfacial factors, such as brine expulsion dynamics and interface geometry. The absence of strong correlations under controlled growth conditions underscores the complexity of sea spray ice adhesion and points to several directions for

further systematic investigations of the adhesion strength of sea spray ice. To improve the information about the adhesion strength of spray ice, it would be useful to improve the spray generation to allow for controllable spray rates and droplet sizes, increasing the repeatability of testing and enhancing control over the surrounding temperature. More detailed observations of spray ice microstructure would be essential to develop a model of the effective surface involved in the adhesion of sea spray ice.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Supporting Information

Appendix A.1. Force–Displacement Curves

While the majority of force–displacement curves follow the example shown in Figure 5b, a variety of curve types occurred during the adhesion tests. Figure A1 shows some of the variations.

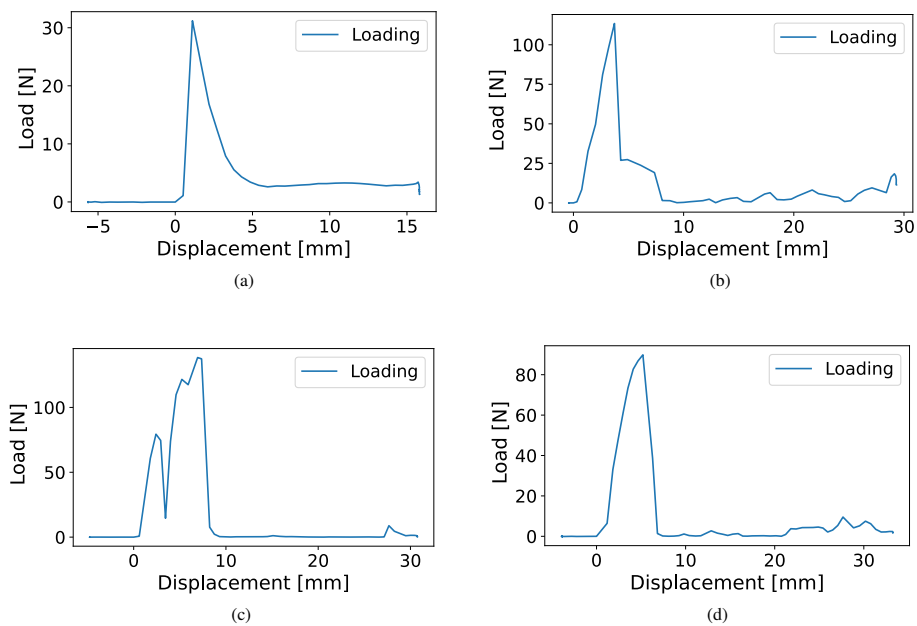


Figure A1. Force displacement curves from the adhesion tests showing abnormal behaviour: (a) remaining force after detachment, indicating sliding of ice, (b) sudden drop after some sliding, (c) the force increasing after the first drop, and (d) non-linear increase in adhesion strength at the beginning. (a,b,d) still provide a max load that can be used to calculate adhesion strength.

Appendix A.2. Correlation of Parameters and Adhesion

Figure A2 contains the double logarithmic plots of the different variables over the adhesion strength, including the linear regressions in the double log space. For representation in the paper, a linear space was chosen.

