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ICING FACTORS AFFECTING RAILWAY TRAFFIC

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ABSTRACT

Niklas Kandelin: Icing Factors Affecting Railway Traffic
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Cold weather causes problems for many different areas, including railway traffic. Low temperature itself can cause problems, but a more significant problem is the ice that cold weather causes. Ice build-up hinders the operating of a train, and it affects both infrastructure and rolling stock. Ice covers railway tracks and stops railway switches from working and can break power lines. Ice build-up increases the weight of a train increasing the strain on the machine, and it can jam brakes and doors, and lower visibility for the operator.

Because of the severity of problems caused by icing, it is studied extensively. Icing in nature can happen mainly in two different ways, by in-cloud icing or precipitation icing. Precipitation icing happens when a liquid water drops fall on a surface and then freeze, while in-cloud icing happens when water freezes from a cloud or fog. Depending on the conditions, such as temperature, wind speed and ice formation type, ice type can change. Ice can be either opaque and porous rime ice, or clear and dense glaze ice, or a mixture of both.

Icing can be studied with modelling or empirically. As a complex phenomenon, icing is hard to model, and many of the models are very situational. A TURBICE model can be used to model icing on wind turbine blades. Another model can be used for modeling icing around a cylinder. In this study icing is studied empirically using the Icing Wind Tunnel (IWiT), where ice is accreted in a wind tunnel in a cold room. This method can be used to copy natural icing, and it can be used to accrete ice rime ice or glaze ice, or mixed glaze ice.

Ice prevention methods can be divided in two ways, into anti-icing and de-icing, or into active and passive methods. Anti-icing methods prevent ice from accreting, and de-icing methods remove ice. Active methods apply when needed, and passive methods work on their own. Most efficient ice prevention is combining methods. In railway traffic, de-icing methods are used. There are de-icing carts, that clear ice from tracks as they drive, and for the train itself, there are de-icing facilities, where hot water or chemicals like propylene glycol are used in de-icing. De-icing is time and energy consuming. Anti-icing can be done with coatings and heaters. Railway switches often have heaters, as they are very vulnerable to icing, and essential for train operation.

In this study, the primary purpose was to test different icing conditions and material properties and how they affected de-icing and ice adhesion. This was done by using samples with top shaped like a train roof and use the icing wind tunnel to accrete three different ice types on them. The ice-covered samples were brought to room temperature, where they were set at a 45-degree angle to shed the ice off as it melted. The de-icing time was then recorded, and the differences in de-icing were connected to differences in ice and material properties. Icing tests also included a set of ice adhesion samples using the same ice types and materials for the samples, to more accurately know about ice adhesion's connection to de-icing.

The de-icing time was used to determine how different factors during icing and in samples affected icing, but it was noticed that the de-icing time alone was insufficient. Instead, a value of time divided by mass was used, because it was noticed how mass affected de-icing time. Using this value, other factors could more accurately be studied. Sample shape was noticed to have a clear effect on de-icing. Even small details added to the shape of the curve on the roof increased icing time. Another factor with great impact was the sample material. Aluminum de-iced fastest, possibly because of better thermal conductivity. Ice types had also affected de-icing clearly, with rime ice being hardest to de-ice, and glaze ice the easiest.

The experiments in this study showed how complex an issue icing is for railways. Icing is affected by many factors. Some of these factors, and their effect were hard to determine in these experiments due to many variables. More research is needed to increase the understanding on icing, and further better cold weather performance of railway traffic.

Keywords: Railway traffic, cold weather, ice, icing research, anti-icing, de-icing

TIIVISTELMÄ

Niklas Kandelin: Rautatieliikenteen jäätymisen aiheuttamat tekijät
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Kylmä sää aiheuttaa ongelmia monella eri alueella, mukaan lukien rautatieliikenteessä. Kylmä ilma itsessään aiheuttaa ongelmia mutta merkittävämpiä ongelmia aiheuttaa kylmässä muodostuva jää. Kertyvä jää haittaa junan toimintaa, ja se vaikuttaa sekä ympäröivään infrastruktuuriin ja juniin. Jää peittää raiteita ja estää rautatievaihteita toimimasta ja se voi myös rikkoa voimalinjoja. Kertynyt jää kasvattaa junan painoa lisäten rasitusta kulkuneuvolle, ja se voi jumittaa jarrut sekä ovet, ja haitata kuljettajan näkyvyyttä.

Jäätymisen vakavien haittojen takia sitä tutkitaan laajasti. Jäätyminen luonnossa tapahtuu joko sateen aiheuttaman jäätymisenä tai pilvessä tapahtuvana jäätymisenä. Sateen aiheuttamaa jäätymistä tapahtuu, kun vesipisarat putoavat pinnalle ja jäätyvät. Pilvessä tapahtuva jäätyminen tapahtuu, kun pilvenä tai sumuna olevat vesipisarat jäätyvät suoraan pinnalle. Olosuhteista, kuten lämpötilasta, tuulen nopeudesta ja jäätymistyypistä riippuen, jäätyyppi voi muuttua. Jää voi olla joko läpinäkymätöntä, huokoista huurrejäätä (rime), tai tiiviimpää, läpinäkyvää kirkasta jäätä (glaze), tai näiden sekoitusta.

Jäätymistutkimus sisältää paljon jäänkertymismallinnusta. Monimutkaisena ilmiönä jäätymistä on vaikea mallintaa, ja monet mallit toimivat vain tietyissä tilanteissa. TURBICE-malli on kehitetty mallintamaan jäätymistä tuulivoimalan lavoissa. Toinen mahdollinen malli on käytössä sylinterimäisen kappaleen jäätymistä varten. Jäätymistä tutkitaan myös empiirisesti, kuten tässä tutkimuksessa käytettävä jäätävä tuulitunneli, jossa kylmähuoneessa olevassa tuulitunnelissa voidaan kerryttää jäätä. Tämä tapa kerryttää jäätä tuottaa luonnollista jäätymistä muistuttavaa jäätä, ja sillä voidaan tehdä huurretta, iljannetta, tai niiden sekoitusta.

Jäänestokeinot voidaan jakaa jäänestoon ja jäänpoistoon. Vaihtoehtoisesti ne voidaan jakaa aktiivisiin ja passiivisiin keinoihin. Jäänehkäiseminen tarkoittaa jään muodostumisen estämistä, ja jäänpoisto tarkoittaa kertyneen jään irrottamista. Aktiivisia keinoja käytetään tarvittaessa, ja passiiviset toimivat jatkuvasti ilman käyttäjää. Tehokkaimmat systeemit yhdistelevät eri keinoja. Junaliikenteessä käytetään jäänpoistovaunuja raiteilla, ja junille on jäänpoistolaitteistoja, joissa käytetään kuumaa vettä tai kemikaaleja, kuten propyleeniglykolia. Jäänpoisto on yleensä aikaa- ja energiaa kuluttavaa. Jäänehkäisyä tehdään pinnoitteilla ja lämmittimillä esimerkiksi vaihteissa, jotka ovat erittäin herkkiä jäätymisongelmille. Lämmitys vie paljon energiaa, ja pinnoitteet kuluvat ajan myötä.

Tässä tutkimuksessa päätavoite oli tutkia erilaisten jäätymisolosuhteiden ja materiaalien ominaisuuksien vaikutusta jään kertymiseen ja sen poistamiseen. Tähän käytettiin näytteitä, joiden yläpuoli oli muodoltaan junan katon mukainen. Näytteille kerrytettiin kolmea jäätyyppiä, huurretta, iljannetta, ja niiden sekoitusta. Sen jälkeen näytteet tuotiin huoneenlämpöön, jossa 45 asteen kulmaan asetettujen näytteiden päällä ollut jää valui pois. Tähän kulunutta aikaa käytettiin vertailukohtana. Kokeissa tehtiin myös jäänadheesionäytteet käyttäen samoja materiaaleja ja jäätymisolosuhteita auttamaan junanäytteiden tulosten tulkintaa.

Jäänpoistumisaikaa käytettiin määrittämään, kuinka eri tekijät koejärjestelyssä vaikuttivat jäätymiseen. Jään massan huomattiin vaikuttavan aikaan erittäin paljon, joten muiden tekijöiden vertailussa käytettiin massaa jaettuna ajalla. Merkittävimpiä vaikuttavia tekijöitä jään poistumiseen olivat näytteen muoto ja materiaali, sekä jäätyyppi. Jää irtosi huoneenlämmössä paljaasta alumiinista helpommin kuin pinnoite, mikä johtui luultavasti lämmönjohtuvuudesta. Jäätyypeistä huonoiten irtosi huurre, parhaiten iljanne.

Kokeet tässä tutkimuksessa näyttivät, kuinka monimutkainen ongelma jäätyminen on rautatieliikenteelle. Jäätymiseen vaikuttaa monet tekijät, sekä jäätymisolosuhteet ja materiaalin ominaisuudet. Näissä kokeissa oli vaikea määrittää kaikkien tekijöiden vaikutus monien muuttujien takia. Enemmän tutkimusta tarvitaan jäätymisen ymmärtämiseen ja rautatieliikenteen kylmänilmankeston parantamiseen.

Avainsanat: rautatieliikenne, jää, jäätutkimus, jäätymisenesto, jäänpoisto
Tämän julkaisun alkuperäisyys on tarkastettu Turnitin OriginalityCheck –ohjelmalla.

PREFACE

This master thesis was conducted at the Tampere University Faculty of Engineering and Natural Sciences, Materials Science and Environmental Engineering, Icing Research Group, during 2020-2021. The work was done in the Nordic Icing Centre of Expertise, NoICE project funded by EU/Interreg Botnia-Atlantica, Region Västerbotten and the Regional Council of Ostrobothnia. The project partners are Luleå University of Technology, Novia University of Applied Sciences, Tampere University, Umeå University and University of Vaasa. The thesis was supervised by Prof. Jun Yu and Dr. Heli Koivuluoto, whose guidance and advice were important in making this thesis and made the final product much better.

I also was privileged to enjoy the help of my colleagues, who guided me in the experimental works, and without whom the work could not have been completed. Their help and support were vital in conducting the experiments needed for this thesis, and they instructed me well when I needed it.

Support from my girlfriend Mari during this thesis, and my studies overall, was significant and essential, and helped me keep working forward.

Tampere, October 16, 2021

Niklas Kandelin

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1. INTRODUCTION

In Finland, Sweden and Norway, railway traffic is an important travelling method. Railway traffic in these countries is mainly state owned and provides an important basic service by giving citizens access to travelling across the country, as well as moving cargo. These services are an essential part of society. Finland, Sweden, and Norway are all large, sparsely populated countries, so a reliable network of railway for long distance travel is a part of peoples' well-being. These countries also have similar climates with long, cold, and snowy winters, which has been a challenge for railway traffic. [1,2,3]

Importance of railway traffic is increasing. Trains are more energy efficient than cars in fuel consumption resulting in less emissions [4]. Trains are also a safer option. In 2008, 1498 people were killed in EU railway accidents, and 1390 people were seriously injured, while over 8000 people were killed in road accidents same year [5]. Trains are often a more comfortable travelling option, as they offer more space and comfortable seating for the passenger. They also make working while travelling possible, because travelers do not have to focus on traffic, and they have enough space for laptops. Trains are faster than cars as well, making shorter travel times possible.

A long and cold winter is a hinderance for the reliability of railway traffic. For example, the Finnish railway company is notorious for being late in the winter. Winter in Nordic countries is typically long, and there is a lot of snowfall. In autumn, it is common for the weather to change from rainy to freezing in a span of one day. These cold weather conditions typical in Nordic countries are favorable for icing. Other cold related problems are snow packing and contraction and brittleness of materials due to lower temperatures [6, 7, 8].

The purpose of this study is to gain understanding on how different ice types affect the icing behavior of rolling stock. In the first part of the study, a literature review is conducted. The literature review provides context for the study, presents earlier research and known theories. Here, the effects of cold weather, especially icing, are studied, and the challenges caused by icing are discussed. Ice accretion as a phenomenon is also studied, as well as the current methods available for ice-prevention. Chapters 2-4 present the findings of this initial literature review.

Next, the methods of this study are presented in Chapter 5. The experiments in this study are conducted with an Icing Wind Tunnel (IWiT) in the Ice Laboratory in Tampere University Hervanta Campus as a part of Nordic Icing Centre of Expertise, NoICE project (EU/Interreg/Botnia-Atlantica). Icing wind tunnel is used for ice accretion of the samples, which are modeled after train carts. The aim in this study is to research possibilities of improving railway traffic's cold weather performance. To achieve this, different icing conditions are used to test how different properties of trains and ice affect railway traffic. They will be covered in different ice types, and then the samples will be de-iced in room temperature.

The results of the experiments are explained in Chapter 6. The icing conditions and material properties affecting the results are also examined. The significance of different factors and their connections to each other is analyzed. Conclusions are presented in Chapter 7 with suggestions for further research.

2. EFFECTS OF COLD WEATHER AND ICING ON RAILWAY TRAFFIC

Cold weather conditions are a significant challenge for society in Nordic countries. Long winter means exposition to cold weather for long periods of time, with winter lasting regularly for over six months in the northern parts of the country. Up to half of the annual precipitation can be snow in the northern Finland. [9]

Significance of railway traffic as a transport method is great and still increasing. In cargo transport, railway is a more efficient method than trucks and causes less emissions, which is an important factor in comparing transport methods from the ecological point of view [10]. A transition from motor vehicles towards railway traffic is a viable option for reduction of emissions because transportation is a significant source of emissions, and railways can transport people and goods while creating less emissions [11].

Aim of this chapter is to investigate the winter weather and icing conditions in Nordic countries and determine their effect on the railway traffic. Especially the effect of icing on railways, both rolling stock and infrastructure, is viewed. Other cold weather effects on railway traffic, such as snow build-up and cold temperature effect on material properties are also investigated. For example, decreased temperature makes tracks and rolling stock material more brittle, changing their properties, and causing problems that do not exist during warm season. [6,7]

The fluency and convenience of railway traffic is significantly hindered by winter. Additional speed limits are often used in winter because trains need to slow down in winter conditions. This is because winter weather changes the track geometry. Cold contraction shortens the tracks, leaving gaps in the rails. Snow packing under the rails elevates them unevenly, when one part of the track is elevated more than the adjoining parts. Because of this, the track smoothness is lowered [7, 12]. High track smoothness is a requirement for reaching high speeds safely [12]. A bar graph in Figure 1 depicts punctuality of trains in long distance passenger transport in Finland and shows a moderate to severe drop during winter months. January 2019 has a very low punctuality for train traffic, only 58,4 percent. February and March of 2019 are also under 80 percent.

A similar drop does not show from same months in 2020, when the winter in Finland was much warmer [14].

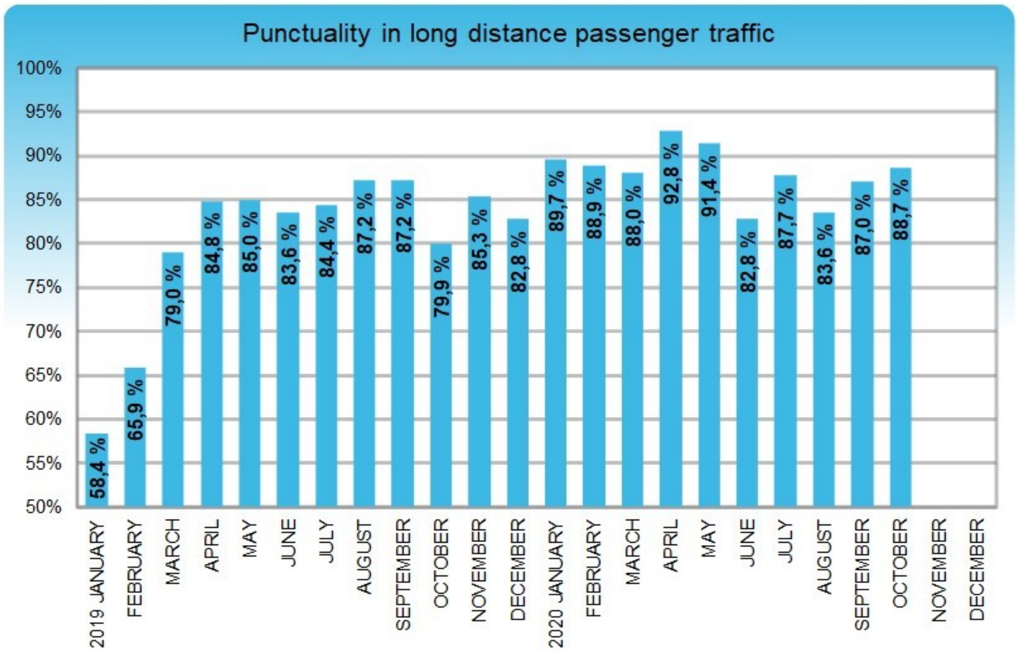

Figure 1: Punctuality of passenger trains by month between January 2019 and December 2020 for the Finnish railway. A drop in punctuality can be seen during winter months in 2019. [13]

Major winter effects concerning railways are snow and ice build-up on rolling stock and infrastructure, icing of electrical components, and hanging ice from overhead structures [7]. Railway companies aim to be prepared for winter every year, but delays and even cancellations are still unavoidable and the cost of these is very high for the both the company and society [15, 16]. The freezing of the ground changes the shape of the ground surface, displacing the tracks. The unevenness of the tracks caused by this require temporary speed limits, that are lower than normal, to be set in winter and spring in Finland [17]. In a study done in Umeå University the connection between train delays and weather was modeled, and temperature and humidity clearly affected the train punctuality. Lower temperature and higher humidity clearly caused delays. [18]

Unpredictable weather is also a source for cold weather problems. In winter the temperature is below freezing with a chance of heavy snowfall, but spring and autumn have their own weather-related issues. Autumn and spring in Nordic countries have a high fluctuation in daily temperatures. Temperature can rise above freezing and drop below it fast, usually between night and day, but there can also be longer periods of cold followed by a warmer weather. This leads to the snow melting, and then freezing, creating ice on the ground [19]. These periods of fluctuation are often coincided with heavy rainfall, which can fall as snow or water, or as a mixture of both, to create wet snow [19].

