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USE OF IN SITU ICE TO BUILD A SUSTAINABLE RADIATION SHIELDING HABITAT ON MARS

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Abstract

Currently responses towards sending humans to Mars are being developed by governmental and private companies. This ambitious goal demands a range of innovative technologies and reflections of the challenges we are facing on Earth. These reflections also apply to the field of Architectural and Building Technology.

In order for humans to stay safely on the surface of Mars they need a radiation shielding habitat. Radiation is currently the greatest challenge to overcome. The use of In Situ Resources (ISRU) is critical to reduce the cost and can also lower the environmental impact of the mission. Literature study suggest that H_2O provides an excellent shield against radiation. Moreover, ice is widely present on Mars. At the moment, little is known about the building properties of ice, especially in a Martian environment. However, building with ice does add quality to a living environment as it lets light through; as opposed to regolith or other stony materials. This paper presents the feasibility to build with ice to create a sustainable Martian habitat. Hence, a number of experiments were performed to test the feasibility of using ice as a building material. The result show that adding sodium chloride (NaCl) improves the mechanical properties of the ice. A further challenge to building a habitat on Mars is that it has to be built semi-remotely. The research singles out the use of robotic technology, which can perform all tasks necessary to build the habitat, ranging from mining the ice to assembling the building. Preliminary studies and experiments on Earth have been conducted on additive manufacturing techniques for sodium chloride ice. The main outcome is that the ice structure has a greater overall strength due to the freezing of the ice layer by layer. This technique also enables the possibility of crack repair during the building phase.

Keywords: Mars, habitat design, ice composite, sustainability, additive manufacturing

Acronyms/Abbreviations

AM:	additive manufacturing
CL:	cargo lander
ISRU:	in-situ resources utilisation
NaCl:	natrium chloride
ppt:	part per thousand
Sv:	Sievert

1. Introduction: Space Architecture

Space Architecture is a new and challenging topic. In the past, space “architecture” was only an engineering field, mainly due to the extreme design requirements which had to be met. Designs were made with an emphasis on efficiency by creating a survivable environment with the lowest cost possible [1,2]. Over the last ten years, however, some studies highlight the need for not only a survivable habitat, but also an engaging working and living environment for the crew [3,4]. A study made in Russia [4], concluded that an engaging environment is critical to the mission’s completion. Therefore, to attend to the needs of the crew for an engaging environment, architects and designers are now also involved in the design of space environments.

2. Requirements

The requirements of every space environment are still extreme and are therefore leading to the design phase. The requirements are set by two variables: the space mission design and the challenges of the location [1]. The location is set in the mission design, therefore, it is critical to choose a mission design, a case study, at an early stage of the research. A currently relevant example of such a mission design is to send humans to Mars.

2.1 *Mission design*

Presently (2018), different companies have set their goal to send humans to Mars [5,6]. For this research, a space mission design developed by NASA [7] is taken as case study. The mission, named *Human exploration of Mars, Design Reference Architecture 5.0* (DRA5.0), has set its aim to send 5 to 7 humans to Mars for 350 days. The exact landing location was not yet set upon doing the research and therefore one of the three proposed locations was chosen: Jezero crater. The mission is divided into two phases: the first phase will sent a cargo lander (CL) containing a habitat, an ISRU plant, and other crew survival necessities to the surface of Mars. Two years after the launch of the CL, the second phase will send the crew to Mars. This is because the habitat should be ready upon crew take off from Earth. Hence, the only way to build this habitat without human presence is by doing it remotely or semi-remotely. The two years will set the timeframe requirements for the building phase. Another requirement set by DRA5.0, is redundancy, which is vital for the completion of the mission and safety of the crew [7].

In order to design a habitat complying to the requirements, NASA created a challenge in 2015 where different parties presented their own design for a Martian habitat. All of the awarded designs have thick outer walls of in situ materials to protect the crew against the harsh environment. Most of the designs used the local regolith to create those walls but one team designed their walls using underground ice instead [8]. The use of ice is interesting for a few different reasons. As ice is a translucent material, an ice wall enables light to pass through the structure. This will enable the crew to see the difference between day and night. As a day on Mars lasts 24h37m on average, the rhythm is very similar to an Earth day. Therefore, the crew will be more aware of their environment and adapt faster, therefore feeling more comfortable in this foreign environment [9]. But using ice mostly addresses the challenges of building a habitat on Mars [1].

2.2 *Challenges of Mars*

There are some challenges to build a habitat on Mars. The challenges with the greatest impact on the research are described below.

2.2.1 *Radiation*

It is known that radiation is present in space and on the surface of Mars [1] and that this radiation is dangerous for human health when exposed to high intensity over a long period of time [9]. The radiation intensity at the Jezero Crater on Mars is 0.2 Sv/year (see figure 1). The guideline developed by space agencies for thorough protection defines the maximum amount of radiation that a human can be exposed to at 50 mSv/year [9]. This means that the crew should be protected from the radiation doses on Mars. Protection can be achieved by shielding the subject with lightweight materials. Each material has a different shielding intensity. Some of the materials which are present throughout the whole planet have good shielding properties like regolith. But H_2O, which is also present on Mars [10], is one of the best radiation shielding material as can be seen in figure 2.

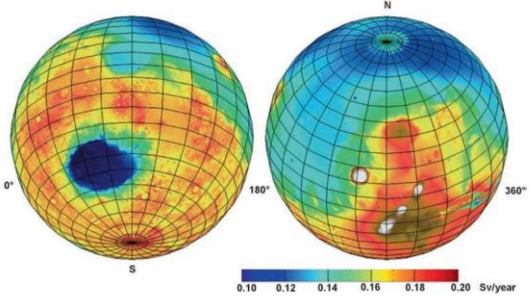

Figure 1. Effective radiation dose rate (in Sv/year) on the surface of Mars [2]

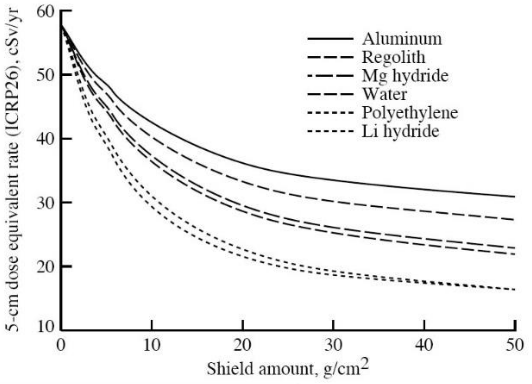

Figure 2. Radiation shielding properties of different materials [11].

To ensure that the crew won't be exposed to higher doses of 50 mSv/year, a high thickness of material is needed. When using water, a thickness of 325 mm is the minimal amount required following the data from figure 1 and 2 and the amount of radiation at Jezero Crater. When using regolith a thickness of at least 975 mm is needed, which is three times more material than H_2O.

2.2.2 *Entry, descend, and landing (EDL)*

Another challenge, is that the materials and tools needed to build a habitat on Mars can only be brought from Earth by the CL. In order for the CL to safely land on the surface of Mars, it needs to pass through the Martian atmosphere. This process is called the entry, descend, and landing (EDL). This process is easiest when the mass of the rocket is as low as possible [1,7]. The previous header concluded that a large amount of material is needed to protect the crew against radiation. This much material has a great mass which will be difficult to land on the surface of Mars. Therefore, it is required to use local Martian resources to provide the needed mass.