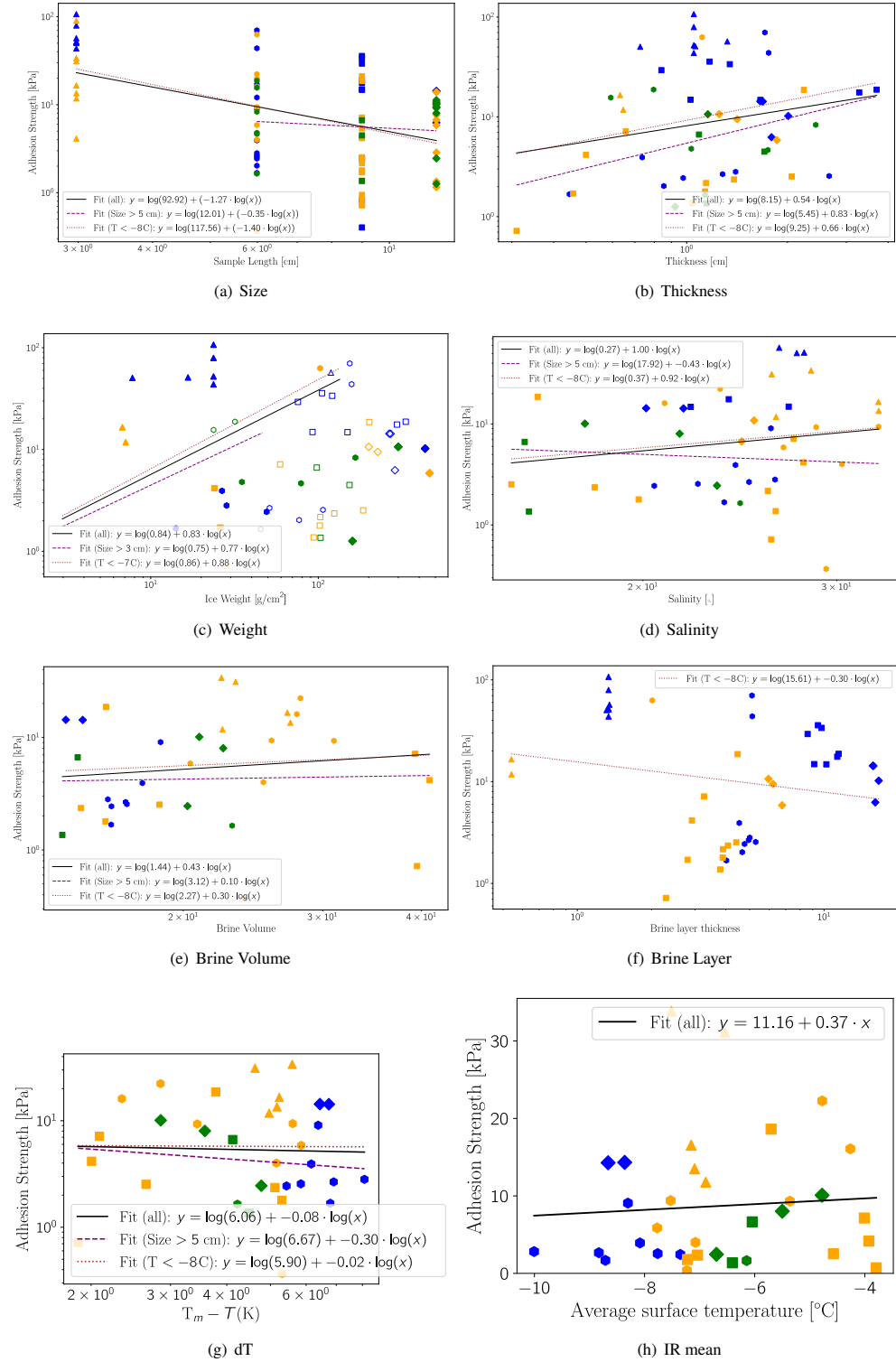


Figure A2. Double logarithmic presentation of the adhesion strength data over (a) edge length, (b) thickness, (c) weight, (d) Salinity, (e) Brine Volume, (f) Brine Layer (g) dT and (h) IR-temperature of the ice samples. The graphs include linear regressions in double logarithmic space for the groups presented in Table A1.