2.1 Infrastructure

Infrastructure in railway traffic includes the railway tracks and the ballast underneath them, platforms and switches, and the overhead electrical wires and other stationary components [7]. These structures are affected by cold weather and icing. As infrastructure covers many different types of structures, there are different ways that winter weather affects it.

As the stationary part of railway traffic, the infrastructure is susceptible to snow and ice build-up. Heavy snowfall and long periods of cold weather during winter months accumulate a large mass of snow and ice, which can at its worst lead to even a derailment of the train, when the track geometry changes due to ice forcing rail parts out of place [7, 17]. Ice and snow build-up on tracks can also make the train move slower, or even get stuck, resulting in train delays [7]. Figure 2 depicts snow-covered tracks.

Figure 2. Railway tracks covered in snow. [20]

Tracks also suffer from decreasing ductility because the cold weather causes steel to become more brittle. Stiffness of the tracks is important for trains at high speed. This affects adversely on maintenance of the tracks and passenger comfort. Track brittleness affects most significantly older rails, and this problem occurs in very low temperatures.

Older rails are more susceptible because the materials that are used today have developed over a long period of time. Oldest railways are made from iron, which is more brittle than steel. After changing to steel, finding the right composition for it took a long time [20]. Increased track brittleness leads to increased wear and can even damage the wheels enough to cause an axle failure. Figure 3 shows statistics on the frequency of rail breaks for each month of the year from 2008 to 2012. Significantly more rail breaks happen during colder months. [6, 7, 8, 22]

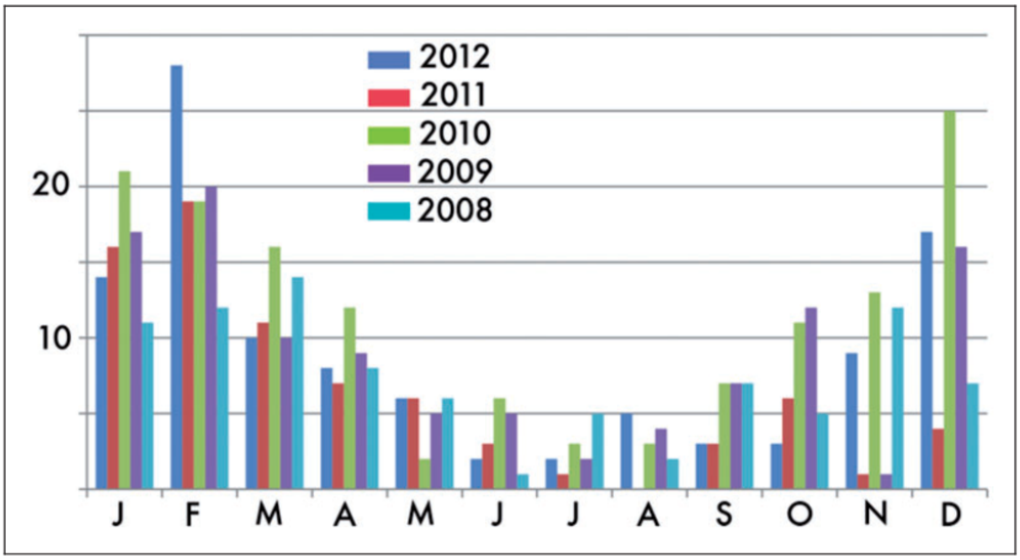

Figure 3. Number of rail breaks each month between 2008-2012 in Sweden [23]

Snow and wind as a combination are the hardest condition for track switches, which are the moving track parts meant for directing the train to the right track. Wind causes snow to move horizontally, packing it between switches moving part and preventing its movement [7, 35]. In Figure 4, snow packing on a railway switch is illustrated. Figure 4 shows the gaps between rails full of snow. Packed snow can prevent switch movement, or lodge it halfway between positions, creating a possible derailment of the train. [7, 23, 24]

Figure 4. A track switch covered in ice and snow, creating a hazard. [25]

Another part of the railway infrastructure are the power lines over the track, or the overhead lines. This also includes the pantograph, which is the structure on the roof of the train, that connects the power line with the train. They are vulnerable to cold weather, because they are out in the open with very little protection against the weather. Pantograph can accumulate snow easier than the power line alone because the pantograph is a more solid structure. Pantograph is also cooled at high speed because of the air flow around it works like strong wind. This does not happen to the overhead lines, as they are stationary [26]. Power lines also become stiffer at low temperatures, and accreted ice can cause arc formation [27]. Stiffer line is easier to break, and arcing can cause problems with electricity conduction, or even break the lines [28]. While snow is not directly a problem for the powerlines, as the snow accretion is minimal on the line itself, snow can still cause for example tree branches to fall on the powerline. However, the vicinity of the track is usually kept free of trees partly for this reason [7]. Figure 5 depicts snow covered wires and a de-icing cart that is used to clear them.

Figure 5. Frost covered overhead wires and a de-icing car. [29]

The biggest problem the track bed encounters in winter is frost [7, 28]. The water that has been absorbed in the ground freezes in the cold weather, and the ground gets harder, and changes shape. Ground freeze creates problems and damages the track when the ground surface elevates under it. The elevation changes from one point to another, and this unevenness results in changed track geometry. This is called frost heaving [28]. The severity of the ground freeze effects depends on the amount of water that is in the ground. Most water on the ground is result of rainfall, which is heaviest during autumn. Autumn usually has also freezing temperatures, often going from freezing to warm within only one day. These factors together are very suitable for freezing ground [30]. Trains need to slow down because of the frozen ground [31]. One way to prevent ground freeze damage is to build a layered track bed. Finnish railway has seven different layers of ground or insulator under the tracks. [32, 33]

2.2 Rolling stock

Rolling stock constitutes of the moving parts of railway traffic, which are the railway engines and the carts. The struggles for rolling stock include ice build-up and added weight from it. Rolling stock also contains a lot of sensitive components, like electronics. Their exposure to snow and water can be a problem if these parts are not properly protected. [7]

Ice build-up in rolling stock on a single train can weigh hundreds of kilograms [7]. This puts extra strain on the carts and the engine. All carts and engines need to be sturdy enough to be able to take the extra weight, and increased burden on the supporting structures. Carts need to be insulated against cold for passenger comfort, and to protect more delicate parts, like tanks, hoses, wires and pipes. Icing hinders passenger safety for example by making steps and floor slippery, and passengers also inadvertently bring in snow, which will then melt and possibly re-freeze. [7, 34, 35]

Ice build-up can jam doors, which reduces passenger comfort and safety. Doors not opening when needed can be a significant inconvenience to the passengers. If doors will not close when needed, it is a hazard to the passengers. Keeping the doors clear of snow and ice is important during winter [36]. South Western Railway company in Britain uses de-icing spray on doors to keep them from jamming [37]. In Figure 6, a train with significant icing is depicted.

Figure 6. Ice covered train. [38]

Another problem area in the train carts is their underside. It is in an exposed position, and often has a lot of equipment attached. While it is supposed to be well covered, it is also required to be accessible for maintenance purposes. And even though there is protection from ice and snow, the cold temperature is not as easy to keep out, so the equipment needs to be able to withstand cold. [7]

Underside of the train cart is also where the brakes are located. Brake system has a lot of moving parts, which can freeze stuck. Some materials commonly used in brake systems, like steel and aluminum, are not suitable to be used in brakes in cold temperatures, because cold contraction changes their geometry. The brake geometry has to be very exact, so cold contraction can diminish their braking efficiency. This should be kept in mind when designing the train. For example, composite materials with metals as the matrix are used [39]. Covering the vulnerable parts and de-icing regularly is vital to keeping the brakes functional during winter. Figure 7 is view of the cart’s underside, where the brakes, and many other parts, are covered in snow. [7, 40]

Figure 7. Snow packed on the underside of a train. [7]

Ice can hinder visibility from the train, making the operator’s job harder. Windows can be frozen over or snowed shut. Heated windows are required for the operator to see, but even then, at a high-speed, which can be 300-350 km/h for fastest trains, wind chill will be a challenge [41]. This means that windows need to be durable enough to stand the heating when the train is not moving and there is no wind chill. Other critical icing points are the windshield wipers, where the motor might break, if the wipers freeze into the window. [7, 8]

Lowered visibility caused by cold weather is one of the many factors affecting the train operator. They face many direct and indirect factors lowering their effectiveness in their work. Figure 8 shows a train engine covered in snow and ice. The front view is obscured by snow, and even snowless part of the window is fogged over. [8]

Figure 8. A train engine covered in ice, with the front window frozen over. [42]

Even train motors encounter cold weather problems, although they are inside the cart. Water getting to the motor can cause electric failures, and it can reach the engine for example because of condensing water, or water used for de-icing. Temperature differences cause condensation even inside the motor. Because of this, insulation is an important feature for trains, and should be taken into account when designing the carts. [7]

Wheels are an important part for the train, and their role in the train's smooth passage is vital. As a moving part, ice accretion on the wheels is not easy, but when the train stops, ice can easily form enough to hinder, or even stop, the wheels of the train from moving. Ice can cause the brakes to be stuck, and when train starts moving again, but a stuck brake is keeping the wheel in place, it will slide, and the wheel becomes a flat. Accreted ice also decreases friction, making braking harder. Also, in case of differently frozen wheelsets, different frictions can alter the wheelset alignment. In Figure 9, a train wheel covered in ice is shown. A wheel frozen like this cannot move freely. [7, 23]

Figure 9. Train wheel covered in ice. [42]

The multitude of problem areas in railway traffic icing make it challenging to develop protection against icing. Every part of the railway has their unique problems regarding different weather conditions. Understanding the ice accretion process is important in developing ice prevention methods that fit the railway traffic's needs.

3. ICE ACCRETION AND STUDY OF ICING

In this chapter, ice accretion is explained. Atmospheric icing is a phenomenon of great complexity and many affecting factors, like many others in nature. A lot of parameters influence the features of the ice that is accreted. Most important ice features are ice type, ice accretion rate and ice adhesion. Atmospheric icing can be either precipitation icing or in-cloud icing. Precipitation icing happens when liquid water falls on the surface and freezes on it. In-cloud icing means icing that happens in a cloud, or in fog for example. Different ice types are possible, depending on the icing conditions. Ice can be divided into three different types: glaze ice, rime ice and mixed ice. Glaze is clear, dense, and hard ice. Rime ice is white and less dense, and softer. Mixed ice is a combination of glaze and rime and has properties from both. The accreted ice type is not defined by only temperature and icing type. Other factors like wind speed, air humidity, precipitation and phases of water determine which type of ice is accreted. Material properties influence ice type as well, like surface topography and chemistry, wetting behavior, and surface temperature. The effect of these factors is explained in detail later in this chapter. Temperature ranges for the ice types vary, and both in-cloud and precipitation can form either glaze or rime. Figure 10 depicts the three different ice types. [27, 44, 45]

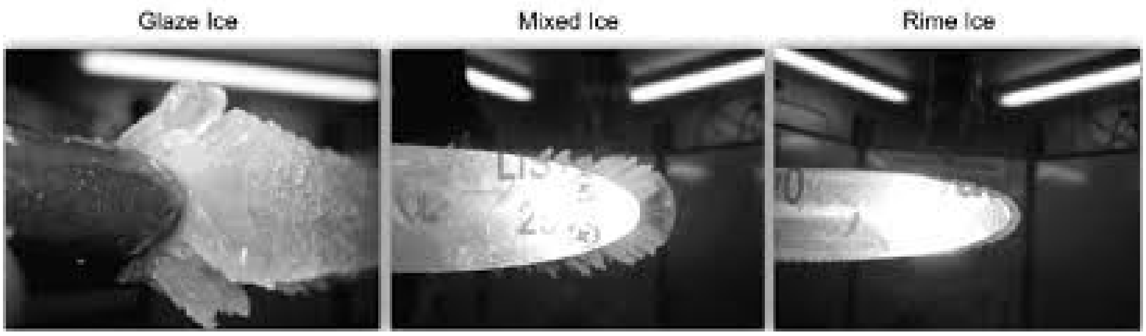

Figure 10. Different ice types. [44]

Water droplet can either stick to the icing surface or bounce of it on collision. A supercooled droplet will not bounce, it will stick to the surface regardless of whether it is dry or wet. Supercooled droplets freeze immediately, and other droplets either freeze or join the water layer on the surface. Conversely, snow particles do not stick so easily. Factors like impact velocity, humidity and temperature, and particle features like wetness affect the sticking efficiency. Dry particles bounce more easily if there is no liquid layer, and lower impact speeds increase sticking efficiency. [44, 45, 46, 48]

Impact velocity of the particle influences the ice type. The water droplet's time to freeze on the surface is important because droplet moves on it. Impact velocity increasing means that the sticking efficiency decreases. [45, 47]

Glaze ice is formed at higher temperatures, from freezing rain. Rime is formed mainly by in-cloud icing, in fog for example. Changing weather parameters, however, will also determine the forming ice type. Roughly speaking when droplets are more tightly together, and freeze slower, they form glaze. When freezing is faster, and droplets are not so well arranged, rime is formed. This is why glaze is denser than rime. Figure 11 shows ice formation types and temperatures for different ice types. [44, 45]

Ice type	Icing type	General characteristics	Adhesion/ Cohesion	Density (kg/m^3)	Temperature (°C)	MVD	LWC (g/m^3)
Glaze	P	transparent, dense	Strong	900	-10 – 0	100 µm-2mm	up to 1.2
	I				-6 – 0	30-50 µm	1 – 10
Wet snow	P	White, eccentric	weak (forming), strong (freezed)	300-600	0 – 3	several mm	1 – 10
Hard rime	I	Opaque, rough	strong	600-900	-20 – 0	5-30 µm	around 0.4
Soft rime	I	White, feathery, fragile	low to medium	200-600	-20 – 0	5-30 µm	under 0.4

Figure 11. Formation parameters of different ice types, and some ice type properties. Icing type is either precipitation (P) or in-cloud (I). [46]

Precipitation icing (P) happens during rain or snowfall, when the precipitation freezes as it contacts the surface. If temperature is between 0 and 3 degrees Celsius, then the falling snowflakes contain liquid water, which enables them to bond weakly with each other. After this, the bond strengthens when temperature drops below zero degrees Celsius. Rain causes precipitation icing when the temperature is below zero. This happens for example with freezing rain. In-cloud icing (I) happens when there are clouds or fog, that is below zero degrees. These clouds have super-cooled droplets in them, which freeze upon contact with the surface. [47, 49, 50]

3.1 Weather conditions affecting icing

Weather has a great effect on icing. Most apparent effect on icing is temperature, which has to be under zero degrees Celsius for water to freeze. Second thing needed for ice is water, so there needs to be enough humidity, for example rain, for ice to form. Snow can also form ice, especially when combined with liquid water. In the experimental part ice accretion is done with the Icing Wind Tunnel, which increases the cold room humidity to about 70-80%. [45, 49]

In nature, a specific set of conditions can cause freezing rain, which results in fast ice accretion. Freezing rain creates glaze ice. Freezing rain is liquid water at zero degrees Celsius or lower. Water can remain liquid even at subzero temperature when it travels through cold air but does not have enough time to freeze into ice pellets. It freezes upon contact with a process known as nucleation. [47, 49]

Nucleation is a crystallization process. Water needs a solid point to freeze into ice, so pure water drops do not freeze. Once they touch the surface, the drops start freezing immediately. [51] Freezing rain happens when frozen raindrops pass through a warm layer of air. This causes the drops to melt. Then the drops need to go again through freezing air, where their temperature falls below freezing, but they remain liquid. Freezing rain happens only in temperatures, where the droplets can unfreeze during their fall. [52]

Wind is also an important factor in ice formation. The speed and direction of the wind have a great effect on the shape of the icing layer. Wind speed can change what type of ice is formed. Wind speed changes the impact velocity, and as explained previously, that influences the ice type. In Figure 12 ice type formations are presented depending on the air temperature and wind speed.