2.2.3 Use of local ice

Based on the radiation challenge, an ice radiation shielding habitat on Mars seems to be an interesting concept to develop further. However, building a structure with ice, especially on Mars, is poorly researched at the moment [9,12]. Due to the difference in pressure on Mars (compared to Earth), H_2O is only present in two states; solid state underneath a regolith layer and gas state in the thin atmosphere [10]. There are already a few examples [12] on building a shelter using ice, here on Earth, like igloos, ice palaces and ice hotels. However these structures are usually small spanned and temporary. There is much more knowledge and experience on how to build with stony materials (like regolith) than with ice [13, 14]. However, the processing of stones and rocks require high energy consumption and heavy processing tools compared to ice [13,14] which would be an enormous economical challenge to bring and produce on Mars. Another consideration is that the Martian ice will already be mined to provide carburant for the Mars Ascend Vehicle (MAV) which will be the return vehicle of the human mission [7].

2.3 Problem statement

To address the mission design requirements and the challenges of building a habitat on Mars, the use of local Martian ice and the method to process the ice is researched. This led to the research question: What are the building options to use in situ ice to design a radiation shielding habitat on Mars?

3. Method and experiments

A method based on experiments is devised to answer the first part of the research question: how can ice be used as a building material?

3.1 Method

Ice is a peculiar material and theory on building with ice is limited to a few publications [12,15,16]. Therefore, the existing theory is analysed first, then, experiments are made in order to add knowledge on building with ice. Experiments are designed and developed to find the mechanical and overall building properties of local ice in a Martian environment. With the output of those experiments, a design is made to verify if those results are relevant. Two aspects of building with ice are researched. First, the potential building properties of Martian ice is analysed. Second, an appropriate building method is researched using the output of the first aspect.

3.2 Properties of ice

Different experiments were made to understand the building properties and general behaviour of ice in a simulated Martian environment.

3.2.1 General properties

As stated before, theory on ice as building material states that ice is a peculiar material which properties are not yet entirely understood [12,15,16]. There are 17 different types of H_2O ice which are formed at different temperatures and pressures all carrying different properties. At the temperature and pressure ranges of the design location (Jezero crater, Mars), H_2O is found as vapour in the Martian air and as ice underneath a regolith layer [10]. This ice is believed to be the same ice crystal: Ih. As evidence has shown liquid water on the surface of Mars, the H_2O is believed to be in fact a brine containing different types of salts, one being natrium chloride (NaCl). The exact composition of the ice is still unknow [10].

3.2.2 Mechanical and structural properties

Ice is very inhomogeneous resulting in varying strength. However, in general, it can be stated that ice is stronger in compression than in tension. The average compressive strength of ice is 7 MPa and the average tensile strength is 2 MPa. Both the compressive and tensile strength increase when the temperature the ice is subjected to decreases as can be seen in figure 3. One of the most specific properties of ice is that it creeps especially under high stress levels. Creep may appear under high stress but also when it is near its melting point (-5˚C and -10˚C) and depends on the nature of the stress, the grain size and the impurity content (impurities being generally water or air bubbles). Ice becomes thus stronger and denser at temperatures well below its freezing point; however it also becomes more brittle. Ice freezes from the outside in thus putting great pressure on the outer ice layer. To avoid this brittleness, proposed methods are to either build up the ice out of thin layers or to keep the water moving under the surface (like a river would). All these mechanical aspects depend on different types of ice whether it is the formation process, the temperature, the type of ice, or the crystal structure [12], which means that every aspect must be considered with caution.

Redundancy is vital for the mission [1]. As ice is a peculiar material with relatively low strengths, the strength should be reinforced in order to achieve a more redundant material. To improve the mechanical properties of the ice, fibrous reinforcements is a well know relatively cheap and effective technique [12].

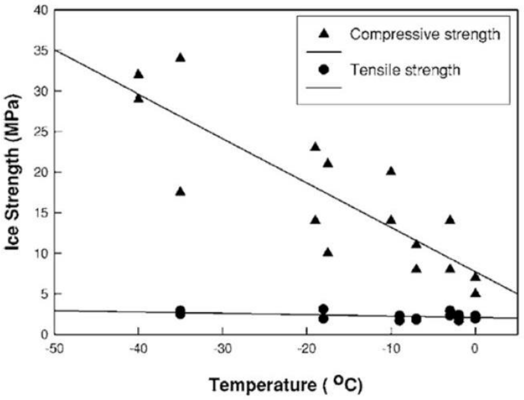

Figure 3. Strength of ice versus temperature of the ice. The compressive strength increases when the ice temperature decreases [12].

3.2.3 *Experiments*

In order to improve the strength of the ice using local resources, experiments were made adding different in situ materials and mission recyclables to H_2O ice. Three experiments were made with a each a different objective. All the experiments comprise of the testing of different specimens under different conditions. Each variable is tested at least three times and compared to a zero measurement. The zero measurement is testing a plain H_2O ice specimen with the same conditions as the variable specimens in order to compare the values.

3.2.4 *Experiment A: Earth Environment tests*

The objective of experiment A is to find a suitable fibre reinforcement material to add to the Martian ice to improve its building properties. This experiment is a benchmarking test. The fibres added are sand, acting as regolith simulant and recycled plastic shreds (PP and HDPE), acting as mission recyclables. In addition to the fibres, table salt is added to the H_2O specimen as theory indicates that salt is present in the Martian ice. Therefore, this experiment also indicates the influence the salt present in the ice has on the tests. Experiment A comprises of two tests. A mix test (test A01), where different ice specimen are formed mixing different quantities of fibres. The ice specimen are made in a freezing environment of -20°C. The test A01 is visually assessed by benchmarking each specimen. The second test (test A02) is a drop test. During this test, the ice specimen made in test A01 are dropped from a height of 1400mm. A02 aims at defining how the added fibres are sticking to the ice crystals. This test is performed at ambient temperature (+/- 1°C 13°C) and at an atmosphere of 1 bar. The behaviour of the ice is then visually assessed, especially the formation of cracks is checked. The input and output table for experiment A can be found in appendix A.

3.2.5 *Experiment B: Mars Analogue tests*

The objective of experiment B is to confirm the conclusions reached in experiment A and to get a value for the new composite which can be used for the design of process and structure for the Martian habitat. The reinforcement used is sodium chloride (NaCl). Experiment B comprises of two tests in a simulated Martian environment using standard testing methods. The first test (B01), is a melting test where different ice specimen are formed at -70°C mixing different quantities of NaCl. Once the ice is formed, the specimen are left to melt at ambient temperature (+/- 1°C 25°C). The observations are made visually by analysing the crack formation upon taking the specimens out of the freezer and the melting phase is timed. The second test (test B02) is a compression test using a standard method to test concrete: the ASTM C39 Compression Test. During B02, the ice specimen made at -70°C are put under compression to assess their mechanical strength. This test aims at defining if the added fibres are changing the compressive strength of the ice. B02 is performed at ambient temperature (+/- 1°C 25°C) and at an atmosphere of 1 bar. The input and output table for experiment B can be found in appendix B.