Appendix A.3. Statistical Analysis and Correlation of Categorical Variables

Appendix A.3.1. Correlation of Parameters with Adhesion Strength

While the observed correlations were generally weak, some of them were significant at the null hypothesis (p -value < 0.05), and are highlighted in **bold**. This is further supported by a statistical analysis of the categorical variables temperature and edge length, as provided in the Appendix A.2. In the linear regression, we observed a significant relationship between both average growth and average test temperatures and the adhesion strength. In double-logarithmic regression, a low yet significant correlation was found between thickness and effective thickness (weight per area) and strength. For both linear and logarithmic regression, we found a size effect for the FULL dataset, but not for the subset LARGE. With the brine layer thickness, the adhesion strength appeared to only be positively correlated for the LARGE samples. The last result is particularly contrary to what one would expect if the brine layer thickness played a role in adhesion.

Table A1. Linear regression results for different parameters and adhesion strengths in original and double logarithmic space. The standard error is given in brackets after the value. Two datasets were been used: all available data without filter (Full) and all available data for all but the smallest samples (Large).

Parameter	Dataset	Linear			Double Logarithmic		
		Slope (SE)	R ²	p -Value	Exponent (SE)	R ²	p -Value
dT _{IR}	FULL	1.13 (0.53)	0.081	0.037	−0.05 (0.35)	0.000	0.885
	LARGE	1.31 (0.47)	0.142	0.008	0.01 (0.35)	0.000	0.983
dT _{set}	FULL	1.80 (0.66)	0.078	0.008	0.67 (0.40)	0.032	0.095
	LARGE	0.97 (0.46)	0.055	0.039	0.38 (0.39)	0.012	0.336
Salinity	FULL	0.69 (0.44)	0.054	0.125	1.02 (0.88)	0.030	0.253
	LARGE	−0.13 (0.23)	0.009	0.579	−0.41 (0.86)	0.006	0.638
Brine Volume	FULL	−42.66 (57.98)	0.012	0.466	−0.37 (0.69)	0.007	0.592
	LARGE	−42.23 (27.63)	0.063	0.135	−0.82 (0.64)	0.045	0.206
Thickness	FULL	0.49 (4.53)	0.000	0.915	0.59 (0.34)	0.056	0.095
	LARGE	3.40 (3.32)	0.024	0.311	0.83 (0.32)	0.137	0.012
Weight/ Area	FULL	5.52 (3.35)	0.053	0.106	0.75 (0.27)	0.138	0.007
	LARGE	3.54 (2.50)	0.045	0.164	0.72 (0.25)	0.156	0.007
Length	FULL	−2.91 (0.63)	0.196	0.000	−1.13 (0.29)	0.145	0.000
	LARGE	−1.02 (0.59)	0.038	0.087	−0.35 (0.48)	0.007	0.474
Edge Overgrowth	Full	46.03 (7.55)	0.299	0.000	3.66 (0.87)	0.170	0.000
	Large	25.20 (13.68)	0.043	0.069	1.53 (1.81)	0.009	0.399
Brine Layer $k^* = 0.26$	FULL	0.22 (0.13)	0.055	0.096	—	—	—
	LARGE	0.18 (0.25)	0.084	0.053	—	—	—
Brine Layer $k^* = 0.5$	FULL	−0.04 (0.11)	0.003	0.719	0.48 (0.41)	0.027	0.247
	LARGE	0.09 (0.12)	0.029	0.267	1.05 (0.38)	0.149	0.009
Brine Layer app. thickness $k^* = 0.5$	FULL	0.06 (0.10)	0.008	0.527	0.74 (0.34)	0.085	0.037
	LARGE	0.11 (0.12)	0.051	0.137	0.92 (0.31)	0.168	0.005