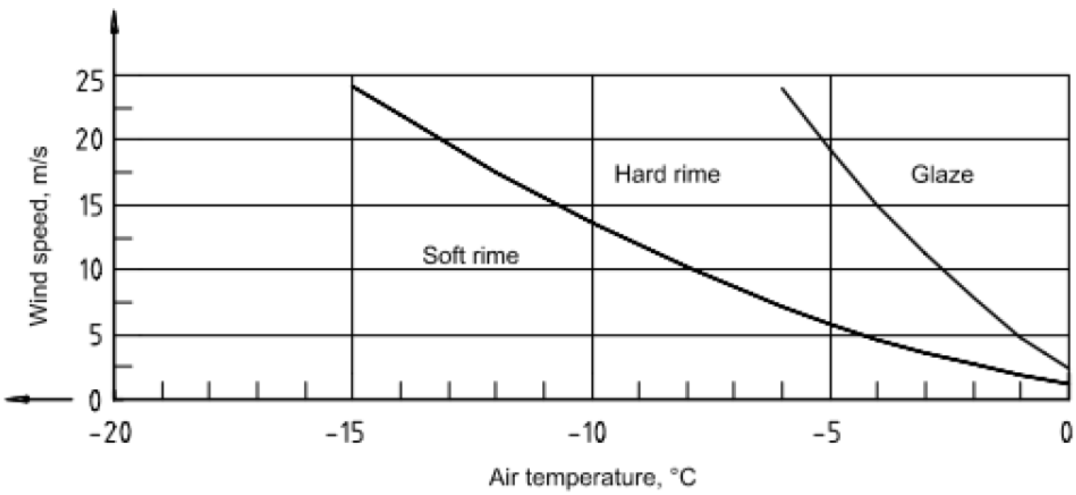

Figure 12. Wind speed effect on the ice type in different temperatures. [44]

Figure 12 shows how higher wind speeds extend the temperature area for the creation of glaze ice. Wind causes the water droplets to move faster. This prevents them freezing on the surface immediately. This means that glaze can form at a lower temperature. However, wind cannot make water into ice above zero degrees Celsius. [44, 52]

Wind speed also has an effect on the icing rate, not just ice type. In a study by K.J. Sanders and B.L. Barjenbruch [53], ice to water ratio was examined in relation to different wind speed. Test temperature was between -1 and -4 degrees Celsius. The study has shown that at wind speeds under 1,5 m/s the ice liquid ratio is 1. When wind speed rises above 4.6 m/s, ice to water ratio starts to rise. Ice to water ratio is about 1.2 when wind speed is 4.6-7.65 m/s. When wind speed is above 7.65 m/s, ice to water ratio was 1.9. The study shows a clear increase of icing rate with the increase of wind speed.

3.2 Material properties affecting icing

Ice accretion and adhesion are affected by the material properties. Metals, like steel and aluminum, are most common train materials, for both the trains and the rails [54]. Ballast and concrete are used under the tracks to make a solid, sturdy base to lay the tracks on. Coatings are used to protect train cart materials. With coating, many important properties relating to icing can be improved. [12, 55]

Coating materials used to decrease icing have a wide variety. Coatings that have been studied and determined to increase icephobicity are for example polymethylsiloxane (PDMS), smooth silicone rubber and ultra-hydrophobic polycarbonate coating. PDMS coating has a very high icephobicity and can shed ice off easily. Slippery liquid infused porous surfaces (SLIPS) have also been studied for their icephobic qualities. Flame sprayed SLIPS has a low ice adhesion value and could therefore be a viable icephobic coating option. [56, 57]

Heat conduction of the surface material affects ice accretion during precipitation icing. Water droplet on the icing surface loses heat through heat conduction, and higher heat conduction makes this faster. [45, 58]

Wetting behavior of the icing surface affects ice adhesion. Wetting behavior determines how the water droplets act upon contact with the surface. Droplet movement on the surface increases icephobicity [45]. Hydrophobicity increases the droplet movement, which can reduce icing. Because of this, superhydrophobic surfaces can delay ice formation [59]. Droplets movement on the surface is dependent on the contact angle. Studies have shown, that when the contact angle grows, the ice adhesion strength decreases [60]. [44]

Superhydrophobicity has been shown as a possible option for icephobicity. However, some studies have shown, that superhydrophobicity does not always mean good icephobicity [61]. One of the main problems against using superhydrophobic surface for icephobicity is that the surface is damaged by icing. Another problem encountered in studies is humidity. In a very humid atmosphere, the anti-icing of superhydrophobic surfaces is greatly diminished [62]. The possibility for superhydrophobicity as an anti-icing surface is recognized by many studies, but their shortcomings are also pointed in many studies. [59, 61, 62, 63]

3.3 Icing models

To model icing, the weather parameters that affect it need to be defined. Most important meteorological parameters for modelling atmospheric icing are air temperature, wind speed and direction, and relative humidity. For precipitation icing, also precipitation rate and air temperature at the surface level matter. In-cloud specific parameters are liquid water content of the cloud and droplet size distribution. Different parameters are used by different models. Parameters for the models are dependent on the situation, that the model is used in. [27, 44, 50]

There have been models created to predict icing on different structures, and for different icing phenomena. For example, icing of power lines has been modelled by several studies, as they are vulnerable to ice, easily breaking under the added weight [64, 65]. Another very common icing modelling field is wind turbines and especially their blades. Ice modelling for wind turbines has been focused on the shape of the accreted ice because the ice changes the aerodynamics of the blade [46, 46, 66]. One commonly used model for wind turbine blades is the TURBICE model developed by Makkonen et al. [67]. There is also a model for in-cloud icing by Makkonen [58], known simply as Makkonen’s model (1981). Another icing model is the axial-growth model for horizontal unheated cylinder, developed by Lozowski et al. [66]. Another model for icing is Weather Research and Forecasting, often abbreviated as the WRF model. It is a Numerical Weather Prediction model (NWP). [50]

The shape of the surface and the primary icing method determine how well the model will fit, and therefore most models focus on a certain shape or structure. While most models are mainly good, problems appear when circumstances are too different from what they are meant model. Previously mentioned models all have their own areas of use, and struggle when outside their normal parameters, either structurally different situations or different weather conditions. [50]

In Makkonen's model icing rate can be modeled with an equation

$$\frac{dM}{dt} = \alpha_1 \alpha_2 \alpha_3 \omega v A \quad (1)$$

where α_1, α_2 and α_3 represent collision efficiency, sticking efficiency and ice accretion efficiency respectively. They are the correction factors, and their value is between 0 and 1. A is area and v is the velocity of the particles, and ω is the mass concentration of particles. Empirical data is used to determine the correction factors, and they are very dependent on the icing conditions. [45 ,58]

Collision efficiency α_1 is the ratio at which water droplets hit the icing surface, as some droplets, especially the smaller ones, can be directed by airflow to miss the icing object. [44, 45, 58]

Sticking efficiency α_2 is the measure of how much of the water droplets, or snow, that hit the surface, stick to the ice layer. Supercooled water droplets do not bounce but freeze immediately. Adversely, snow can bounce off. Snow increases the complexity of icing and therefore many icing models have a hard time modelling icing events with snowflakes. [44, 45, 58]

Ice accretion α_3 efficiency is a measure of how many of the particles contacting the material surface form ice on it. Some droplets do not freeze to from ice, leading to wet ice growth. The heat balance of the object surface affects the number of droplets that freeze. The surface heat balance follows equation

$$Q_f + Q_v = Q_c + Q_e + Q_l + Q_s \quad (2)$$

where Q_f is latent heat of freezing, Q_v is frictional heating of air, Q_c is loss of sensible heat to air, Q_e is heat loss due to evaporation, Q_l is heat loss because of warming of supercooled water to freezing point, and Q_s is heat loss due to radiation [58]. The ice accretion efficiency is strongly affected by how well the latent heat of freezing can leave the surface. [45 ,58 ,67]

Lozowski model is used for horizontal unheated non-rotating cylinder with perpendicular airflow. It works for both wet and dry conditions. The model was created in 1983, and a cylinder shape was chosen, because it works as a first estimate in many icing situations. In the model, first the impingement flux of droplets is calculated on small segments of the cylinder. Secondly, a steady-state heat equation is solved. Lozowski model is empirically fitted to numerical icing data. By comparing the data of the model with test results, it has shown to be relatively correct in its specified conditions. [50, 66]

TURBICE model is meant for modelling icing on wind turbine blades. Both glaze and rime can be modeled, and the model can include blades with anti-icing systems, like heated blades. The model can show the shape and size of accreted ice and includes the effect of liquid water on the blades. [50, 67]

TURBICE model has equations to account for the air flow and droplet trajectories. Figure 13 shows how TURBICE model can be used to estimate the shape of the ice. Blue line on the graph is the ice formation, and the black line is the turbine blade. [50, 67]

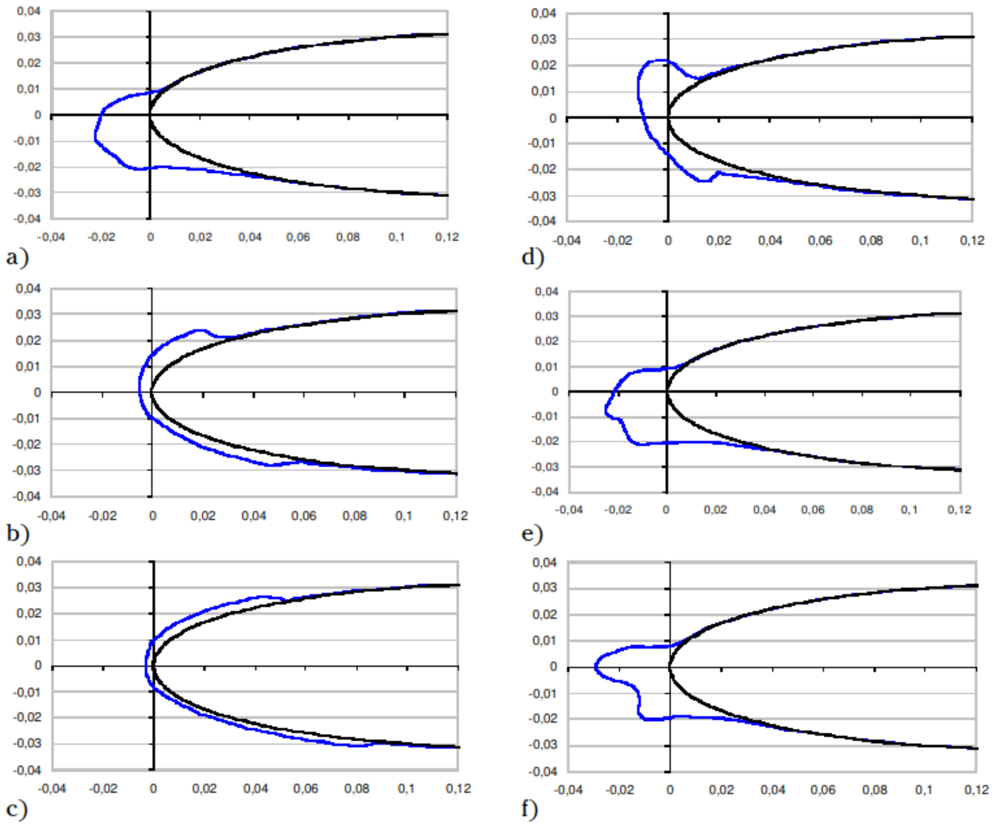

Figure 13. TURBICE simulation results for ice shapes in different air temperatures. The modeled temperatures are a) -27,8ºC b) -19,8ºC c) -13,9ºC d) -6,7ºC e) -3,9ºC f) -2,8ºC. [69]

In addition, the model considers the surface roughness of ice, which affects the heat transfer from the blade. Ice roughness equation uses meteorological parameters liquid water content, air temperature, free stream velocity and median volume of the droplet. TURBICE accounts for wet icing caused by blade heating and density of accreted ice as well [50, 67]. TURBICE has been tested both in laboratory and in practice. The modelled icing was close to the real results. However, close to 0 degrees Celsius, TURBICE is possibly less accurate.

Icing modelling programs can be used for simulating icing. Icing modelling programs are used for example in calculating shape and size of accreted ice. Modelling programs are commonly used for modelling icing on aircrafts. In FENSAP-ICE, developed by Ansys, an icing modelling program, 3D ice formation of glaze, rime or mixed ice can be calculated. The program can be used for any aircraft surface in any icing conditions. Detailed and complex icing events and accretion can be modeled, and their effect on the aerodynamics is calculated by the program. Using modelling program like FENSAP-ICE is useful because mathematical models are often very limited in what conditions they work in. Figure 14 shows an example of ice simulated with the modelling program. [70]

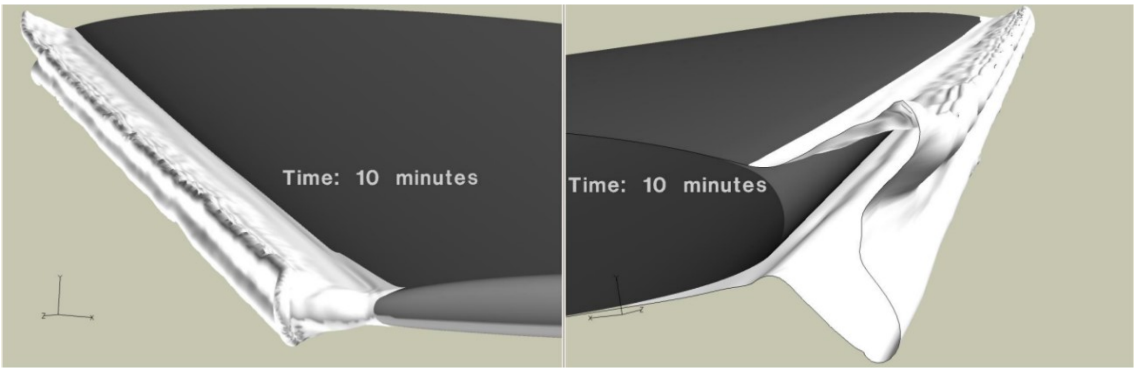

Figure 14. Simulated ice accretion on an airplane wing created using FENSAP-ICE. [70]

FENSAP-ICE can evaluate anti-icing performance in addition to just simulating ice accretion. The program is capable of using meshes generated in other programs. FENSAP-ICE can also generate its own icing protections. With no limitations on the object shape, many different objects can be modeled for icing and anti-icing with the program. [70]

3.4 Icing research empirically

Ice accretion is studied experimentally in different ways, and there are no standardized testing methods. In the ice laboratory at Tampere University different ice types can be created in the Icing Wind Tunnel (IWiT). This is done by controlling water and air flow rates through two nozzles in the IWiT. The room temperature can be lower to freezing, and -10 degrees Celsius is commonly used. Distilled water is used to spray water mist into the tunnel, which the wind tunnel blows downwards to the freezing surface. The test parameters that affect the accreted ice type and accretion rate are water flow, air flow, temperatures of the cold room and water, nozzle height and wind speed. For example, decreasing the water flow or increasing the air flow, will make the accreted ice dryer, but it will also accrete slower. [71]

Icing research is also done with different icing methods, than just using a wind tunnel. In some research ice is formed with molds, just freezing water, not using any precipitation. Another method is to use supercooled water without a wind tunnel, where the water droplets impact at a freefall speed rather than with wind speed. [72]

Some empirical studies use specific object to accrete ice on. This is done, if the research is about some specific situation. For example, a rotating wind turbine blade was placed in a cold chamber and water spray was directed on it to study ice accretion on a rotating wind turbine blade. [46]

Icing laboratory is used for example to test the ice adhesion of different surface materials. This is done by accreting ice on a sample, and then testing the adhesion in a centrifugal ice adhesion test device, or CAT. Experimental studies can also be done about different icing conditions. These studies are done to understand how different types of ice are accreted, and how they adhere on the icing surface. Centrifugal ice adhesion test is commonly used in icing research. In addition to centrifugal testing, ice adhesion can be tested with direct mechanical tests, or with a wide variety of miscellaneous testing methods, like vibration beam test or laser spallation. Centrifugal ice adhesion tester is explained in more detail in Section 5.3. [71, 73]

4. CURRENT ICE PREVENTION METHODS

Ice prevention is done by either de-icing or anti-icing. De-icing means removal of accreted ice. Anti-icing means treating the material against ice formation. Both methods are used in railway traffic. Ice prevention, de-icing and anti-icing, can also be divided to active and passive methods. This chapter surveys these ice prevention methods used for railways.