3.2.6 *Experiment C: Mars Analogue rectification tests*

The objective of experiment C is to rectify the inconsistency made during experiment B. These inconsistencies were highlighted in the result of B02. Indeed the B02 zero measurement have values differing greatly with the theory. The reinforcement used for experiment C is still sodium chloride (NaCl). Experiment C comprises of one test in a simulated Martian environment using standard testing methods. The test (C01) is a compression test using a standard method to test concrete: the ASTM C39 Compression Test. During this test, the ice specimen made at -70°C are put under compression to assess their mechanical strength. This test is performed at a simulated Martian temperature of -70°C and at an atmosphere of 1 bar. The only variable assessed is the percentage of NaCl added to the ice specimens, 0 part per thousand (ppt), 10ppt and 15ppt. The input and output table for experiment C can be found in appendix C.

3.3 Processing of the ice

The first part of the research analysed how Martian ice can be used as building material. This second part analyses how a habitat can be build using that ice. DRA5.0 [7] set the requirement that the habitat should be built remotely or semi-remotely. This is because humans can only safely be sent to Mars when the habitat is completely before take-off as well as the ISRU plant and return journey. Therefore, a preliminary study [17] states that the habitat should be built using robotic engineering. After an analysis of the different possible methods, additive manufacturing (AM) proves to be the most promising technique. To assess if that technique would be applicable for the ice in a Martian environment, another experiment is needed.

3.3.1 Experiment D: process principle

The objective of experiment D is to find out if the ice layers bond well with each other and if they can indeed be "stacked" using an AM technique. This experiment is visually assessed. The experiment set up is a linear frame with a micro drip system mounted onto the frame (pictured in figure 4). This micro drip system allows a constant rate of water droplet to fall onto the surface based on the Mariotte's bottle principle. The drip system is mounted onto the frame which makes back and forth linear movements, allowing to "print" the ice. The whole setup is placed in a freezing environment of -30°C.

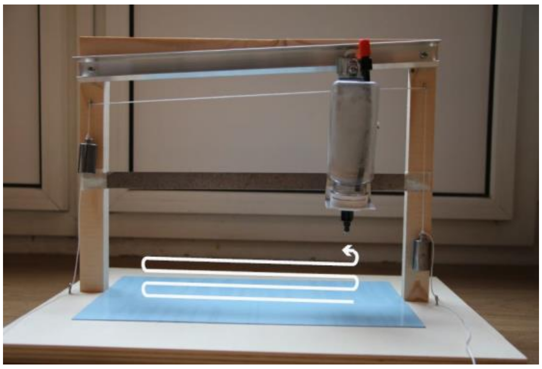

Figure 4. Setup of the frame and micro drip system for experiment D.

4. Results

In this header, the results of the four experiments are shown. Those results are then interpreted in the discussion.

4.1 Experiment A: Earth Environment tests

The result of the A01 mixing test indicates that the sand and plastic did not mix well with the H_2O and the added fibres sunk to the bottom. Therefore, in the drop test (A02), the reinforcement fibres have little to no effect on the resistance to break. However, the specimen where table salt is added show a more even distribution of the fibres compared the pure H_2O mixes as can be seen in figure 5. Early observation shows that the consistency of the ice changes towards a granular structure when table salt is added. This granular structures also prevents large cracks to run through the whole specimen, therefore only damaging a small part of it rather than breaking into multiples pieces like the pure H_2O specimen did.

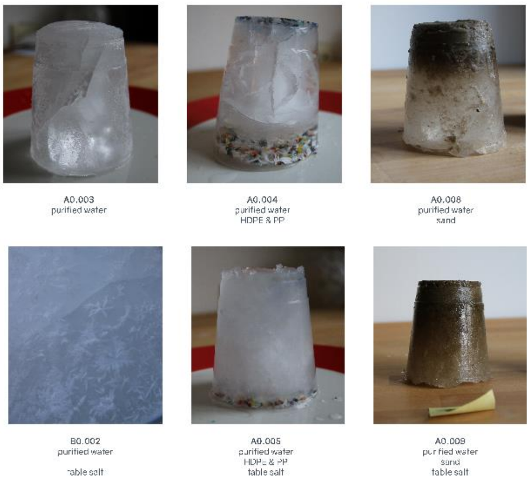

Figure 5. Visual outcome of experiment A: adding salt changes the structure of the ice allowing the reinforcement to be more evenly dispersed.

4.2 Experiment B: Mars Analogue tests

The results of experiment B show that adding NaCl to H_2O creates a denser ice where less cracks occur even when the ice is subjected to extremely low temperatures of -70°C. The higher the salinity of the specimen, the more opaque and milky the ice looks. The results of the melting test (B01), indicate that pure H_2O melts faster and in an uneven shape compared to the salt ice specimen. To perform the compression tests (B02), the ice specimen are sanded on the top side as the ice expanded heterogeneously which would have prevented the specimen to be properly tested. The result shown in the deformation and standard force graph (see figure 6) indicates that the higher the salinity, the more ductile the ice behaves. Indeed the specimen with a lower salinity (0ppt to 2,8ppt) have a more brittle behaviour which is comparable to standard building materials like concrete.

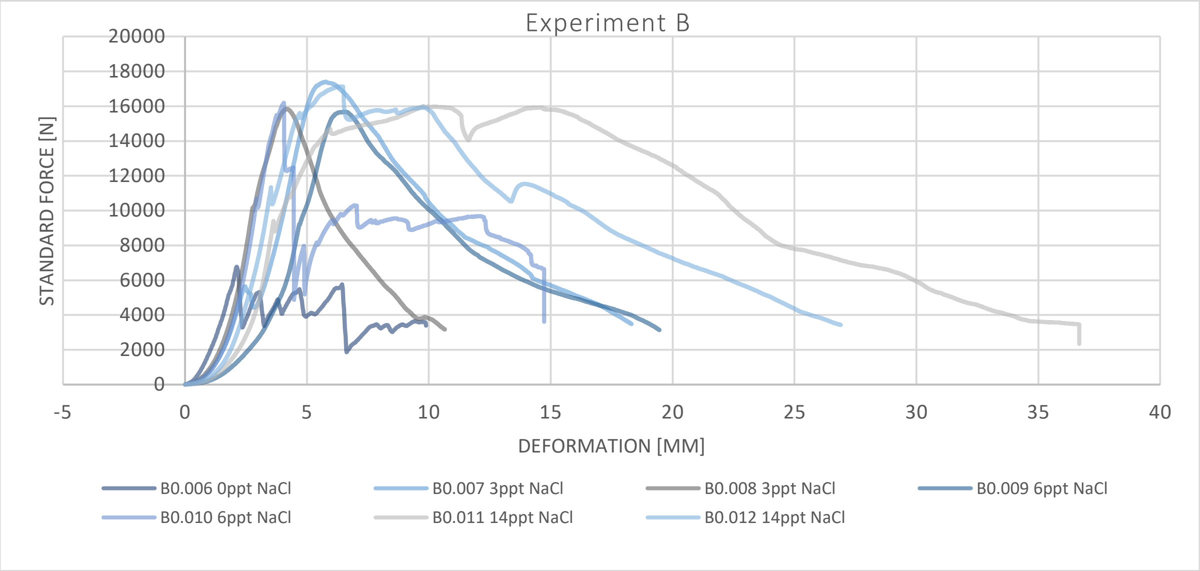

Figure 6. Deformation graph of experiment B test B02. The standard force (N) is plotted against the deformation (mm) of the ice specimen.