References

1. Ono, N. Studies of ice accumulation on ships. Part II. Conditions of icing and accreted weights. *Low Temp. Sci. Ser. A* **1964**, A22, 171–181.
2. Borisenkov, Y.; Panov, V. *Osnovnyye rezultaty i perspektivy issledovaniy gidrometeorologicheskikh usloviy obledeneniya sudov* (Primary Results and Prospects for the Investigation of the Hydrometeorological Conditions of Ship Icing); Technical Report Trudy No. 298; Arkticheskii i Antarkticheskii Nauchnoissledovatel'Skii Institut, Gidrometeoizdat: Leningrad, Soviet Union, 1972.
3. Borisenkov, Y.; Pchelko, I. *Indicators for Forecasting Ship Icing*; Technical Report; U.S. Army Cold Regions Research and Engineering Laboratory: Hanover, NH, USA, 1975.
4. Ono, N. Studies of ice accumulation on ships. Part IV. Statistical analysis of ship icing conditions. *Low Temp. Sci. Ser. A* **1974**, A32, 235–242.
5. Minsk, L. *Icing on Structures*; CRREL Report; U.S. Army Cold Regions Research and Engineering Laboratory: Hanover, NH, USA, 1980.
6. Overland, J.; Pease, C.; Preisendorfer, R.; Comiskey, A. Prediction of Vessel Icing. *J. Appl. Meteor. Climatol.* **1986**, 25, 1793–1806. [\[CrossRef\]](#)
7. Samuelsen, E. Ship-icing prediction methods applied in operational weather forecasting. *Q. J. R. Meteorol. Soc.* **2018**, 144, 13–33. [\[CrossRef\]](#)
8. Kulyakhtin, A. Numerical Modelling and Experiments on Sea Spray Icing. Ph.D. Thesis, NTNU, Trondheim, Norway, 2014.
9. Dehghani-sanij, A.; Muzychka, Y.S.; Naterer, G.F. Analysis of Ice Accretion on Vertical Surfaces of Marine Vessels and Structures in Arctic Conditions. In Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering, St. John's, Newfoundland, Canada, 31 May–5 June 2015; p. V007T06A056. [\[CrossRef\]](#)
10. Dehghani, S.; Naterer, G.; Muzychka, Y. Droplet size and velocity distributions of wave-impact sea spray over a marine vessel. *Cold Reg. Sci. Technol.* **2016**, 132, 60–67. [\[CrossRef\]](#)
11. Dehghani-Sanij, A.; Dehghani, S.; Naterer, G.; Muzychka, Y. Sea spray icing phenomena on marine vessels and offshore structures: Review and formulation. *Ocean Eng.* **2017**, 132, 25–39. [\[CrossRef\]](#)
12. Ryerson, C.C.; Gow, A.J. Crystalline Structure and Physical Properties of Ship Superstructure Spray Ice. *Philos. Trans. R. Soc. London. Ser. A Math. Phys. Eng. Sci.* **2000**, 358, 2847–2871. [\[CrossRef\]](#)
13. Dehghani-Sanij, A.; Muzychka, Y.; Naterer, G. Droplet Trajectory and Thermal Analysis of Impinging Saline Spray Flow on Marine Platforms in Cold Seas and Ocean Regions. *Ocean Eng.* **2018**, 148, 538–547. [\[CrossRef\]](#)
14. Jones, K.F.; Andreas, E.L. Sea Spray Concentrations and the Icing of Fixed Offshore Structures. *Q. J. R. Meteorol. Soc.* **2012**, 138, 131–144. [\[CrossRef\]](#)