Ice prevention in railways is often, virtually always, a combination of methods, both active and passive, because there is no method that would be enough on its own. Different methods work together, often one method designed to boost the working of another method. For example, anti-icing can be used to degrease ice adhesion, which will make it easier to remove through de-icing methods. De-icing methods benefit from the decreased ice adhesion granted by anti-icing. [7, 73, 74, 75]

4.1 De-icing

De-icing of rails and train carts can be done for example with electrical heating and using hot water to power wash the carts [76, 77]. Snow ploughs can be used for the rails. Carts can be cleared with hot air blowers and compressed air for example. All de-icing methods have their strengths and weaknesses. Combining different methods is done to minimize the weaknesses. [7, 35]

One common de-icing weakness is the need to do it regularly. It has to be done frequently enough that the ice load never gets too big to hinder the operation. A related problem is the available de-icing capability, for example, the amount of de-icing washing facilities. If there is more icing than anticipated, the de-icing facilities cannot match the required de-icing speed. In this, anti-icing is needed, because it does not need an active application, but it is continuously in effect. [7, 35]

Strength of de-icing when compared with anti-icing, is that it can be responsive. When icing conditions get harder, the de-icing methods in use can be done more frequently, or with more power. Another strength over anti-icing is that anti-icing can be worn down, because it is always exposed to the elements. De-icing, especially active methods, are only applied when needed, so they do not need to be exposed. [7, 74]

Some railway companies have specialized trains to be used for ice clearance of the track. They have de-icing tools attached to them. These trains are equipped with snow ploughs, brushes or scrapers, and hot air blowers, steam jets and anti-freeze sprays. Train engines like this are prepared for winter. Dedicating engines for this purpose are an investment for a railway company and keeping the rails free of ice is in the end more profitable. [77, 79]

Train carts are de-iced by washing them in. This washing can also include applying of antifreeze substances. In Figure 15, a train cart washer is depicted. It is fully automated to save time in de-icing. [77]

Figure 15. Train cart washing system. [77]

De-icing faces many problems. It takes a lot of time; one train might take eight hours to be de-iced completely. During de-icing, the train is away from being used for railway travel. If de-icing is done by water, the drying needs to be meticulous, because any leftover water will freeze again. Hot water is efficient only for short term de-icing but can increase icing in the long term. De-icing with glycol is an alternative to water, but glycol dripping from the train is another issue that needs to be taken care of. [7,59, 74]

Propylene glycol has been used for de-icing in aviation for years. It has been shown to be more effective than air or water in de-icing. Heated propylene glycol can be used the same way that water is used, sprayed at the ice-covered train. This would also leave propylene glycol on the train, which has an anti-freeze effect. The effect would only be temporary, because propylene glycol is water soluble, and would eventually be washed of by weather. But time needed for de-icing would be reduced. It is also more environmentally friendly than ethylene glycol. [7, 59, 76]

4.2 Anti-icing

Icephobic surface means a surface that repels ice. The higher the icephobicity is, the more suitable the surface is for anti-icing. When making icephobic surfaces, three aspects should be considered: lowering ice adhesion, decreasing ice nucleation and slowing freezing [71, 74]. Anti-icing can be done for example with heaters, chemicals or coatings [7, 44]. Icephobicity can also be increased with surface topography, like biomimetic surfaces [59]. The aim is to either lessen ice accretion, or lower ice adhesion strength. [7, 80]

Icephobic coatings in use are often polymers. Biomimetic surfaces have also been explored because of their hydrophobicity. Some of these coating materials are covered in chapter 3.2 Material properties affecting icing. [56]

Heating of the railway track against icing is a common method. Installing heating systems on the tracks is an efficient anti-icing technique. It also consumes a lot of energy. A Swiss railway company uses about 2,7 million euros per winter for heaters' energy costs. Electronic heaters are also used in aircrafts. Drawback for heating is their power consumption. [61, 75]

Anti-icing agents are widely used. The aim is to coat rails with chemicals that prevent ice adhesion. Ethylene glycol, propylene glycol and urea are used as anti-icing chemicals. Difficulty with these is application and uncertain duration. Chemicals will wear off structures in time. In Figure 16, anti-icing chemical propylene glycol is applied to a train. [7, 75]

Figure 16. Propylene glycol used for anti-icing. [7]

One anti-icing method used for the rails is to keep trains running regularly. Some railway companies use empty trains to prevent ice build-up on the rails, or on stationary carts. Actively operated railway route will not freeze as easily as an inactive one. Using empty trains to compensate inactivity during the night is can be used to prevent large ice or snow build-up. [77]

Problems with anti-icing methods are either their energy consumption or wearing off. This increases the cost of anti-icing, and a more permanent solution would be appreciated. The ideal anti-icing method can ensure freedom from ice with little need of constant renewal. For example, a coating could outlast anti-icing chemicals, or a surface structure with anti-icing properties. [7, 75]

5. RESEARCH METHODS AND MATERIALS

In this research, the effect of different icing conditions on railway traffic are studied. Differences between ice types and their adhesion are investigated. The ice accretion and ice adhesion with different icing parameters is investigated. The relation between water droplet behavior and ice adhesion is also studied, so droplet size and speed were measured to find out their effect on, ice type, ice adhesion and de-icing.

The focus of the research was train profile icing. Ice adhesion samples were tested to learn more about the icing of the materials that were chosen, and to provide information to help study the train profile data.

5.1 Train profiles

To study the icing and de-icing in railway traffic, samples were chosen to mimic roofs of train engines and carts. The profile of the samples was modeled after Finnish railway company VR's train engine models DR12 and DR14, which are currently used diesel powered engines. The engine blueprints are presented in Figures 17 and 18.

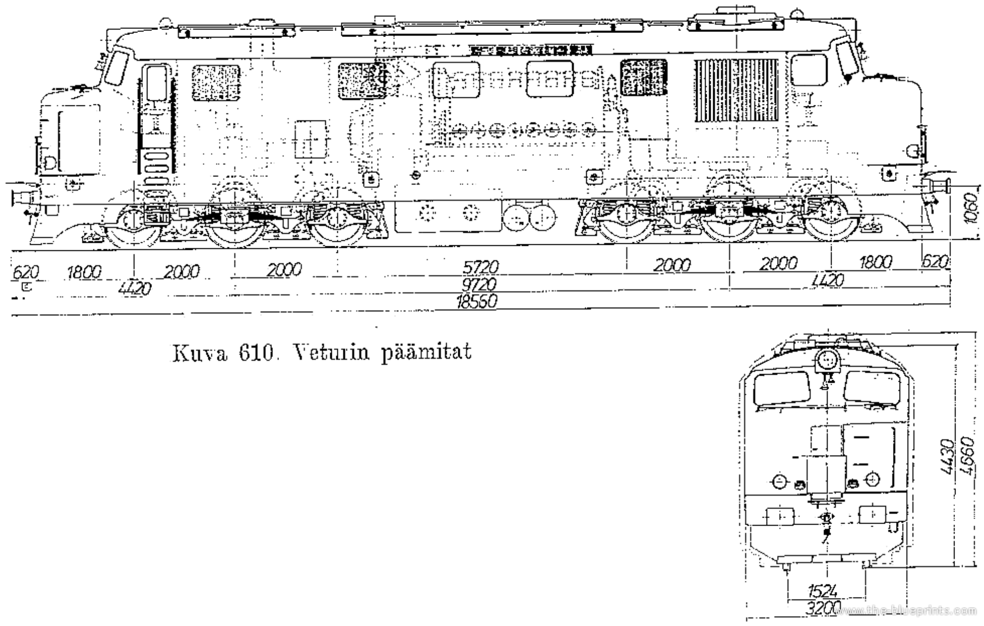

Figure 17. DR12, a diesel engine used by the Finnish railway company. [81]

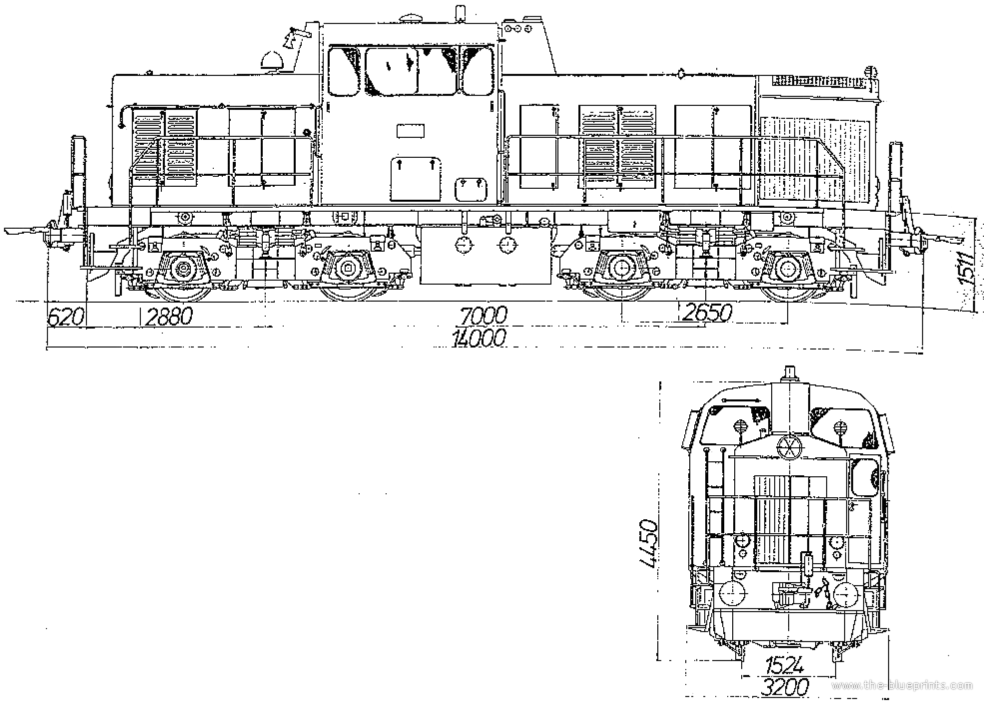

Figure 18. DR14, a diesel engine used by the Finnish railway company. [82]

Using the blueprints in Figures 17 and 18, the train profile samples were modeled. The curve of the roof from the front profiles was used as a model for the samples. The slight flat part on DR14 roof was modeled on two of the profiles, one aluminum and one coated. This was done by machining a two centimeters wide flat area in the middle of the samples. The elevated middle part seen on DR14 in Figure 18 was not imitated for the profile samples, because it would have added more variables than wanted. One goal of the profile design was to be straightforward and simplified, and not needlessly complex. Samples are pictured in Figure 19. Samples are designated by their surface type, aluminum and coated, and by their roof shape, round or flat. Round roof profile was designed according to DR12, and the flat roof according to DR14.

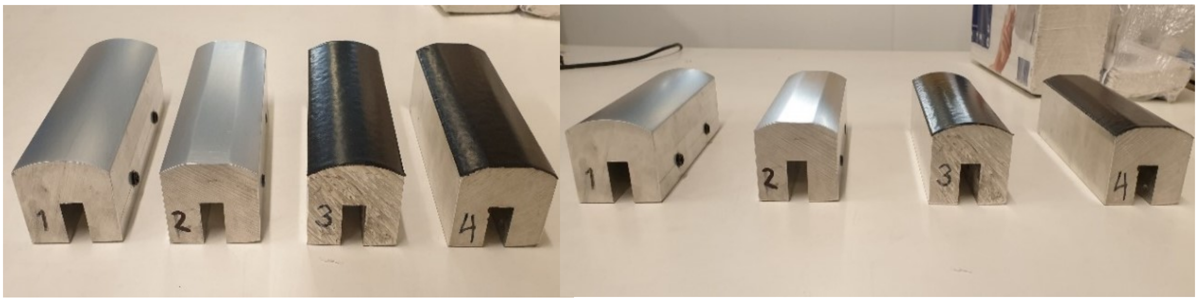

Figure 19. Train profiles pictured: 1. Aluminum, round 2. Aluminum, flat 3. Coated, round 4. Coated, flat.

The profiles were given different shapes to help evaluation of the effect on icing from details on the train roof. Different materials were used to see the effect of different ice adhesions of surface on the de-icing.

Material for the samples was chosen to be 6082-aluminum (Alumeco, Denmark), because 6000-series aluminum is commonly used in trains [83]. 6082-aluminum is composed of 95.2-98.3 percent of aluminum, 0.7-1.3 percent of silicon, 0.6-1.2 percent of magnesium, and 0-0.5 percent of iron, chromium, zinc, titanium, and copper [84]. Two of the train samples were polished with 1200-grit sandpaper, and two were coated.

The two coated samples were flame sprayed with low-density polyethylene, LDPE (Plascoat, The Netherlands). Before coating production, the aluminum samples were grit-blasted with mesh 40 alumina grits. Spraying was done with CastoDyn DS 8000 thermal spray (Castolin Eutectic, Switzerland). Spraying parameters for the flame spraying were oxygen 4.0 bar, acetylene 0.7 bar, with step size 5 mm. The substrate was preheated to 155 degrees Celsius. Spraying distance was 325 mm and speed 750 m/s. Six layers were sprayed in three-layer series. This coating was chosen, because it has been shown to increase icephobicity. [57, 85]

The length of the train profile samples is 15 cm, and the width is 5 cm. These dimensions were chosen because they would fit in the ice accretion area under the icing wind tunnel and were not too long to get an even ice layer. To get an even ice layer for the entire length of the sample, it cannot be too long. The icing wind tunnel has some differences in icing rates depending on the sample placement, so too long a sample would not fit under a certain rate. Instead, it would accrete at different rates in different spots, and the layer would not be even. The width of the samples was also decided based upon what would fit under the icing wind tunnel.

5.1.1 Ice accretion

Ice accretion was done in a climatic room with an icing wind tunnel. The climatic room was cooled to -10 degrees Celsius. This temperature is commonly used in icing test in Tampere University, so it was chosen for these tests. It is also the temperature, where accreting all three ice types is easiest for the icing wind tunnel [44, 62, 72, 95].

Ice is accreted by spraying water and air through two nozzles that are inside the wind tunnel, 165 centimeters above the samples. Both nozzles have an air tube and a water tube, through which pressurized air and distilled water is lead into the icing wind tunnel. Controlling the air pressure and water flow rate, the type of accreted ice can be controlled. Increasing the air pressure or decreasing the water flow makes the ice dryer, so rime ice is accreted at higher air pressures than mixed glaze ice or glaze ice. For accreting glaze, a high water flow and low air pressure is used. This also leads to rime accretion being slower, as there is less water. For the train profile ice accretion, this meant that rime was accreted for eight minutes, mixed glaze for four minutes, and glaze only two minutes. Even so, the ice mass for glaze samples was significantly higher, and for rime, clearly lowest.

The wind tunnel uses a 1,1 kW centrifugal fan to accelerate the water droplets [44]. Fan speed can be set up to 50 Hz, which will accelerate the particles. Under the wind tunnel, above the sample level, is a funnel, that constricts the air flow to 10 cm wide area. This makes the wind speed about 25 meters per second on average at the sample level. The particle speed varies depending on the particle sizes, and the spraying parameters (water flow and air pressure). The snow accumulation on the wind tunnel walls can also change the particle speed because the snow and ice inadvertently change the tunnel geometry, and it can affect the air flow. Snow must be cleared at regular intervals to keep the air flow even. In Figure 20, the wind tunnel system is pictured.

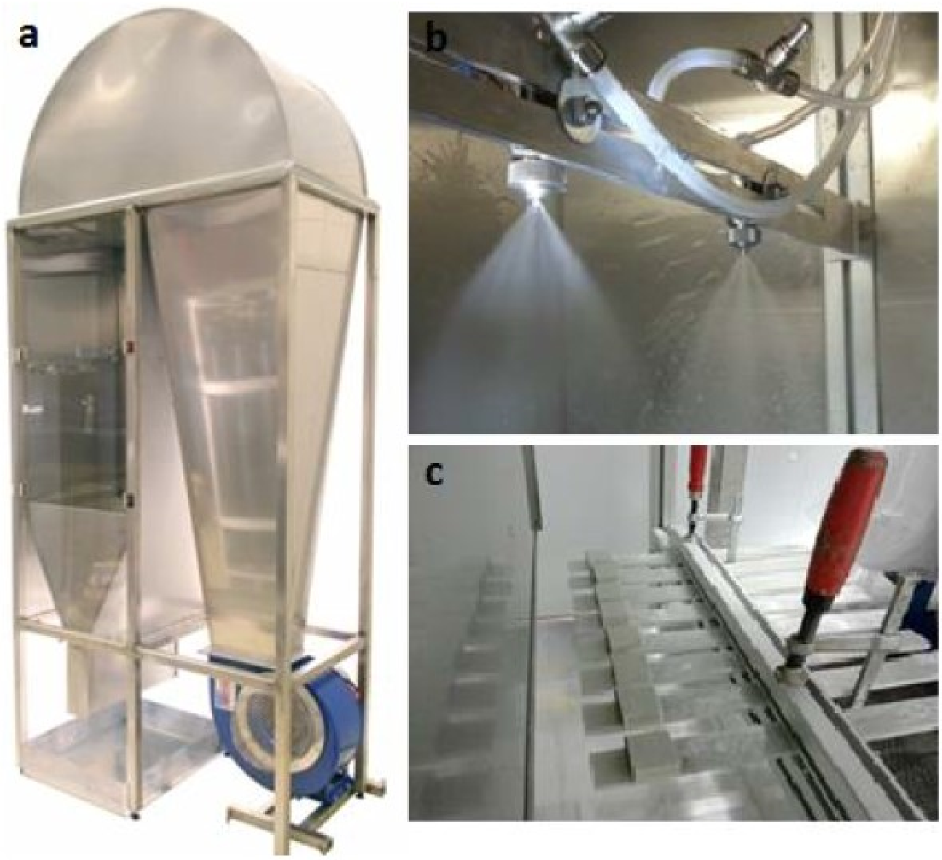

Figure 20. The wind tunnel machinery: a) The complete wind tunnel, b) water and air nozzles inside the tunnel, c) adhesion samples under the tunnel during icing. [44]

The samples pictured in figure 20c are the sample types used in the adhesion tests. Figure 20a shows how the centrifugal fan is situated on the bottom of the structure. The curved roof turns the wind downwards, to blow on the water and air nozzles, which can also be seen in the figure. Table 1 shows the different parameters used to accrete the different ice types during train profile ice accretion. Each sample was iced with the same ice type, then left over night in the cold room at -10 degrees Celsius. Next morning the samples were weighed, and the ice shedding test was performed, and after that the next ice type was accreted, and they were left again overnight.