During the B02 test, the compressive strength of the zero measurements differ by a factor 10 from the values found in literature. After an analysis [17], the conclusion was drawn that the stress due to the sanding of the specimen as well as the temperature fluctuation (from -70°C to +25°C), are the probable reason for the inconsistency between the tested results and the literature findings. Therefore another experiment is needed to rectify these inconsistencies.

4.3 Experiment C: Mars Analogue rectification tests

The visual observation of the specimen are similar to the observations made in experiment B. The ice was made under similar conditions, therefore reinforcing the conclusions drawn from experiment B that the higher the salinity, the less cracks the ice structure present. However, the results from the compression test C01 differ greatly compared to experiment B. As can be seen on figure 7, the curvature of the deformation and standard force table is much steeper with a clear break, as opposed to the longer more ductile behaviour of the specimen in experiment b. The graph shows a compressive strength for the zero measurements comparable to the literature. It also indicates that the increase in salinity from 10ppt to 15 ppt does not affect the results. The last observation is that specimen C0.009 does present a more ductile behaviour although it has a high salinity of 15ppt.

This could be due to the fact that the liquid nitrogen tank, which kept the testing temperature at -70°C, was empty during the testing of the last three specimen. Meaning that the actual temperature of the testing environment was -50°C for specimen C0.007 and -20°C for specimen C0.008 and C0.009. The results from figure 7 can also clearly be seen in figure 8, where a high salinity of the ice presents a clean break. The conclusion drawn from experiment C is that ice has a brittle behaviour when exposed to temperatures of -70°C and that adding natrium chloride increase its compressive strength. At 15ppt of salinity at -70°C, the ice specimen present clean cuts. However, at higher temperatures the ice has a more ductile behaviour. These fluctuations in temperature, which also occur on mars between day and night, have great influence on the mechanical properties of the ice.

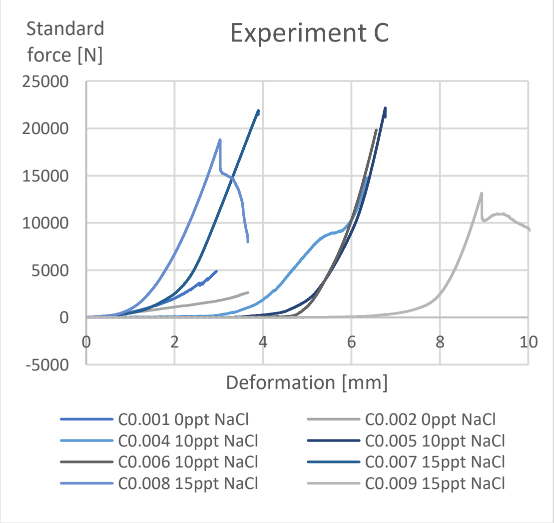

Figure 7. Deformation graph of experiment C test C01. The standard force (N) is plotted against the deformation (mm) of the ice specimen.

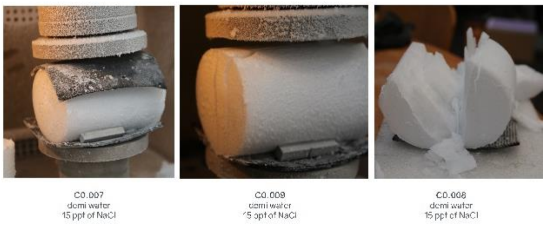

Figure 8. Ice specimen with 15ppt of NaCl, before, during and after the compression test at -70°C.

4.4 *Experiment D: process principle*

The first observations indicate that, although the water drip system is regular, the layers are built irregularly. The first two layers form large droplets ranging from 2mm to 35mm in diameter. However, the more layers are “printed” the higher and more linear the structure becomes, creating a thin wall. A peculiar occurrence is that the eighth layer cracked the structure, probably due to the temperature difference between the water being deposited and the already frozen structure underneath. After printing a ninth layer, the crack was gone. This occurrence led to a simple test, where a force was applied onto both end of the printed structure until it broke. The resistance offered by the structure was high and it broke in one straight line, even though the structure was built irregularly.

5. Discussion

In the discussion, the results of the research are discussed, in order to answer the research question: What are the building options to use in situ ice to design a radiation shielding habitat on Mars?

5.1 *Material: local ice*

The main outcome of the research is that already 15 ppt of NaCl reinforces the compressive strength H_2O ice when exposed to extremely low temperatures (-30°C to -70°C). On average the compressive strength of the ice composite increase from 1 MPa to 4 MPa. This means that the ice composites could be used to design a habitat on Mars to effectively shield the crew from radiation if the structure is built under compression. Ice also proved to be a peculiar material which will behave differently throughout the day and night due to the difference in temperature fluctuation. Indeed, the ice structure presents a brittle but strong behaviour when exposed to extremely low temperatures (from -30°C down). The ice structure presents a more ductile behaviour when exposed to higher temperatures of -30°C to +5°C.

5.2 *Process of the ice*

The most probable explanation for the ice crack to disappear while printing is that the deposited water filled the crack which froze and expanded, filling in the crack completely. The printed structure has therefore an ability to repair itself. The structure also yields a higher strength, this is probably due to the formation of the ice layer by layer, which is supported by theory. This means that when “printing” the ice layer by layer it is even more reinforced.

However, when exposed to high temperatures of above -21°C or to a lower pressure of 580 Pa for an extended period of time the ice will sublimate into the atmosphere. Therefore, when designing a habitat, the ice thickness should be increased to provide enough shielding for a year-long mission. The experiments were performed to simulate the Martian environment as best as possible, however the difference in pressure could not be tested. On top of that, each variable was only tested two or three times with similar conditions. Therefore, the results and interpretation of the results should be taken as a concept idea rather than an empirical result.

5.3 *Design exercise: Ice Hab*

The results were assessed with a design exercise which resulted in de Ice Hab design. The Ice Hab is designed to be built at Jezero Crater, Mars. The habitat is formed by two large ice domes, with one dome containing the living quarters and the other dome the work environment (see figure 9). The use of two domes as well as two ice walls is mainly for redundancy. However, it also architecturally improves the general living environment. Also two different building techniques are used for the different ice walls as an experiment. The first ice wall is a plastic membrane filled with water which will freeze as well as aerogel to insulate the habitat. This membrane also allows the pressurization of the habitat, therefore, allowing for an adequate indoor environment which complies to the requirements of DRA5.0. The membrane is a translucent type of plastic which will enable the outdoor daylight to shine through the ice and into the habitat. This will upgrade the living and working experience of the whole crew. However, more experiments are needed to assess if the outdoor environment such as the rim of the crater can be seen through ice at such low temperatures. Most probably, it will be possible to distinguish the outdoor environment during the day when temperatures rise. The second ice wall is formed using additive manufacturing. This wall will mainly absorb radiation to protect the crew. As additive manufacturing has not been tested on Mars (yet), this wall will be an experiment to assess its feasibility. This wall creates an intermediate environment between the outdoor Martian climate and the indoor climate. This environment can be used to perform experiments by the crew while inhabiting the Ice Hab.