15. Makkonen, L. Salinity and Growth Rate of Ice Formed by Sea Spray. *Cold Reg. Sci. Technol.* **1987**, 14, 163–171. [\[CrossRef\]](#)
16. He, Z.; Xiao, S.; Gao, H.; He, J.; Zhang, Z. Multiscale crack initiator promoted super-low ice adhesion surfaces. *Soft Matter* **2017**, 13, 6562–6568. [\[CrossRef\]](#)
17. Azimi Dijvejin, Z.; Jain, M.C.; Kozak, R.; Zarifi, M.H.; Golovin, K. Smart low interfacial toughness coatings for on-demand de-icing without melting. *Nat. Commun.* **2022**, 13, 161. [\[CrossRef\]](#)
18. Zhuo, Y.; Xiao, S.; Håkonsen, V.; He, J.; Zhang, Z. Anti-icing Ionogel Surfaces: Inhibiting Ice Nucleation, Growth, and Adhesion. *ACS Mater. Lett.* **2020**, 2, 616–623. [\[CrossRef\]](#)
19. Dhyani, A.; Choi, W.; Golovin, K.; Tuteja, A. Surface design strategies for mitigating ice and snow accretion. *Matter* **2022**, 5, 1423–1454. [\[CrossRef\]](#)
20. Zhang, Y.; Zhang, Y.; Luo, G.; Cui, B. Effects of Freezing Temperature and Salinity on the Adhesion Shear Strength of Amphibious Aircraft Tires under Static Icing. *Aerospace* **2022**, 9, 170. [\[CrossRef\]](#)
21. Mu, Z.; Guo, W.; Li, Y.; Tagawa, K. Wind tunnel test of ice accretion on blade airfoil for wind turbine under offshore atmospheric condition. *Renew. Energy* **2023**, 209, 42–52. [\[CrossRef\]](#)
22. Makkonen, L. Ice Adhesion Theory, Measurements and countermeasures. *J. Adhes. Sci. Technol.* **2012**, 26, 413–445. [\[CrossRef\]](#)
23. Laroche, A.; Grasso, M.J.; Dolatabadi, A.; Bonaccorso, E. Tensile and Shear Test Methods for Quantifying the Ice Adhesion Strength to a Surface. In *Ice Adhesion*; Mittal, K.L., Choi, C.H., Eds.; John Wiley & Sons, Ltd.: London, UK, 2020; Chapter 9, pp. 237–284. [\[CrossRef\]](#)
24. Maus, S.; Rübsamen-von Döhren, P. Sea Spray Ice Microstructure and Brine Entrapment. In Proceedings of the 27th International Conference on Port and Ocean Engineering Under Arctic Conditions, Glasgow, UK, 12–16 June 2023.
25. Maus, S. *On Brine Entrapment in Sea Ice: Morphological Stability, Microstructure and Convection*; Logos: Berlin, Germany, 2007; 538 p.
26. Pustogvar, A.; Kulyakhtin, A. Sea ice density measurements. Methods and uncertainties. *Cold Reg. Sci. Technol.* **2016**, 131, 46–52. [\[CrossRef\]](#)
27. Cox, G.F.N.; Weeks, W.F. Changes in the salinity and porosity of sea ice samples during shipping and storage. *J. Glaciol.* **1986**, 32, 371–375. [\[CrossRef\]](#)
28. Samuelsen, E.; Graversen, R. Weather situation during observed ship-icing events off the coast of Northern Norway and the Svalbard archipelago. *Weather Clim. Extrem.* **2019**, 24, 100200. [\[CrossRef\]](#)