Table 1. The icing parameters for the train profile ice accretion. Water temperature is measured from the nozzles, inside the icing wind tunnel.

	Rime	Mixed Glaze	Glaze
Room temperature (°C)	-10	-10	-10
Water temperature (°C)	7.3	8.7	9.3
Air Pressure (Bar)	4.4	3.9	3.0
Air Flow (NL/min)	65	65	40
Water Pressure (Bar)	3.3	3.2	3.2
Water Flow (l/min)	0.19	0.19	0.25
Accretion time (min)	8	4	2

Table 1 can be used to compare the different conditions for different ice types. The icing parameters can be hard to set exactly right by looking at the numbers from previous testing. For example, comparing these numbers with the numbers from ice accretion done for the ice adhesion samples, some difference can be seen. Variables like outside temperature, humidity and water temperature in tanks affect the ice accretion, and the values of these parameters cannot be controlled during icing. Accreting the right ice type can often be a challenging task of changing the parameters and visually inspecting the accreting ice, and adjusting the parameters again accordingly, until the ice is of a desired kind. The quality of ice is more important than sticking to certain parameters.

5.1.2 Ice shedding tests

To study the effect of different sample characteristics, an ice shedding test was used. Ice covered train profile samples were placed in the room temperature until there was no ice left on the samples. In order to observe the effect of different sample characteristics, the samples were set at a 45-degree angle, rather than horizontally. Horizontally placed samples tend to show only the melting on top of the samples, making the heat conduction of the sample only affecting characteristic. Placing the samples at an angle makes the profile shape and ice adhesion between the surface and ice also an affecting characteristic, because rather than just melting, the ice eventually slides of the sample, and more affecting conditions can be evaluated. The method helps in evaluating different properties of the surface, like shape and material, and how they affect de-icing,

Before the de-icing, the samples were weighed to find out the ice mass, and after de-icing, only the sample was weighed, to calculate the ice layer’s mass.

Placing the samples at the angle in the room temperature caused them to start melting, and the bond between the surface and the ice mass started to weaken. In Figure 21, the test set-up is pictured.

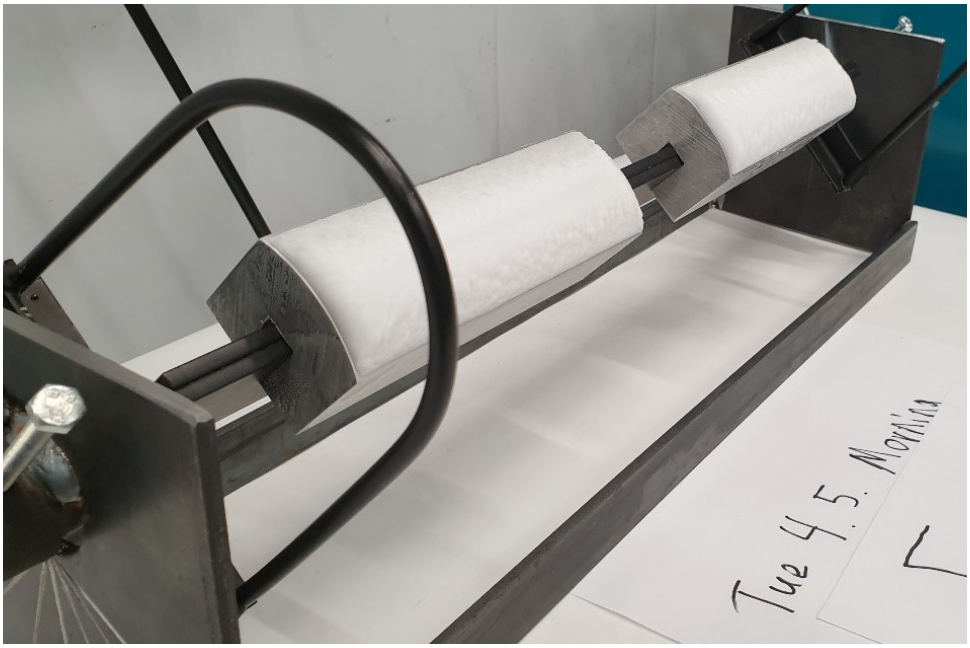

Figure 21. Ice shedding test set-up, where the rime covered train profiles are at an angel of 45 degrees. Rime ice on samples 1 and 2 is pictured.

Using the setup shown in Figure 21, the time to ice detachment was measured. The process was photographed at 5-minute intervals, and when the ice was shed off. The time when the ice came completely off was used as matric to compare the profiles with each other. Figure 22 shows the ice mass sliding off.

Figure 22. Glaze ice sliding off the sample 2.

In Figure 22 the glaze ice is shown sliding down off the sample before falling off. This happened for each sample in the similar manner. The ice started to melt, and due to melting it detached from the surface and fell off. When the ice finally fell, it fell as one piece.

5.2 Water droplet size and speed measurement with diagnostic camera

Water droplet size and speed when impacting the icing surface are important factors on icing. The behavior of droplets affects the properties of the ice. Therefore, water droplets were studied more closely during the train profile icing.

Data about water droplets was gathered during train profile icing using HiWatch HR2 particle camera made by Oseir, a company who specialize in diagnostic systems for thermal spray and cold spray. HiWatch HR2 uses a uniform laser against a backlight to measure the particles. Usually, the diagnostic camera has the ability to measure particle speeds up to 2000 m/s. For use in ice laboratory, the camera was developed to measure particles with a much slower speeds, as the water droplet top speed in the Icing Wind Tunnel is far less than the lowest speeds it normally needs to measure. The camera measures particles with the laser by detecting them at three separate positions, enabling it to calculate the particle speed using these three points. In addition to droplet velocity, the camera measures and records droplet size and amount as well. HiWatch HR2 is pictured in Figure 23. [86]

Figure 23. Oseir's HiWatch HR2 diagnostic camera. [86]

The camera was placed under the icing wind tunnel. The camera was positioned under the wind tunnel at the same level as the samples were during their ice accretion. This way the droplets that the camera measured were just like during train profile sample ice accretion. The laser comes through the aperture shown in Figure 23. HiWatch HR2 has compressed air keeping the particles out of the laser's aperture, which helped to keep the ice and snow away from the laser. Even with the compressed air, the snow and ice needed to be cleared from the aperture periodically. The diagnostic camera in measurement position under the Icing Wind Tunnel is depicted in Figure 24.

Figure 24. HiWatch HR2 mounted on a track under the wind tunnel. The centrifugal fan can also be seen on the right.

The indentation, where the aperture is located, is 10 cm wide, exactly the same width as the funnel below icing wind tunnel. Figure 24 shows how the diagnostic camera is placed under the funnel, at the same level where the samples are during ice accretion.

5.3 Ice adhesion tests

Ice adhesion tests were done using the same materials for samples that were used for the train profiles to examine the ice adhesion of these materials. Ice adhesion tests provided additional information for analyzing the data from ice shedding tests and helped understanding what material properties affected during the ice shedding tests.

Ice adhesion samples were covered with the three different ice types to evaluate the effect of the ice type, as was done with the train profiles. In Table 2, the icing parameters for each ice type that was accreted for the ice adhesion samples, are presented. In addition to aluminum and PE-coating, also Teflon tape samples were used as a reference surface. The Teflon tape samples were polished steel samples, which were covered with Teflon tape, and ice was accreted on them along each different ice type accretion.

***Table 2**. The icing parameters for the train profile ice accretion. Water temperature is measured at the nozzles, in the icing wind tunnel.*

	Rime Ice	Mixed Glaze Ice	Glaze Ice
Room temperature (℃)	-10	-10	-10
Water temperature (℃)	7.8	8.0	7.2
Air Pressure (Bar)	4.4	3.6	3.3
Air Flow (NL/min)	65	65	50
Water Pressure (Bar)	3.3	3.3	3.3
Water Flow (l/min)	0.20	0.20	0.25
Accretion time (min)	16	4	2

The ice accretion parameters in Table 2 differ slightly from the parameters used in train profile ice accretion, as seen in Table 1 in Section 5.1.1. One conspicuous difference with the train profile parameters is the icing time needed for rime ice accretion. It is twice the time that was used for the rime ice accretion for train profiles. The uneven ice accretion in the sample area is one reason for this. When accreting the train profiles, the accretion is almost even for the length of the sample, but ice adhesion samples are accreted side by side. The row of ice adhesion samples is longer than a single train profile sample, so moving the samples is necessary to get an ice mass of a same size for each adhesion sample. Figure 25 shows the ice adhesion samples masked and ready for ice accretion. Masking of the samples is done to limit the ice accretion only on a limited area of the samples, which around 3 mm by 3 mm. The height of the ice is about 10 mm, which is also the height of masking pieces, which are placed on the sample area where ice is not wanted. The accreted ice differs from the ice that was accreted on train profiles, because for ice adhesion tests the ice thickness should be as even as possible, when in train profiles the ice thickness was allowed to be shaped more freely and have apparent curve for example.

Figure 25. Ice adhesion samples before ice accretion.

Masking pieces shown in figure 25 affect the air flow during icing, so water droplets sometimes miss the sample surface right next to the masking piece. This can be fixed by moving the pieces under the icing wind tunnel, but it makes ice accretion a little slower overall.

Besides ice accretion time, more differences between train profile icing and ice adhesion sample icing can be seen. There are differences in air pressure and water pressure for example. The purpose was to accrete the certain ice types, so getting the right ice type was more important than using the exact same icing parameters. When using the icing wind tunnel, visual examination of the ice is more important than following the parameters that have worked previously. Once the right is type is reached, the samples can be iced with it, and the parameters used in the icing are recorded. In figure 26, the examples of ice adhesion samples with different ice types are pictured.

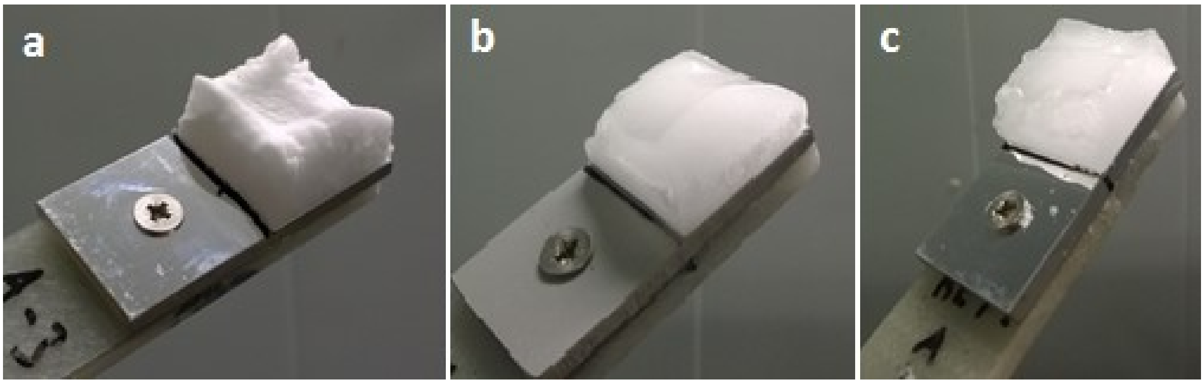

Figure 26. Ice adhesion samples after accretion a. rime, b. mixed glaze, c. glaze.

Figure 26 depicts different ice types on the ice adhesion samples. Rime is oblique because of its porosity and looks almost like snow. Glaze ice is clearer and denser than rime. Features of mixed glaze ice, which is most commonly used in ice adhesion tests, are a mix of the two. It is clear but has no run back ice like glaze ice. [44, 45, 71]

The ice adhesion values are determined using centrifugal ice adhesion tester. CAT testing was done for the ice adhesion samples after leaving them overnight after ice accretion. CAT testing was done in -10 degrees Celsius, like ice accretion. The machine used for the ice adhesion testing is depicted in Figure 27.

Figure 27. Centrifugal ice adhesion tester CAT.

Centrifugal ice adhesion tester that is pictured above is based on the ice adhesion tester used by Laforte and Beisswenger in University of Quebec [44, 87]. The iced samples are weighted before testing, and after the ice is removed in the tested, they are weighed again. The area of ice is also measured.

The iced adhesion samples are attached to glass fiber beams during ice accretion, and these beams can be attached to CAT. The beams are attached from their center, and a counterweight is placed on the other end. Then the dome is lower over the sample. CAT accelerates the beam, and once the RPM of the sample is high enough, the ice detaches from the sample due to centrifugal force. Ice hits the dome, where a sensor detects the impact. From this, and the ice weight and the area that is covered by ice on the sample, the ice adhesion strength can be solved. The centrifugal force can be calculated using the following equation.

$$F = mr\omega^2 \quad (3)$$

F is the centrifugal force, m is the ice mass, r is the radius of the circle and ω is the angular velocity. For this machine, the radius that is used is 17 cm. Ice adhesion is then calculated with equation 2:

$$\tau = \frac{F}{A} \quad (4)$$

In equation 2 τ is the ice adhesion shear strength, and A means the area of ice on the sample. The force from equation 1 is divided by the area of the ice, and this gives the value of the ice adhesion. [44]

5.4 Surface roughness measurements

The surface roughness of the samples was measured using Mitutoyo SJ-301 surface roughness tester. Surface roughness was measured to evaluate the icing properties of both train profiles and adhesion samples more accurately. Ten different measurements were done for each sample type, measuring both Ra and Ry parameters for the sample surfaces. Ra is the arithmetical deviation of the surface profile, and Ry is the maximum depth below the mean line of the profile.

6. RESULTS AND ANALYSIS

In this chapter the results from the icing tests are presented and analyzed. Section 6.1 contains the analyses of ice adhesion samples, that were studied with centrifugal ice adhesion testing, or CAT. In Section 6.2 the results of train profile ice shedding tests are analyzed. In Section 6.3 the data gathered from the water droplets with a particle camera is analyzed.

Two types of tests were conducted: ice adhesion test and ice shedding test. The focus of this study was the ice shedding tests. Ice adhesion test was done to accompany the ice shedding tests, providing more detailed information for the used materials, and differences between ice types. Ice adhesion tests also provide more accurate data which can be compared when the ice shedding test is more qualitative than quantitative testing method.

6.1 Train profiles

In ice shedding testing for the train profiles, the main variable observed was the time it took for de-icing. In all cases, this happened by the ice mass sliding of the angled samples, eventually dropping in one piece. Even rime ice exhibited this behavior, though it has higher possibility of cohesive failure than other ice types tested [88].

Accreted ice types are pictured below. The shape of the ice mass is same between the round and flat roofs and is more influenced by the accretion method than the shape of the surface. Rime ice is pictured in Figure 28, mixed glaze in Figure 29, and glaze in Figure 31.

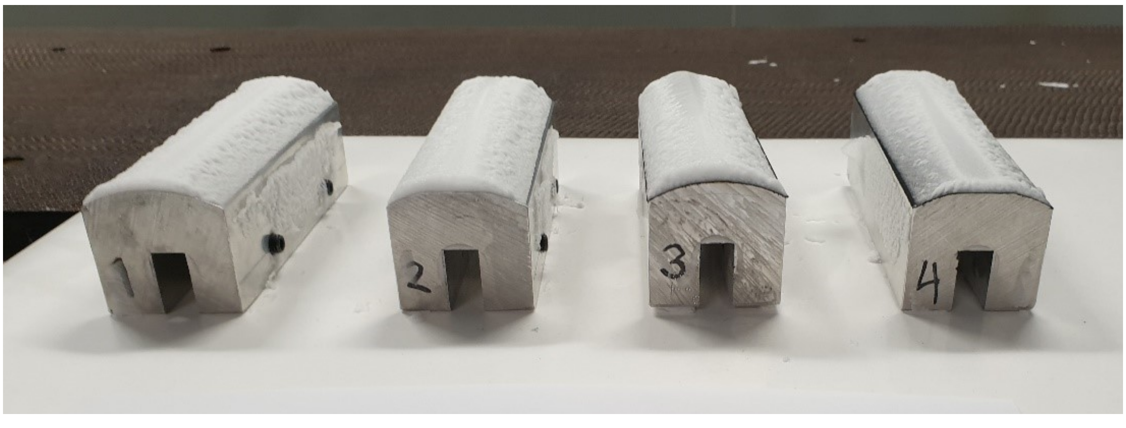

Figure 28. Train profile samples covered in rime ice. 1. Aluminum, round 2. Aluminum, flat 3. PE, round 4. PE, flat.

In Figure 28 the rime ice accretion is seen. The rime ice layer was thinner than in other types even though the icing time was the longest, 8 minutes. Slow accretion of ice is typical when using icing wind tunnel for rime accretion. Rime ice is accreted slowly, because the air pressure is increased for the accretion, increasing the air flow in the nozzle. Increased air flow decreases water flow. Decreased water flow means less water in the wind tunnel, and less water droplets to form ice. The ice layer looks evenly accreted, and the top does not have a clearly higher middle part like the other ice types. The shape of the sample top does not seemingly influence the shape of the ice layer. Both flat and round roof accrete an ice layer with similar shape.