5.4 Conclusion of the discussion

The research answers the research question by discovering a new building material, sodium chloride ice, and a specific technique (additive manufacturing) to process the ice into a habitat.

The research specifies that local Martian ice can be used as building material. The ice not only assesses the engineering requirements to protect the crew from radiation but also the psychological requirements. Indeed, the ice, although quite opaque at such low temperatures, will let some daylight through which allow the crew to see the difference between day and night and maybe even distinguish some of their environment outside. These characteristics will enhance the liveability of the crew's environment and will increase the overall mission's success. In general, it can be said that the design of the Ice Hab complies well to the set requirements of the mission design and the challenges of the location.

These findings are relevant for a Martian environment but also open a door on issues on our own planet. Using the methodology used in this research, other structures could be build using widely available materials instead of shipping traditional materials to remote locations. This is particularly interesting for remote places on Earth like Antarctica or the Atacama desert. This research could be a step towards solving the issue of building shelters everywhere on Earth in a sustainable way.

6. Conclusions

The aim of this research was to find the building options to use in situ ice to design a radiation shielding habitat on Mars. Experiments were made to assess and improve the ice within an analogous Martian environment. The outcome is that the use of locally available H_2O ice is suitable. The research highlights that the already present natrium chloride (NaCl) in the ice reinforces the compressive strength of the ice as well as it enables the possibility for repair during the building phase due to a layered process. Therefore, a suitable building process is the use of additive manufacturing, which is not only a remotely activated system, but also, this technique reinforces the overall structure of the ice.

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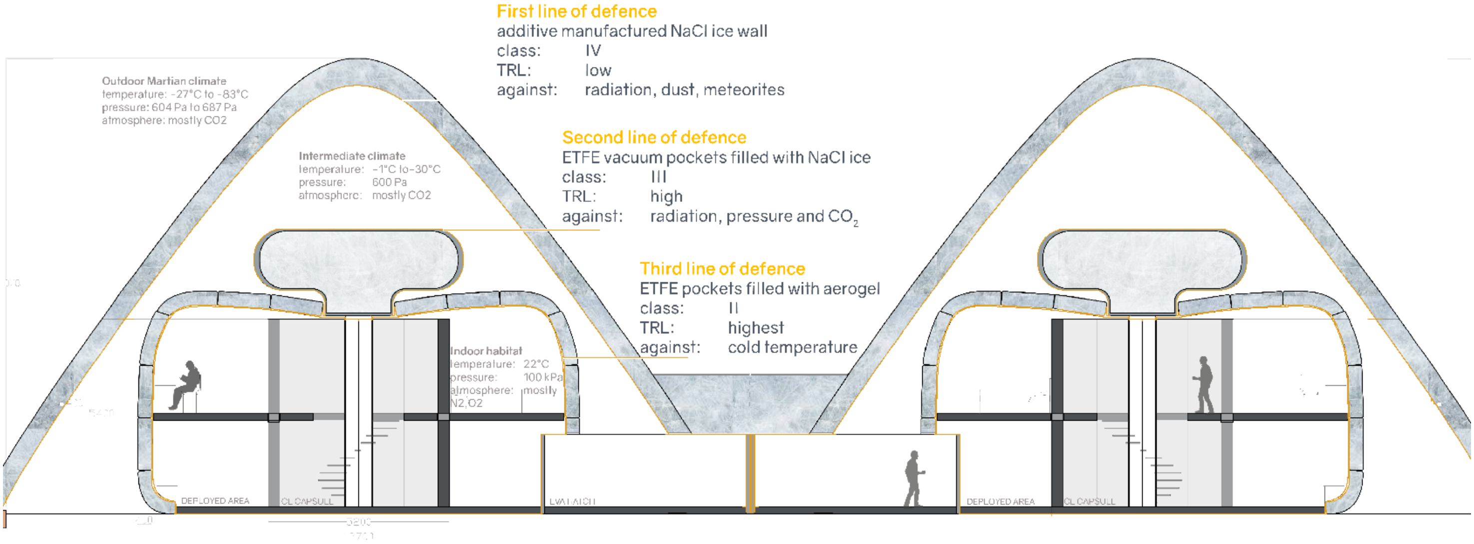

Figure 9. Section of the Ice Hab: the two different ice walls can clearly be seen.