29. Maus, S.; Schneebeli, M.; Wiegmann, A. An X-ray micro-tomographic study of the pore space, permeability and percolation threshold of young sea ice. *Cryosphere* **2021**, *15*, 4047–4072. [CrossRef]
30. Maus, S.; Bahafid, S.; Hendriks, M.; Jacobsen, S.; Geiker, M. X-ray micro-tomographic imaging and modelling of saline ice properties in concrete frost salt scaling experiments. *Cold Reg. Sci. Technol.* **2023**, *208*, 103780. [CrossRef]
31. GeoDict. Geometric Material Models and Computational PreDictions of Material Properties. 2012–2025. Available online: <https://www.geodict.com> (accessed on 15 January 2025).
32. Rübsamen-von Döhren, P.; Maus, S. Adhesion of laboratory grown sea spray ice. In Proceedings of the 27th International Conference on Port and Ocean Engineering under Arctic Conditions, Glasgow, UK, 12–16 June 2023.
33. Ryerson, C.; Gow, A. *Ship Superstructure Icing: Crystalline and Physical Properties*; CRREL Report; CRREL: Hanover, NH, USA, 2000.
34. Kulyakhtin, A.; Kulyakhtin, S.; Løset, S. Measurements of thermodynamic properties of ice created by frozen sea spray. In Proceedings of the Twenty-Third International Offshore and Polar Engineering Conference, Anchorage, Alaska, 30 June 2013; pp. 1104–1111.
35. Lieb-Lappen, R.; Golden, E.; Obbard, R. Metrics for interpreting the microstructure of sea ice using X-ray micro-computed tomography. *Cold Reg. Sci. Technol.* **2017**, *138*, 24–35. [CrossRef]
36. Golovin, K.; Dhyani, A.; Thouless, M.; Tuteja, A. Low-interfacial toughness materials for effective large-scale deicing. *Science* **2019**, *364*, 371–375. [CrossRef]
37. Bleszynski, M.; Clark, E. Current Ice Adhesion Testing Methods and the Need for a Standard: A Concise Review. *Standards* **2021**, *1*, 117–133. [CrossRef]
38. Luo, W.; Alasvand Zarasvand, K.; Azimi Dijejin, Z.; Nadaraja, A.V.; Golovin, K. Influence of Salinity on Surface Ice Adhesion Strength. *Adv. Mater. Interfaces* **2024**, *11*, 2300606. [CrossRef]
39. Schwarz, J.; Weeks, W.F. Engineering properties of sea ice. *J. Glaciol.* **1977**, *19*, 499–530. [CrossRef]
40. Petrich, C.; Eicken, H. Growth, Structure and Properties of Sea Ice. In *Sea Ice*, 2nd ed.; Thomas, D.N., Dieckmann, G.S., Eds.; John Wiley and Sons: New York, NY, USA, 2010; Chapter 2.
41. Weeks, W.F. *On Sea Ice*; University of Alaska Press: Fairbanks, AK, USA, 2010; p. 600.
42. Chatterjee, R.; Thanjukutty, R.U.; Carducci, C.; Neogi, A.; Chakraborty, S.; Bapu, V.P.B.R.; Banik, S.; Sankaranarayanan, S.K.R.S.; Anand, S. Adhesion of Impure Ice on Surfaces. *Mater. Horizons* **2024**, *11*, 419–427. [CrossRef]
43. Wang, C.; Zhang, W.; Siva, A.; Tiea, D.; Wynne, K.J. Laboratory Test for Ice Adhesion Strength Using Commercial Instrumentation. *Langmuir* **2014**, *30*, 540–547. [CrossRef]
44. Rønneberg, S.; He, J.; Zhang, Z. The Need for Standards in Low Ice Adhesion Surface Research: A Critical Review. *J. Adhes. Sci. Technol.* **2020**, *34*, 319–347. [CrossRef]
45. Rośkowicz, M.; Godzimirski, J.; Komorek, A.; Jasztal, M. The Effect of Adhesive Layer Thickness on Joint Static Strength. *Materials* **2021**, *14*, 1499. [CrossRef]
46. Dempsey, J. Scale effects of the fracture of sea ice. In *The Johannes Weertman Symposium. The Minerals, Metals and Materials Society*; University of Michigan: Ann Arbor, MI, USA, 1996; pp. 351–361.
47. Cole, D.M. The microstructure of ice and its influence on mechanical properties. *Eng. Fract. Mech.* **2001**, *68*, 1797–1822. [CrossRef]
48. Maus, S. The tensile strength of sea ice: Revising its dependence on microstructure and growth velocity. In Proceedings of the 27th Conference on Port and Ocean Engineering Under Arctic Conditions, Glasgow, UK, 12–16 June 2023; p. 41.
49. Makkonen, L. Solid fraction in dendritic solidification of a liquid. *Appl. Phys. Lett.* **2010**, *96*, 091910. [CrossRef]
50. Horjen, I. Numerical modeling of two-dimensional sea spray icing on vessel-mounted cylinders. *Cold Reg. Sci. Tech.* **2013**, *93*, 20–35. [CrossRef]
51. Blackmore, R.; Makkonen, L.; Lozowski, E. A new model of spongy icing from first principle. *J. Geophys. Res.* **2002**, *107*, D21. [CrossRef]
52. Nield, D.A.; Bejan, A. *Convection in Porous Media*, 3rd ed.; Springer: Berlin/Heidelberg, Germany, 2006.
53. Rees Jones, D.; Grae Worster, M. A physically based parametrization of gravity drainage for sea ice modeling. *J. Geophys. Res.* **2014**, *119*, 5599–5621. [CrossRef]
54. Worster, M.G.; Rees Jones, D. Sea-ice thermodynamics and brine drainage. *Phil. Trans. R. Soc. A* **2015**, *373*, 20140166. [CrossRef] [PubMed]
55. Hobbs, P. *Ice Physics*; Clarendon Press: Oxford, UK, 1974. 837 pp.
56. Pruppacher, H.R.; Klett, J.D. *Microphysics of Clouds and Precipitation*, 2nd ed.; Springer: Dordrecht, The Netherlands, 1997; Volume 18, 954p.
57. Maus, S. *Physics and Chemistry of Ice*; Royal Society of Chemistry: Cambridge, UK, 2007; pp. 371–382.
58. Maus, S. The plate spacing of sea ice. *Ann. Glaciol.* **2020**, *61*, 408–425. [CrossRef]
59. Freitag, J. Untersuchungen zur Hydrologie des Arktischen Meereises—Konsequenzen für den Stofftransport. Ph.D. Thesis, Universität Bremen, Bremen, Germany, 1999.
60. Maus, S. Growth rate dependence of the permeability and percolation threshold of young sea ice. *Faraday Discuss.* **2025**, *258*, d4fd00172a. [CrossRef] [PubMed]