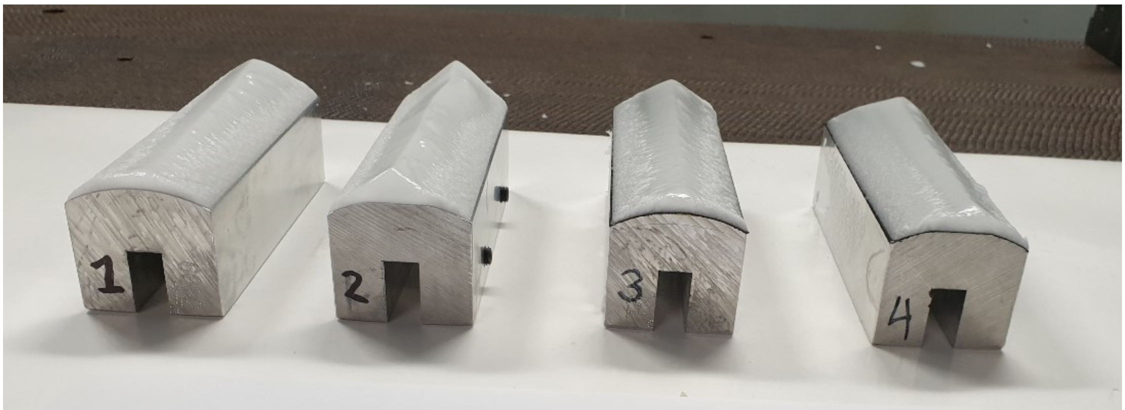

Figure 29. Train profile samples covered in mixed glaze ice. 1. Aluminum, round 2. Aluminum, flat 3. PE, round 4. PE, flat.

Mixed glaze covered samples in Figure 29 demonstrate, how the ice layer is highest at the middle of the sample. Some unevenness of the ice layer can be seen lengthwise on these samples, more closely demonstrated in Figure 30.

Figure 30. Unevenness of the ice layer during ice accretion.

Figure 30 also shows that even though there were two different roof shapes, all the ice layers are shaped in same way, not showing the shape of the roof. Same can be seen with the glaze ice in Figure 31 below.

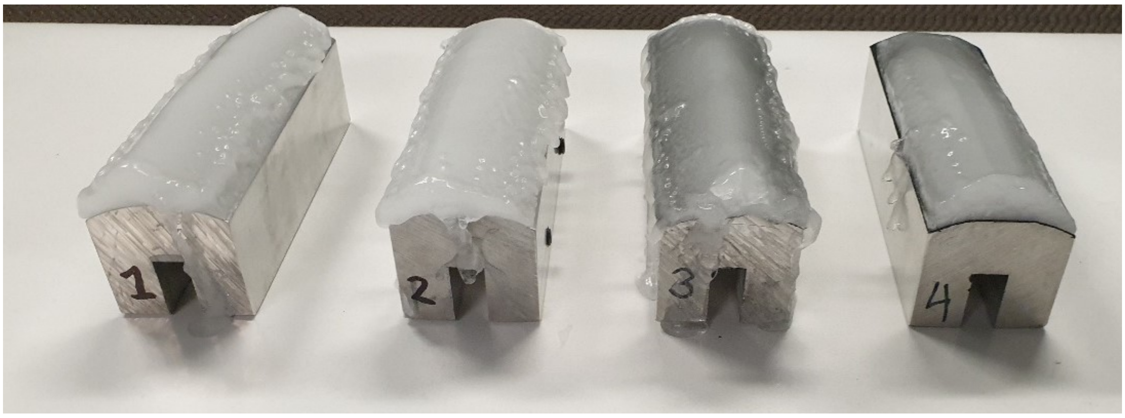

Figure 31. Train profile samples covered in glaze ice, with significant run back ice. 1. Aluminum, round 2. Aluminum, flat 3. PE, round 4. PE, flat.

In Figure 31 the train profiles are presented after glaze ice accretion and a night in the climate room. Comparing the ice layer to previous ice types, it can be seen that the ice layer is thicker. The unevenness of the layer can also be seen more clearly that previously. This is because it is difficult to get an even accretion rate for the whole length of the wind tunnel. Even though this was kept in mind when designing the samples, glaze ice still accreted unevenly.

Another prominent feature of the glaze ice is the run back ice on the sides. High liquid water content during glaze ice accretion causes some liquid water to flow down the sides [44, 71]. This creates run back ice, which means icicle-like formations on the sample sides. Figure 32 has a close-up of the most significant run-back ice formations during testing.

Figure 32. Run back ice on samples 2 and 3.

Run back ice in Figure 32 was the most significant formation of run back ice during testing. For ice shedding testing, the sample 3 was most affected by this. For other glaze ice samples, the run back ice quickly melted off, in first five to ten minutes of being in the room temperature. For sample 3, run back ice was more impactful. Even after 40 minutes, there was still a hook of ice formed from ice holding the remaining ice mass to place. Even though in these experiments the run back ice was not subject to attention, this single sample has shown how much it can actually affect the icing situation.

Run back ice can cause problems for real world applications as well. For example, run back ice is a huge factor affecting aerodynamics of planes and wind turbines [46]. In addition to hindering de-icing, run back ice affects the aerodynamics of an object as well. Even a small amount of ice changes the aerodynamics of an object, due to the changed geometry and surface roughness [89]. Run back ice is also added weight on the object. This can be seen in train profile samples, that have on average a heavier ice layer than other samples.

Table 3 has all the de-icing times collected, as well as the ice mass of each sample. Below it, in Figure 33, are all icing times grouped according to the certain profile, showing differences in ice type.

Table 3. Results of the ice shedding tests, with the samples in order according to ice types, with ice drop off time and ice layer mass.

ice type	sample type	de-icing time(min)	ice mass(g)
Rime ice	Al-round	22.55	18.00
	Al-flat	24.10	22.72
	PE-round	24.05	33.61
	PE-flat	26.58	18.15
Mixed glaze ice	Al-round	27.50	30.02
	Al-flat	29.28	37.86
	PE-round	26.95	28.74
	PE-flat	30.33	30.99
Glaze ice	Al-round	20.78	59.85
	Al-flat	24.03	60.55
	PE-round	45.23	72.80
	PE-flat	19.85	55.76

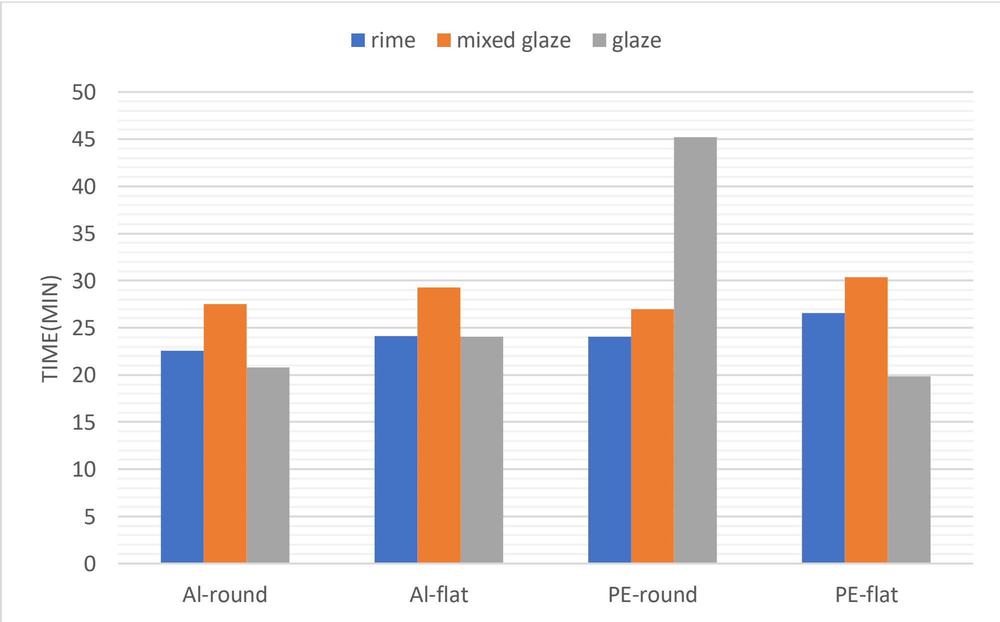

Figure 33. Comparison of de-icing times for each train profile.

Figure 33 shows how mixed glaze ice took generally the longest time. However, differences in the weight of the ice proved to be a challenge in analyzing the results, and because of the mass differences, the results need to be put into the right perspective. It was hard to determine the effect of different characteristics, when all of them changed somewhat between different test iterations. This made comparing the ice shedding times between different ice types difficult. This was why the aim was to accrete similar ice layer on samples, but the accretion rate differed significantly for different ice masses. Relation of ice mass and shedding time can be seen from the results, though its exact relation cannot be determined using the test results. In most cases, a comparison between samples can be done, as the difference in ice masses is minimal. The differences were often small within the same ice type. In Figure 34, the relation of mass and time is demonstrated.

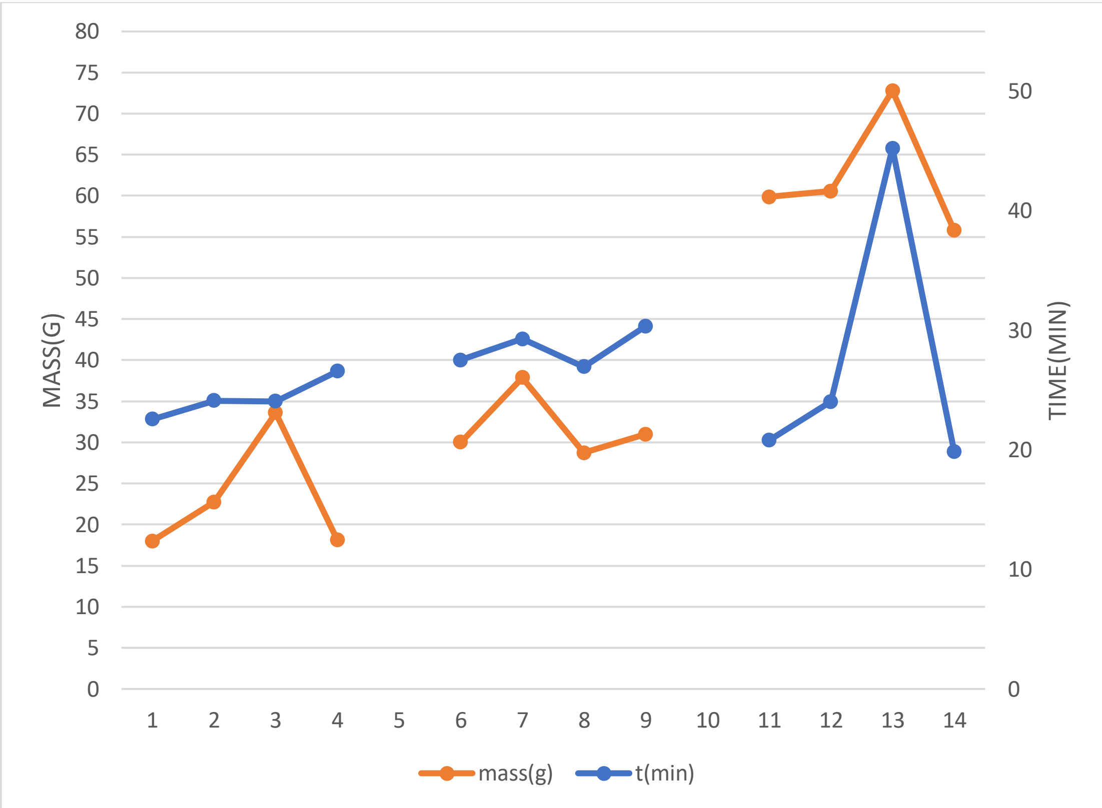

Figure 34. All sample masses in blue, and ice shedding times in orange. Data points 1 through 4 are rime, 6 through 9 are mixed glaze, and 11 through 14 are glaze.

Figure 34 demonstrates the relation between the time it takes for the ice to shed of a profile and the mass of the ice. This correlation of mass and time was expected because a larger ice mass takes a longer time to melt. For rime ice no clear correlation between time and mass was observed. For mixed glaze ice and glaze ice (datapoints 6 through 14) the shape of the time graph (blue) follows the shape of the mass graph (orange), which indicates a positive correlation. However, the correlation is not linear, because different factors also affect the time to de-ice. Figure 34 only shows a loose correlation between time and mass across the whole series. More experiment with fewer variables would be needed to define the relation of time and mass more accurately.

When comparing differences in time in cases where the difference in ice mass is significant, an alternative to pure time could be used. A metric of time per mass can be used to present a more neutral way of looking at the data. By this way the differences caused by changes in ice mass can be taken into account. This becomes important when analyzing results between different ice types, because for that metric the mass differences are most significant. The effect of mass on the de-icing time is still hard to estimate based on these experiments alone. In Figure 35, the de-icing times divided by mass are presented.

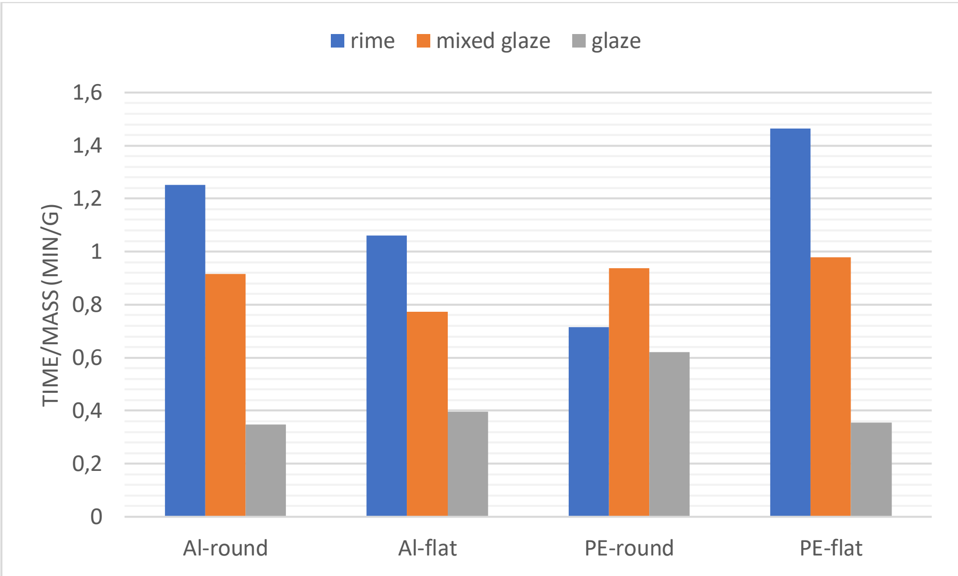

Figure 35. Comparison of de-icing time divided by ice mass.

Figure 35 shows that the relations between ice type de-icing varies with respect to the ice mass. Now the fastest to de-ice is glaze, and rime is the slowest. Comparing Figure 33 with Figure 35 shows that when the mass is taken into account, the results look different. Figure 35 shows more consistently the differences in de-icing time caused by ice type.

6.1.1 The effect of the ice type

The experiments showed that there is a difference between ice types when it comes to ice shedding. The time per mass value is used for comparing different ice types. In Figure 36, the time per mass value differences between different ice types are compared.

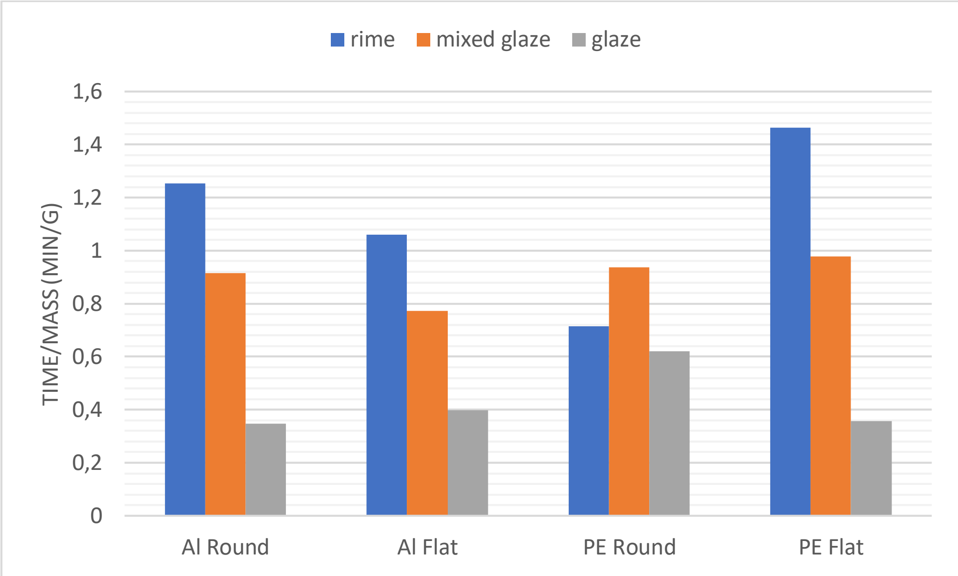

Figure 36. The effect of ice type to time/mass -value for each sample type.