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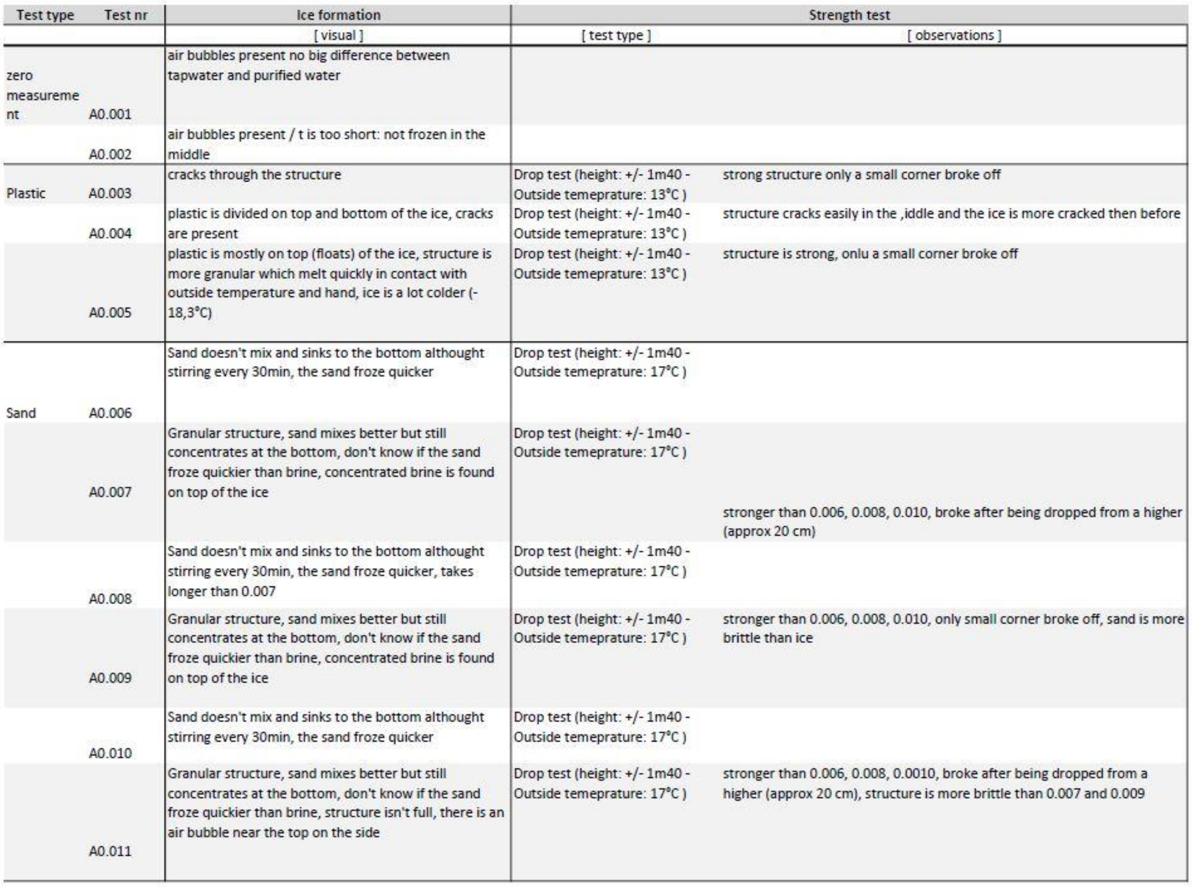
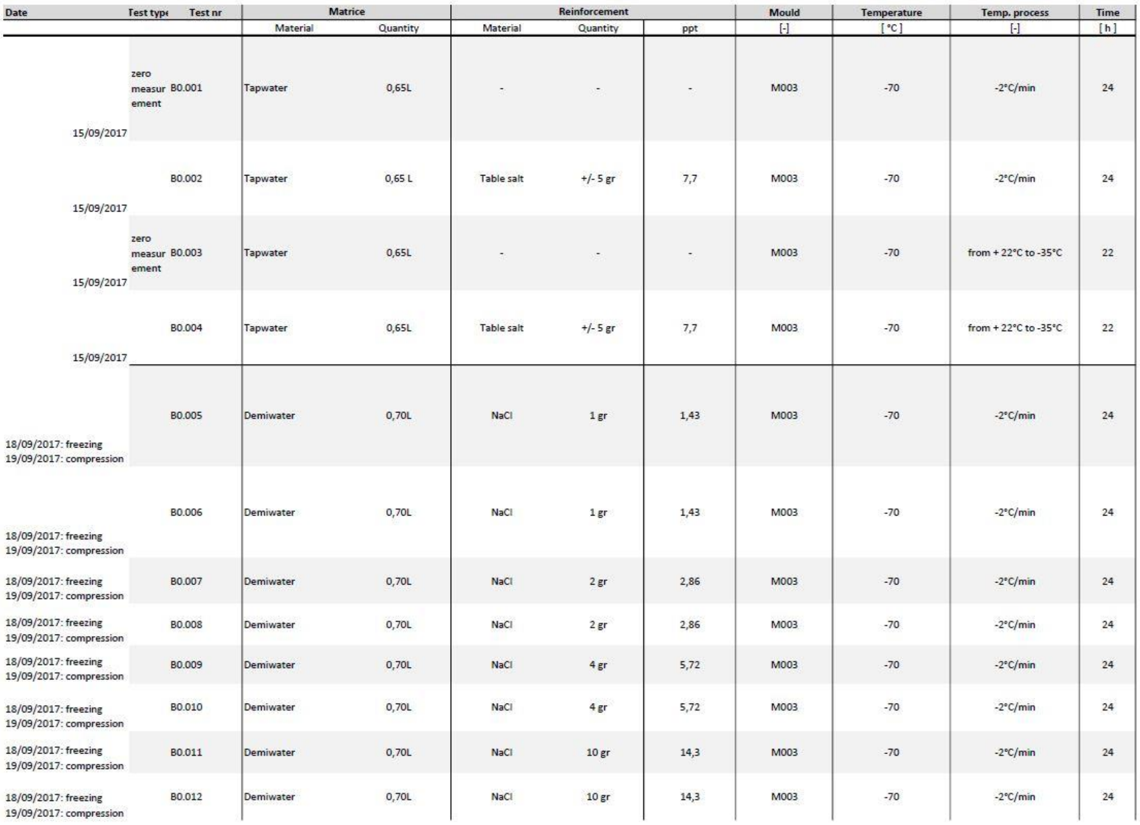
Appendix A (Experiment A: specimen data)

Date	Test type	Test nr	Picture nr	Movie nr	Matrice		Reinforcement		Mould	Temperature	Time
					Material	Percentage	Material	Percentage	[-]	[°C]	[h]
04/09/2017	zero measurement	A0.001	5682 - 5687 - 5692 t/m 56	-	Tapwater	100	-	-	M001	-20	16
04/09/2017		A0.002	5685 - 5688 t/m 5691 - 56	-	H2O purified	100	-	-	M001	-20	16
08/09/2017	Plastic	A0.003	5704 t/m 5711	5712	H2O purified	100	-	-	M002	-20	36
08/09/2017		A0.004	5702 - 5703 - 5715 t/m 57	5722	H2O purified	355 mL	Plastic PP & HDPE	1 tablespoon	M002	-20	36
08/09/2017		A0.005	5700 t/m 5702 - 5725 t/m	5732	H2O purified	355 mL	NaCl Plastic PP& HDPE	+/- 10 gr - 2 teaspoons 1 tablespoon	M002	-20	36
12/09/2017: freezing 13/09/2017: drop test	Sand	A0.006	5740 t/m 5753 - 5765 t/m	5774	H2O purified	355 mL	Sand	1 tablespoon	M002	-20	20
12/09/2017: freezing 13/09/2017: drop test		A0.007	5740 t/m 5747 - 5754 t/m	5778	H2O purified	355 mL	Sand NaCl	1 tablespoon +/- 5 gr - 1 teaspoon	M002	-20	20
12/09/2017: freezing 13/09/2017: drop test		A0.008	5740 t/m 5747 - 5760 t/m	5782	H2O purified	355 mL	Sand	2 tablespoons	M002	-20	20
12/09/2017: freezing 13/09/2017: drop test		A0.009	5740 t/m 5747 - 5787 t/m	5808	H2O purified	355 mL	Sand NaCl	2 tablespoons +/- 5 gr - 1 teaspoon	M002	-20	20
12/09/2017: freezing 13/09/2017: drop test		A0.010	5740 t/m 5747 - 5792 t/m	5812	H2O purified	355 mL	Sand	5 tablespoons	M002	-20	20
12/09/2017: freezing 13/09/2017: drop test		A0.011	5740 t/m 5747 - 5797 t/m	5818	H2O purified	355 mL	Sand NaCl	5 tablespoons +/- 5 gr - 1 teaspoon	M002	-20	20