61. Puolakka, O. Droplet supercooling in marine icing tests. *Cold Reg. Sci. Technol.* **2024**, *219*, 104121. [[CrossRef](#)]
62. Petrich, C.; Langhorne, P.J.; Sun, Z.F. Modelling the interrelationships between permeability, effective porosity and total porosity in sea ice. *Cold Reg. Sci. Techn.* **2006**, *44*, 131–144. [[CrossRef](#)]
63. Samuelsen, E.M.; Edvardsen, K.; Graversen, R.G. Modelled and observed sea-spray icing in Arctic-Norwegian waters. *Cold Reg. Sci. Technol.* **2017**, *134*, 54–81. [[CrossRef](#)]
64. Deshpande, S.; Sæterdal, A.; Sundsbø, P.A. Experiments With Sea Spray Icing: Investigation of Icing Rates. *J. Offshore Mech. Arct. Eng.* **2024**, *146*, 011601. [[CrossRef](#)]
65. Eicken, H.; Weissenberger, J.; Bussmann, I.; Freitag, J.; Schuster, W.; Dlegado, F.V.; Evers, K.U.; Jochmann, P.; Krembs, C.; Gradinger, R.; et al. Ice tank studies of physical and biological sea ice processes. In Proceedings of the 14th IAHR International Symposium on Ice (Potsdam 1998), Potsdam, NY, USA, 27–31 July 1998; Volume 1, pp. 363–370.
66. Petrich, C.; Brekke, M.O.C.; Myrnes, M.; Maus, S.; Salomon, M.; Woelk, S.; Grydeland, T.; Jenssen, R.O.; Eicken, H.; Oggier, M.; et al. Mosideo/cirfa tank experiments on behavior and detection of oil in ice. In Proceedings of the 25th International Conference on Port and Ocean Engineering Under Arctic Conditions, Delft, The Netherlands, 9–13 June 2019.

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