Figure 36 shows how the different ice types shed off the train profile samples. All sample types follow the same pattern, except for the polyethylene coated round sample. In that sample, mixed glaze ice de-icing time per mass value is highest. Other samples follow the same order, where highest value is for rime ice, second highest is for mixed glaze ice, and the lowest is for glaze ice.

One reason for the lowest values of glaze ice could be that the calculations over value the impact of mass. The glaze ice mass was significantly higher than other ice types, so dividing the time with mass gives the smallest values for glaze.

Other reasons for the differences in de-icing can be caused by different structure of different ice types. Rime ice is the most porous, and glaze ice most dense [72]. This makes the heat conduction of glaze higher, so it can melt faster, when in rime ice, the porosity of the ice slows the melting [90]. Glaze melting faster generates more liquid water between the ice layer and the surface, making the surface slippery faster. This speeds the de-icing.

The difference caused by ice type seems to be different for the de-icing tested with train profiles, than when compared to ice adhesion tests. When comparing the surface material effect in train profile tests, the same can also be seen. This might be due to experiment set up, and how it emphasizes the effect of heat conduction. The results seem to favor those material and ice types, which have better heat conduction. The heat conduction is 205 $\frac{W}{m\times K}$ for aluminum, and 0.33 $\frac{W}{m\times K}$ for polyethylene. The experiment process is new, and it can still be improved. Other interesting points of view can be taken, like de-icing in different temperatures, or under some external forces.

6.1.2 The effect of the profile shape

Shape of the train profile had an effect on the de-icing. Round roof sheds ice faster than flat roof, and this was seen in every sample pairing, when observing the same ice type and material. In Figure 37, the difference can be seen. Figure 37 is only a comparison of de-icing times without accounting for the mass of the ice. Time per mass values are compared in Figure 38. However, the mass differences were very small within the same ice type, so when comparing different profile shapes within the same ice type, a graph with only the de-icing time can show relatively well what happens between different profile shapes.

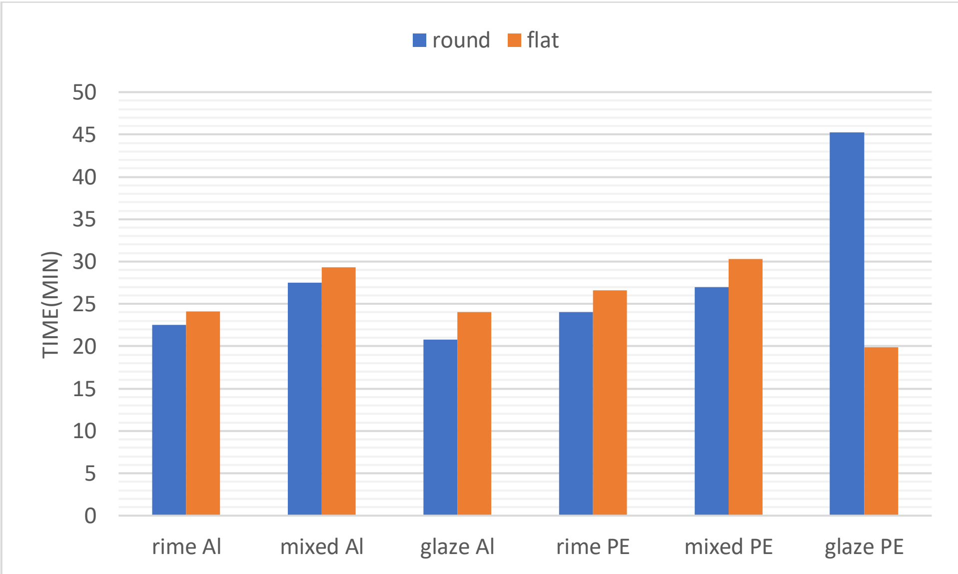

Figure 37. De-icing time comparison between round and flat samples.

From Figure 37 the de-icing times of samples can be seen. Each column pair has a sample pair of same material and ice type, making the shape the differentiating factor. In all cases but one, the round roof was faster. The reverse difference in PE-coated glaze experiment comes from the run back ice on round PE-sample, which formed a hook, that held the ice in place far longer than the ice without a hook would have remained. The effect of the run back ice on glaze samples is explained in more detail on general analysis of the train profile samples in Section 6.2.

Figure 34 only compares the de-icing times. The mass difference between different profile shapes with same ice types were generally small, so some approximate comparison can be done with de-icing time alone. However, because of the difference in ice layer weights, a comparison of the relation of time to mass is better, presented in Figure 35.

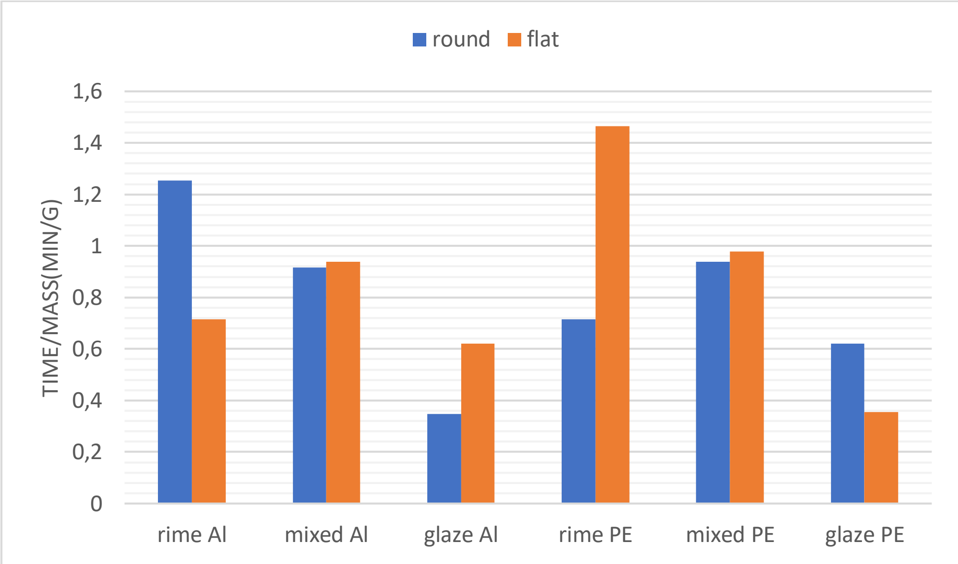

Figure 38. Comparison of the time/mass -relation to see differences in

Figure 38 shows that the flat roof is poorer for de-icing when using the time per mass metric as well. The flat profile shape is still worse in de-icing. Now the differences in profile shapes have clearer differences, and rime ice aluminum samples are reversed. This could be due to very low mass of round roof aluminum sample's rime ice mass, only 18 grams.

From the effect of roof shape can be seen that even small details can influence the de-icing for the samples. The profile shapes are still very simplified in comparison to real life trains. This means that the more detailed train roof could be even more susceptible for the ice to cling on to. Geometry of the object has been shown to affect the icing rate [91]. Differences in icing situation also changes the properties of the ice, in this case it could affect how well the water droplets adhere to the surface. In this test, the flat roof gives a perpendicular area for the droplets to impact on. The rounded roof is impacted with an angle by the water droplets. This could mean that the droplets impact the flat roof better and increase the ice adhesion.

Train roofs are more complicated than the profiles used in these experiments. Not only the shape is more complex, but all the electronic gear increases complexity. If the roof was shaped more smoothly, it could improve its performance in cold weather by decreasing the amount of snow and ice stuck to it. This would mean less weight because of snow, and better aerodynamics for the train.

6.1.3 The effect of the surface material

The material of the sample influences the ice shedding time. Figure 36 shows that the aluminum sheds ice faster in every case, except with mixed ice with round samples, and glaze with flat samples. Figure 37 also demonstrates the material effect, but it uses time per mass relation. Like previously with the roof shape, the mass difference is small, when comparing different profiles under same ice type. Using both Figure 36 and Figure 37, the effect of dividing time with mass can be also evaluated. Dividing time by mass makes the difference between aluminum and PE-coating clearer.

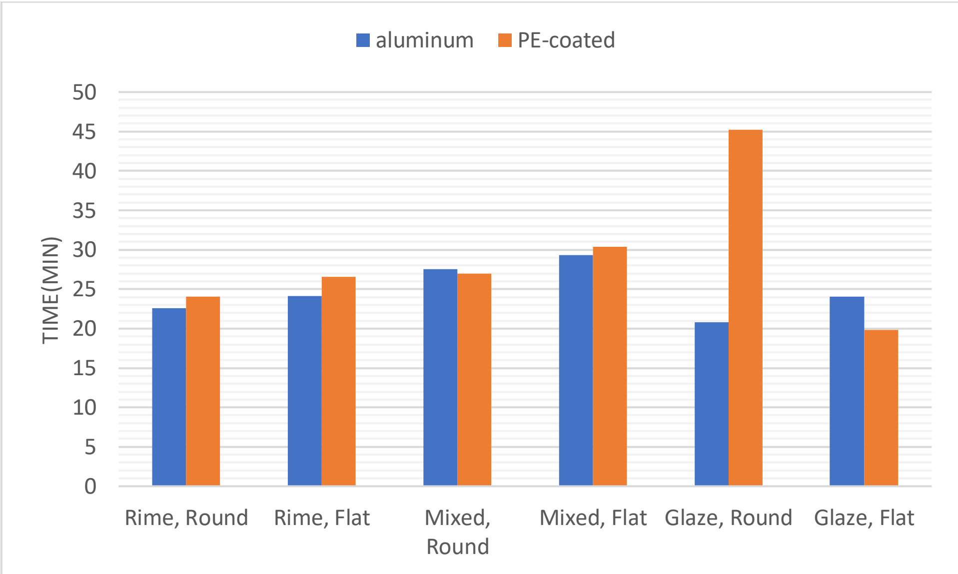

Figure 36. Ice shedding times paired according to sample type and ice type, to compare differences in ice types.

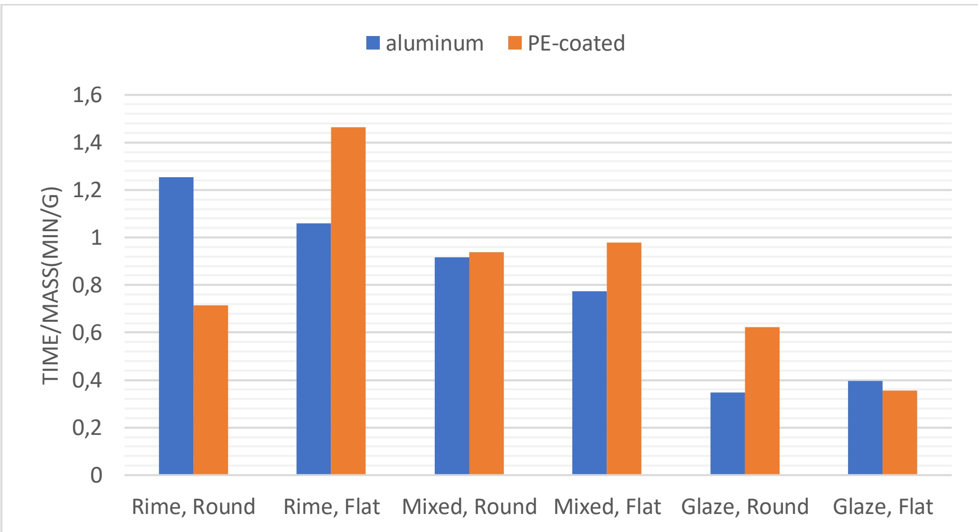

Figure 37. Ice shedding time per mass -relation paired according to sample and ice type, for material type's effect comparison.

Both Figures show how predominantly ice falls away faster by the aluminum surface in the room temperature.

As previously mentioned, heat conduction could play a bigger role in de-icing in the room temperature in this experiment. The small layer of polyethylene coating acts as an insulator when compared to aluminum. Thermal conductivity of aluminum is 205 $\frac{W}{m \times K}$, and that is significantly higher than polyethylene's thermal conductivity, which is 0.33 $\frac{W}{m \times K}$ [92, 93]. Higher heat conduction means faster melting, and the substrates heat conduction strongly affects how much heat gets to ice-substrate -interface. Faster melting at the interface means that the ice detaches from the surface faster. This enables the ice to fall off faster.

6.2 Water droplet data from train profile ice accretion

Water droplet data was gathered during train profile icing. The data is presented in Table 4. Icing conditions used for the droplet data gathering is presented in Table 1 in Section 5.1.1.

Table 4. Droplet size data from the train profile ice accretions.

		Rime Ice	Mixed Glaze Ice	Glaze Ice
Particle size (µm)	Mean size	28.65	21.90	26.20
	DV50	57.01	42.73	51.01
	DV90	83.74	63.61	75.87
Particle velocity (m/s)		25.20	23.21	24.57

Droplet data in table 4 shows that the droplet speeds are very close to each other across all ice accretions. The water droplet speeds ranged from about 5 m/s to over 45 m/s the speed distribution is illustrated in Figures below. The differences in icing parameters of ice accretions do not change the particle speed very much, because the speed is more dependent on the fan speed and the tunnel geometry. The changes in speed could be because of the snow and ice accreted on the wind tunnel walls, that change the tunnel geometry. At warm temperature, without changes in geometry, the droplet speed is about 24 m/s. The number of droplets differs a lot between different ice type accretions, because the water flow and the air flow are changed so the amount of droplets changes. This depends on the measurement time but does not change the distribution. The droplet velocity distribution is shown for each train profile icing in Figures 38, 39 and 40.

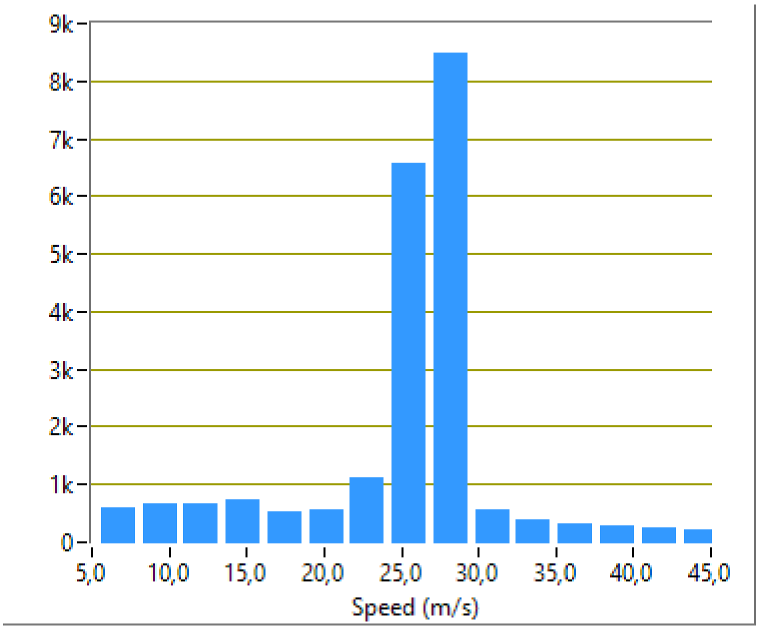

Figure 38. Droplet velocity distribution of rime ice accretion, with number of water droplets that were measured for each velocity.

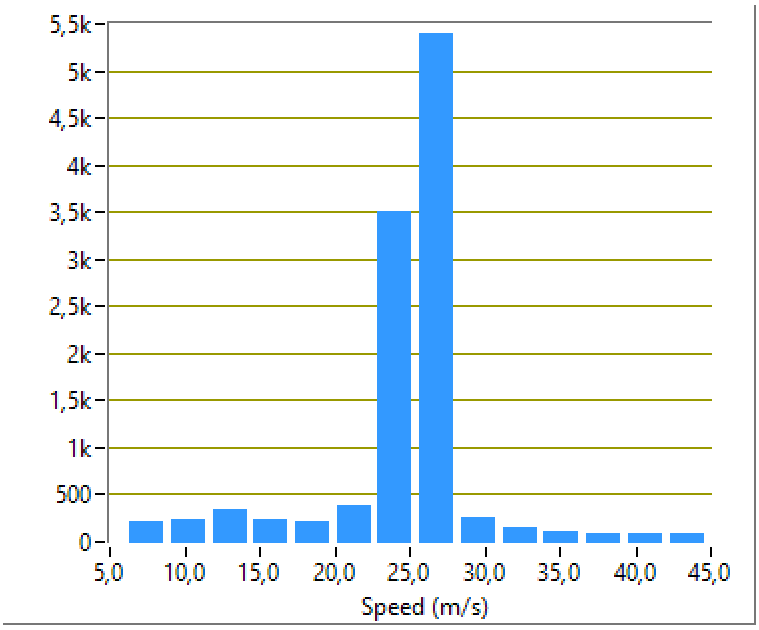

Figure 39. Droplet velocity distribution of glaze ice accretion, with number of water droplets that were measured for each velocity.