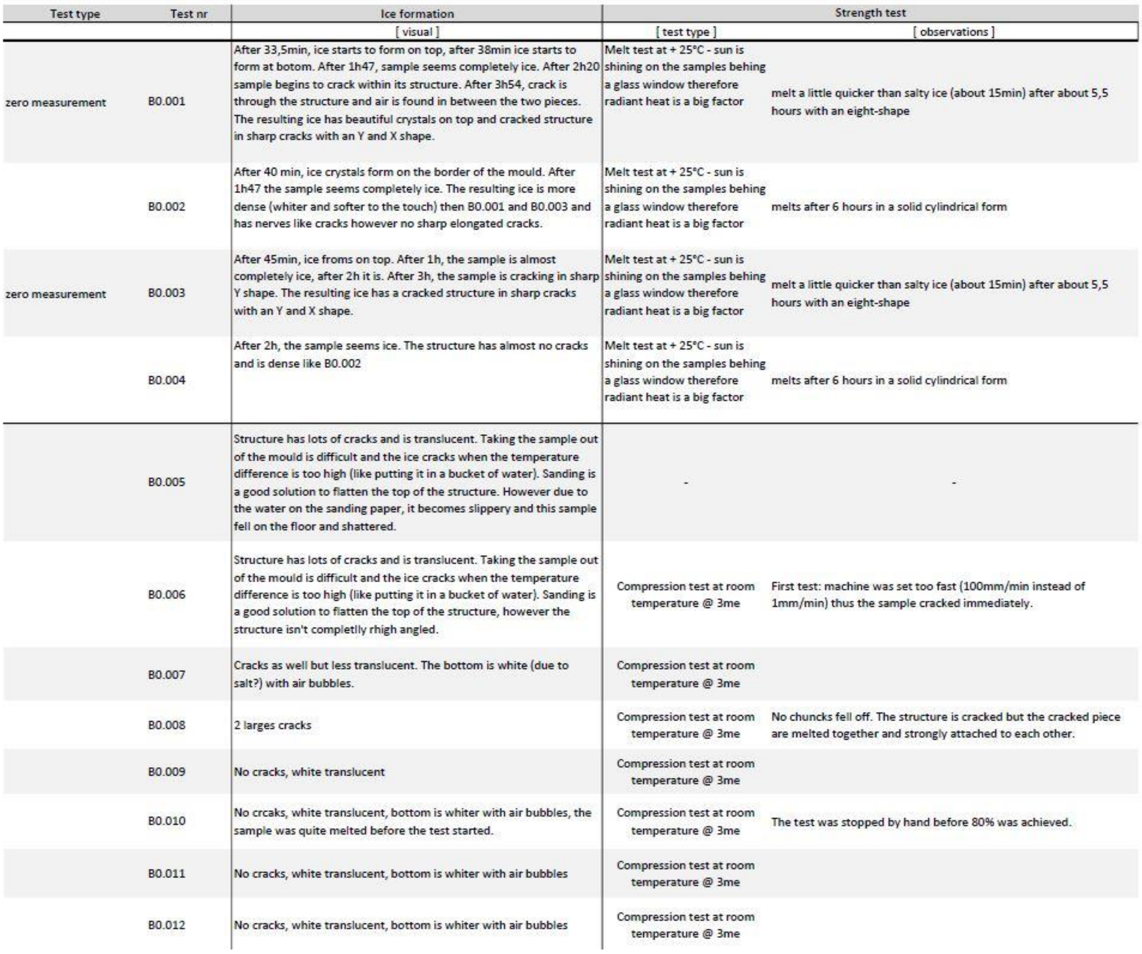


Test type	Test nr	Ice formation	Strength test	
		[visual]	[test type]	[observations]
zero measurement	A0.001	air bubbles present no big difference between tapwater and purified water		
	A0.002	air bubbles present / t is too short: not frozen in the middle		
Plastic	A0.003	cracks through the structure	Drop test (height: +/- 1m40 - Outside temeprature: 13°C)	strong structure only a small corner broke off
	A0.004	plastic is divided on top and bottom of the ice, cracks are present	Drop test (height: +/- 1m40 - Outside temeprature: 13°C)	structure cracks easily in the ,iddle and the ice is more cracked then before
	A0.005	plastic is mostly on top (floats) of the ice, structure is more granular which melt quickly in contact with outside temperature and hand, ice is a lot colder (-18,3°C)	Drop test (height: +/- 1m40 - Outside temeprature: 13°C)	structure is strong, onlu a small corner broke off
Sand	A0.006	Sand doesn't mix and sinks to the bottom althought stirring every 30min, the sand froze quicker	Drop test (height: +/- 1m40 - Outside temeprature: 17°C)	
	A0.007	Granular structure, sand mixes better but still concentrates at the bottom, don't know if the sand froze quickier than brine, concentrated brine is found on top of the ice	Drop test (height: +/- 1m40 - Outside temeprature: 17°C)	stronger than 0.006, 0.008, 0.010, broke after being dropped from a higher (approx 20 cm)
	A0.008	Sand doesn't mix and sinks to the bottom althought stirring every 30min, the sand froze quicker, takes longer than 0.007	Drop test (height: +/- 1m40 - Outside temeprature: 17°C)	
	A0.009	Granular structure, sand mixes better but still concentrates at the bottom, don't know if the sand froze quickier than brine, concentrated brine is found on top of the ice	Drop test (height: +/- 1m40 - Outside temeprature: 17°C)	stronger than 0.006, 0.008, 0.010, only small corner broke off, sand is more brittle than ice
	A0.010	Sand doesn't mix and sinks to the bottom althought stirring every 30min, the sand froze quicker	Drop test (height: +/- 1m40 - Outside temeprature: 17°C)	
	A0.011	Granular structure, sand mixes better but still concentrates at the bottom, don't know if the sand froze quickier than brine, structure isn't full, there is an air bubble near the top on the side	Drop test (height: +/- 1m40 - Outside temeprature: 17°C)	stronger than 0.006, 0.008, 0.0010, broke after being dropped from a higher (approx 20 cm), structure is more brittle than 0.007 and 0.009

Appendix B (Experiment B: specimen data)