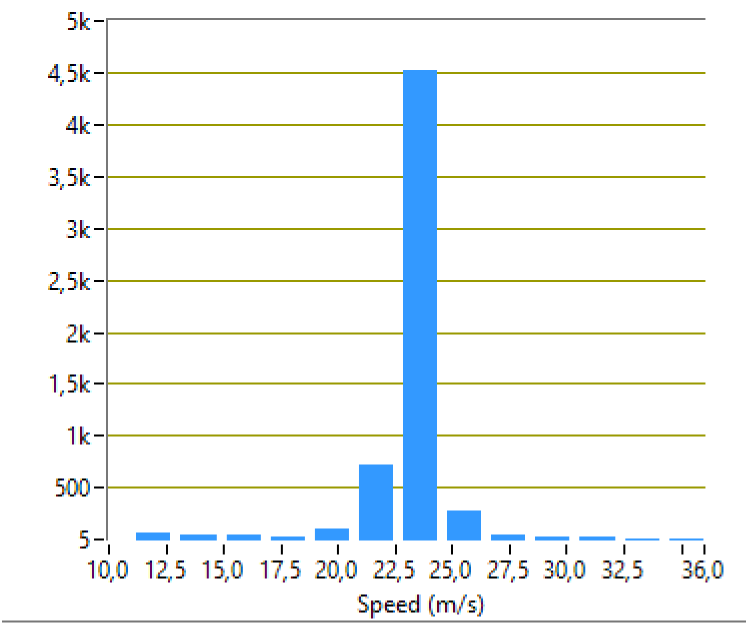

Figure 40. Droplet velocity distribution of mixed glaze ice accretion, with number of water droplets that were measured for each velocity.

Figures 38, 39 and 40 show, that the distribution of speed for each train profile icing looks almost same. Slightly slower speeds in mixed glaze ice accretion can be due to different level of snow on the ice tunnel wall.

For water droplet size measurements, there were more differences detected. In table 4, the mean size of measured particle is shown, as well as DV50 and DV90. DV50 means that 50 percent of particles were below that size, and DV90 means that 90 percent of the particle were below that size. Table 4 shows how mixed glaze ice had smallest droplet diameter with 22 µm, glaze ice was second largest, with mean diameter 26.20 µm, and rime ice had largest droplets, with mean diameter of 28.65 µm. The droplets in the icing wind tunnel have generally increased in size when the air pressure is lowered [44]. However, these measurements show the opposite happening.

6.3 Ice adhesion

Table 5 presents the averages and standard deviations of ice adhesion for polished aluminum. They were calculated for each ice type. The differences between ice types are distinct.

Table 5. *Ice Adhesion for polished aluminum. Average and standard deviation are calculated for each ice types adhesion.*

Sample Type	Average Ice Adhesion (kPa)	Standard deviation (kPa)
Aluminum Rime Ice	181	89
Aluminum Mixed Ice	99	42
Aluminum Glaze Ice	178	50

From Table 5 it can be seen how highest ice adhesion was with rime ice, and lowest with mixed glaze. Glaze ice had almost as high ice adhesion as rime. Standard deviations were high in the testing. One reason for this could be because of the polishing. Samples were polished by hand with 1200 grit sandpaper under water, so the polish between samples could have been different. In literature mirror polished aluminum usually has around 360 kPa ice adhesion value [72]. However, the ice adhesion values vary widely depending on the conditions and testing methods. Aluminum type can also affect the values, and the aluminum type that was used in this study was not previously tested. Differences between different ice types for aluminum samples can be seen in the ice adhesion values.

Table 6 has the ice adhesion values presented for the PE-coated samples. Ice adhesion averages and standard deviations are calculated.

Table 6. *Ice adhesion for PE-coated aluminum. Average and standard deviation are calculated for each ice types adhesion.*

Sample Type	Average Ice Adhesion (kPa)	Standard deviation (kPa)
PE Rime Ice	95	27
PE Mixed Ice	77	40
PE Glaze Ice	132	37

Table 6 has all the PE-coated adhesion samples and their values. For PE-coatings the ice adhesion values show that glaze ice had the highest ice adhesion, and mixed glaze the lowest. The difference between rime and mixed glaze was a lot smaller than for the aluminum. The standard deviation here is generally lower than for the aluminum, supporting the argument that the polishing raised the deviation for aluminum sample, because PE-coating did not need polishing.

For reference, the ice adhesion samples also included Teflon tape samples. Their ice adhesion values for each ice type are presented in in Table 7 below. Standard deviation could not be calculated for the glaze ice Teflon tape sample, as the ice fell of some of the samples before putting them into the centrifugal ice adhesion tester.

Table 7. *Ice adhesion average and standard deviation for Teflon tape samples, which were used as reference samples*

Sample Type	Average Ice Adhesion (kPa)	Standard Deviation (kPa)
Teflon Rime Ice	117	22
Teflon Mixed Ice	48	1
Teflon Glaze Ice	90	N/A

In Figure 40, there are the ice adhesion values paired by the ice type to see the difference made by material. After that, in Figure 41, the adhesion values are grouped by the material, to show the difference that the ice type makes.

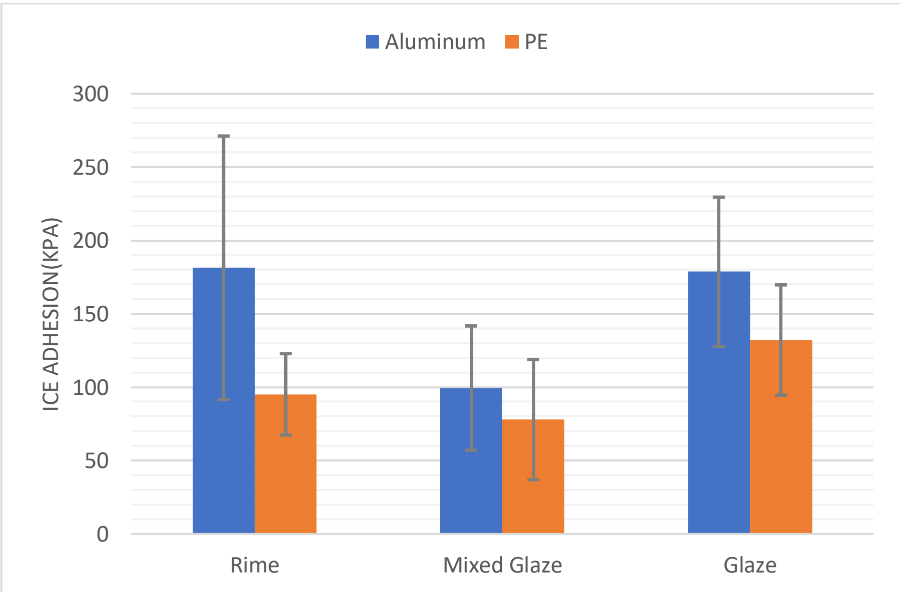

Figure 40. Ice adhesion values for aluminum (blue) and PE (orange) with different ice types. Standard deviation is also visible.

Figure 40 shows a comparison between the ice adhesion of different materials for each ice type. Aluminum is consistently higher. PE-coating was expected to have lower ice adhesion, which has been shown in previous studies [85]. It was one of the reasons for choosing to use PE-coating as a comparison to polished aluminum. That pairing of materials helped to see the significance of ice adhesion for train profile testing. In train profile de-icing tests, the ice shed off aluminum faster than the PE-coating, but ice adhesion results show that the ice adhesion is higher for aluminum. This suggests that there are more important factors affecting de-icing than ice adhesion during train profile de-icing. The train profile testing results suggest that more important than ice adhesion could be the roof shape, ice type, and the thermal conductivity of the samples.

Ice adhesion tests showed that the ice adhesion of PE-coating was lower than ice adhesion of aluminum, which is supported by literature [57, 85]. Because PE-coating has higher water contact angle than aluminum, PE-coating also has higher hydrophobicity than aluminum. High hydrophobicity can decrease ice adhesion in high liquid water content icing, which is glaze icing [44, 85]. For icing with super cooled droplets, the effect of hydrophobicity is not clear [85, 96]. Studies have also shown that the water contact angle correlates with ice adhesion only with similar surface roughness [44, 96, 97]. In Figure 41, the differences between ice types are demonstrated.

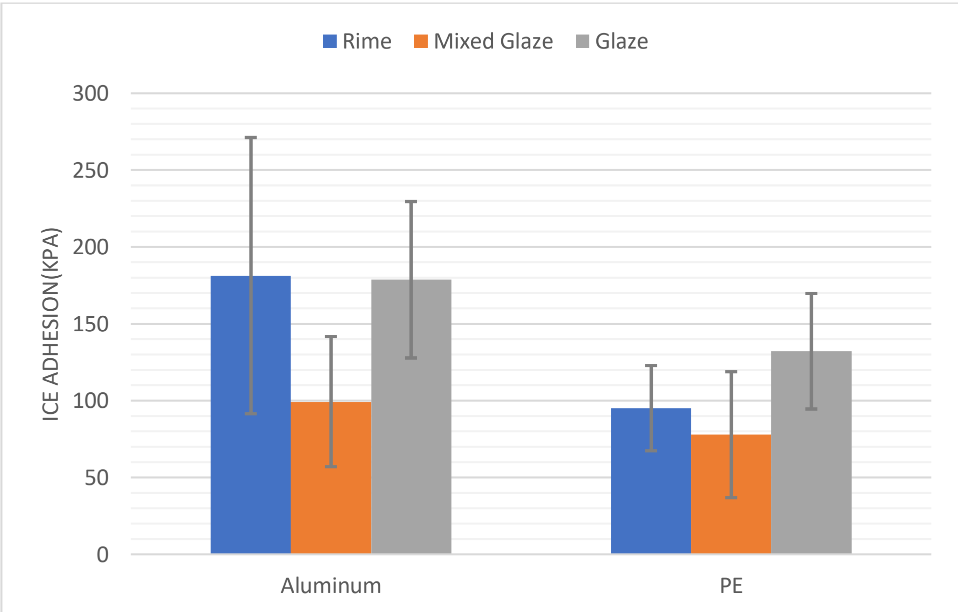

Figure 41. Ice adhesion values grouped by materials, to see the differences between ice types. Standard deviation is also visible.

Figure 41 shows how different ice types had different ice adhesions. Glaze ice has a high ice adhesion because in wet icing, like glaze icing, droplet size is high, and water forms mechanical interlocking effect [44]. This increases ice adhesion. Another thing increasing the ice adhesion for glaze ice are the run back icicles. Even though most prominent icicles are removed from the sample, there might still be some left. Removing some of the run back ice is challenging, because too intrusive removal can affect the ice mass on the sample.

The difference caused by ice type differs from previously done studies [44]. A previous study shows aluminum ice adhesion being highest with mixed glaze ice, which was reversed in this study, but this study used a different aluminum type. However, the study had many different polymer coatings where mixed glaze ice had lowest ice adhesion, as it did with PE-coating in this study.

6.4 Surface roughness measurement

The surface roughness of samples is presented in Table 7 (train profiles) and Table 8 (adhesion samples). For train profiles, each sample was measured from ten different points, and their average was calculated. For ice adhesion samples, five different samples were chosen at random, and each one was tested twice, and their average was calculated.

Table 7. *Surface roughness of the train profiles. Ra is the arithmetical mean deviation and Ry is the maximum deviation from the mean line. The values are an average of ten measurements.*

Train profiles	**Ra (µm)**	**Ry (µm)**
Aluminum, round roof	0.4	3.7
Aluminum, flat roof	0.5	4.1
PE, round roof	4.1	22.5
PE, flat roof	4.2	24.6

Table 8. *Surface roughness of the ice adhesion samples. Ra is the arithmetical mean deviation and Ry is the maximum deviation from the mean line. The values are an average of ten measurements.*

Adhesion samples	**Ra (µm)**	**Ry (µm)**
Aluminum	0.5	6.3
PE-coating	8.5	42.1

Tables 7 and 8 show how the surface roughness is higher for the PE-coating for both sample types. For adhesion samples, the Ra values differed from each other considerably, which can be one reason for high deviation of ice adhesion values in adhesion testing. The values ranged from 0.35 micrometers to 0.65 micrometers for aluminum, and from 3.33 micrometers to 14.12 micrometers for polyethylene. The divergence of the roughness values between samples could be one reason why there was high deviation in their ice adhesion values.

Surface roughness also affects ice adhesion. Generally, increased roughness increases ice adhesion [44, 96, 97]. Aluminum surface roughness was lower than PE-coating surface roughness. The relation between surface roughness and ice adhesion is also affected by wetting behavior and surface chemistry, so the effect surface roughness on ice adhesion can only be compared with samples with the same surface chemistry [44, 98]. The connection between surface roughness and ice adhesion is unclear, but ice adhesion is a combination of many things [98]. The surface materials here have many differences besides the surface roughness, which explain the differences in ice adhesion. There is no single set of factors that determine the ice adhesion. The ice adhesion is affected by different factors in different situations, and different ice types respond differently to different factors. The effect of surface roughness on ice adhesion is complex.

7. CONCLUSIONS

7.1 Summary of the results

The purpose of this research was to study icing in railway traffic. The results showed that several factors affect both ice accretion and de-icing of trains.

Train cart profile shaped samples were tested by accreting different ice types, rime ice, mixed glaze ice, and glaze ice. The samples were polished aluminum 6028 and aluminum coated with flame sprayed polyethylene. Samples also had two different shapes, a round roof and a roof with a flat top. The train profile de-icing tests were performed in the room temperature and the ice adhesion tests were done with centrifugal ice adhesion tester in -10 degrees Celsius.

De-icing time was affected by the ice mass. The results of the train profile testing show how it took the longest time for the heaviest ice masses to fall off the sample. A value of time divided by mass was used to evaluate de-icing while controlling for mass, to see the impact of other factors. Ice type affected de-icing clearly as well. Rime ice was slowest, mixed glaze ice was second slowest, and glaze ice the fastest.

Sample surface material affected de-icing in the room temperature, and de-icing of aluminum was faster than de-icing of PE-coating. This was opposite to the ice adhesion of these materials, which could mean that outside forces and other material properties had more effect. One reason could have been the thermal conductivity for example, which is higher for aluminum. Also, sample shape showed a clear effect on de-icing. Flat roof on train samples increased the de-icing time, whereas samples with round roof de-iced faster. Designing actual train roofs with this in mind could decrease the accreted snow and ice and make de-icing faster.

In addition to train sample profiles, adhesion samples were also tested. The adhesion tests were performed as an auxiliary test, to help understand the train profile testing results. The samples were polished aluminum surface, and aluminum coated with polyethylene. Ice adhesion of aluminum was significantly higher for each ice type. The results also showed that ice adhesion of mixed glaze ice was smaller for both materials. Rime ice adhesion was almost equal with glaze ice adhesion for aluminum, but noticeably lower for polyethylene.

The ice adhesion results showed how the de-icing time in the room temperature for train profiles was faster for aluminum surface, even though it had higher ice adhesion. Ice adhesion test are done in cold, and there is a centrifugal force that removes the ice. In the train profile ice shedding, the samples are de-iced in room temperature with only gravity as an external force. Since the de-icing mechanisms between the tests are different, different factors have an influence on the results. This should be kept in mind when designing ice prevention for trains, in what conditions is the ice prevention meant to work, outside in the cold, or inside a de-icing facility.

Icing and ice adhesion are intricate phenomena, and that was apparent in this study as well. Many factors affect icing, and the many variables used in this study all had an effect on icing.

7.2 Limitations of the study

Ice adhesion testing methods are great at studying icephobicity of different surfaces, but an additional method for studying de-icing, like the ice shedding test used in this study, could be useful. That would give more insight to de-icing in different situations. In the tests that were done as a part of this study, the ice layer weight affected more than anticipated. Using time divided by mass as the comparable value, the train profiles could be compared with each other. Accreting ice masses of same size is not possible, and it does not happen in reality either, so modelling the de-icing could help in studying de-icing with changing masses.

Also, the samples were designed in a way, which together with the testing method emphasized for example heat conductivity more than ice adhesion. In the train profile tests, the difference between the two materials seemed to be due to the difference in their thermal conductivity. An alternative research method could be developed, for example some mechanical removal method, in either room temperature, or in a cold room. The effectiveness of heating as de-icing in cold conditions could also be tested.

The geometry of the wind tunnel made getting the particle data during de-icing hard. Particle camera could only fit under the tunnel when there were no samples, so the particle data was measured immediately after samples were taken out. When the particle data is collected carefully, and the conditions are kept same as for the sample ice accretion, the particle data is accurate for the sample situations. For this study, the particle data was collected from train profile icing, so the sampling is small, but can still provide good information of the water droplet properties. The equipment is new, and the camera can gather data that previously could be gathered, so the equipment can enhance the ice adhesion testing.

7.3 Future research

Earlier research has shown that icing conditions affect the ice adhesion, which was also seen in the results of this study. This research thus contributed to the growing body of knowledge regarding icing behavior. Ice adhesion experiments were done with a coating that was not previously used with aluminum as a substrate. These experiments were in line with what had been concluded before, and the coating decreased ice adhesion. Also, the differences that were caused by changing the ice type, were in line with previous studies where the effect of the ice type was studied.

Ideas for future research include studying similar phenomena with various wind speeds and temperatures. In addition, other coatings could also be studied. The study could be continued with more emphasis on anti-icing as well. Combining the diagnostic camera with the icing studies is also a way to expand the understanding of icing phenomenon. More focus can be directed in the effect of icing conditions and droplet properties on ice adhesion. Modelling could be a help in expanding the icing tests. A model for de-icing, which can take into account the temperature and ice mass would be useful. Future research could also be done with more samples and statistical hypothesis testing to see how the parameters affect. Larger number of samples and statistical modelling to further confirm the observations made in this study.

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