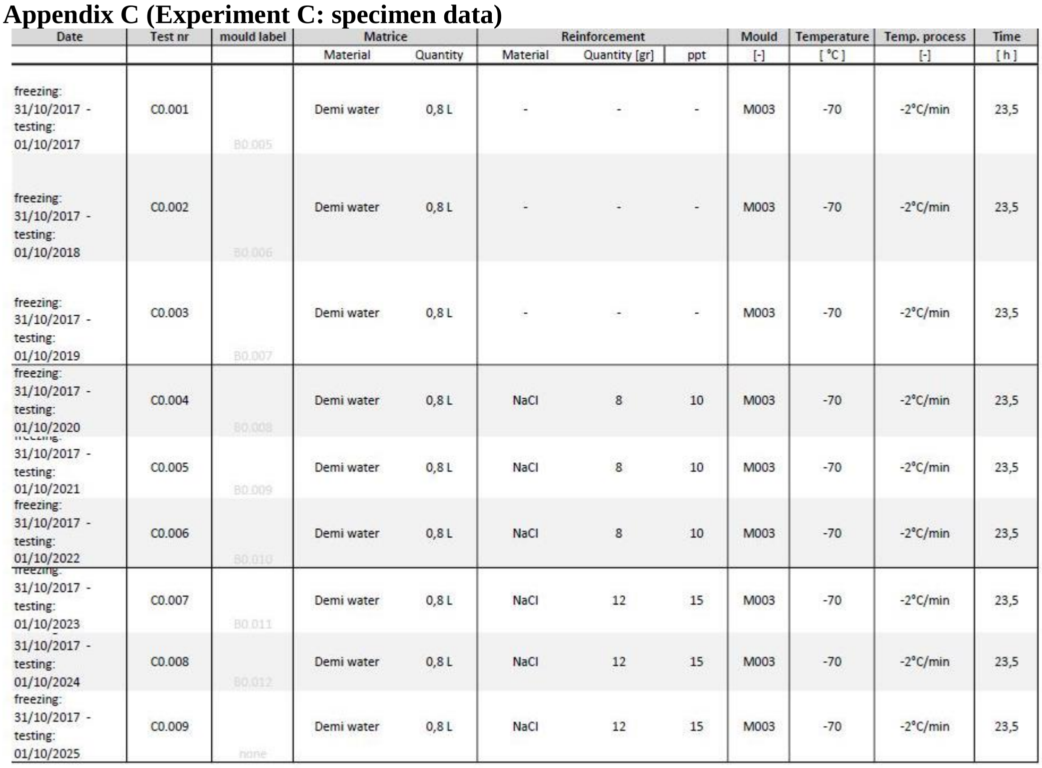


Date	Test typ	Test nr	Matrice		Reinforcement			Mould	Temperature	Temp. process	Time
			Material	Quantity	Material	Quantity	ppt	[-]	[°C]	[-]	[h]
15/09/2017	zero measurement	B0.001	Tapwater	0,65L	-	-	-	M003	-70	-2°C/min	24
15/09/2017		B0.002	Tapwater	0,65 L	Table salt	+/- 5 gr	7,7	M003	-70	-2°C/min	24
15/09/2017	zero measurement	B0.003	Tapwater	0,65L	-	-	-	M003	-70	from + 22°C to -35°C	22
15/09/2017		B0.004	Tapwater	0,65L	Table salt	+/- 5 gr	7,7	M003	-70	from + 22°C to -35°C	22
18/09/2017: freezing 19/09/2017: compression		B0.005	Demiwater	0,70L	NaCl	1 gr	1,43	M003	-70	-2°C/min	24
18/09/2017: freezing 19/09/2017: compression		B0.006	Demiwater	0,70L	NaCl	1 gr	1,43	M003	-70	-2°C/min	24
18/09/2017: freezing 19/09/2017: compression		B0.007	Demiwater	0,70L	NaCl	2 gr	2,86	M003	-70	-2°C/min	24
18/09/2017: freezing 19/09/2017: compression		B0.008	Demiwater	0,70L	NaCl	2 gr	2,86	M003	-70	-2°C/min	24
18/09/2017: freezing 19/09/2017: compression		B0.009	Demiwater	0,70L	NaCl	4 gr	5,72	M003	-70	-2°C/min	24
18/09/2017: freezing 19/09/2017: compression		B0.010	Demiwater	0,70L	NaCl	4 gr	5,72	M003	-70	-2°C/min	24
18/09/2017: freezing 19/09/2017: compression		B0.011	Demiwater	0,70L	NaCl	10 gr	14,3	M003	-70	-2°C/min	24
18/09/2017: freezing 19/09/2017: compression		B0.012	Demiwater	0,70L	NaCl	10 gr	14,3	M003	-70	-2°C/min	24



Test type	Test nr	Ice formation	Strength test	
		[visual]	[test type]	[observations]
zero measurement	B0.001	After 33,5min, ice starts to form on top, after 38min ice starts to form at botom. After 1h47, sample seems completely ice. After 2h20 sample begins to crack within its structure. After 3h54, crack is through the structure and air is found in between the two pieces. The resulting ice has beautiful crystals on top and cracked structure in sharp cracks with an Y and X shape.	Melt test at + 25°C - sun is shining on the samples behing a glass window therefore radiant heat is a big factor	melt a little quicker than salty ice (about 15min) after about 5,5 hours with an eight-shape
	B0.002	After 40 min, ice crystals form on the border of the mould. After 1h47 the sample seems completely ice. The resulting ice is more dense (whiter and softer to the touch) then B0.001 and B0.003 and has nerves like cracks however no sharp elongated cracks.	Melt test at + 25°C - sun is shining on the samples behing a glass window therefore radiant heat is a big factor	melts after 6 hours in a solid cylindrical form
zero measurement	B0.003	After 45min, ice froms on top. After 1h, the sample is almost completely ice, after 2h it is. After 3h, the sample is cracking in sharp Y shape. The resulting ice has a cracked structure in sharp cracks with an Y and X shape.	Melt test at + 25°C - sun is shining on the samples behing a glass window therefore radiant heat is a big factor	melt a little quicker than salty ice (about 15min) after about 5,5 hours with an eight-shape
	B0.004	After 2h, the sample seems ice. The structure has almost no cracks and is dense like B0.002	Melt test at + 25°C - sun is shining on the samples behing a glass window therefore radiant heat is a big factor	melts after 6 hours in a solid cylindrical form
	B0.005	Structure has lots of cracks and is translucent. Taking the sample out of the mould is difficult and the ice cracks when the temperature difference is too high (like putting it in a bucket of water). Sanding is a good solution to flatten the top of the structure. However due to the water on the sanding paper, it becomes slippery and this sample fell on the floor and shattered.	-	-
	B0.006	Structure has lots of cracks and is translucent. Taking the sample out of the mould is difficult and the ice cracks when the temperature difference is too high (like putting it in a bucket of water). Sanding is a good solution to flatten the top of the structure, however the structure isn't completlly rhigh angled.	Compression test at room temperature @ 3me	First test: machine was set too fast (100mm/min instead of 1mm/min) thus the sample cracked immediately.
	B0.007	Cracks as well but less translucent. The bottom is white (due to salt?) with air bubbles.	Compression test at room temperature @ 3me	
	B0.008	2 larges cracks	Compression test at room temperature @ 3me	No chuncks fell off. The structure is cracked but the cracked piece are melted together and strongly attached to each other.
	B0.009	No cracks, white translucent	Compression test at room temperature @ 3me	
	B0.010	No crcaks, white translucent, bottom is whiter with air bubbles, the sample was quite melted before the test started.	Compression test at room temperature @ 3me	The test was stopped by hand before 80% was achieved.
	B0.011	No cracks, white translucent, bottom is whiter with air bubbles	Compression test at room temperature @ 3me	
	B0.012	No cracks, white translucent, bottom is whiter with air bubbles	Compression test at room temperature @ 3me	

Appendix C (Experiment C: specimen data)



Date	Test nr	mould label	Matrice		Reinforcement			Mould	Temperature	Temp. process	Time
			Material	Quantity	Material	Quantity [gr]	ppt	[-]	[°C]	[-]	[h]
freezing: 31/10/2017 - testing: 01/10/2017	C0.001	B0.005	Demi water	0,8 L	-	-	-	M003	-70	-2°C/min	23,5
freezing: 31/10/2017 - testing: 01/10/2018	C0.002	B0.006	Demi water	0,8 L	-	-	-	M003	-70	-2°C/min	23,5
freezing: 31/10/2017 - testing: 01/10/2019	C0.003	B0.007	Demi water	0,8 L	-	-	-	M003	-70	-2°C/min	23,5
freezing: 31/10/2017 - testing: 01/10/2020	C0.004	B0.008	Demi water	0,8 L	NaCl	8	10	M003	-70	-2°C/min	23,5
31/10/2017 - testing: 01/10/2021	C0.005	B0.009	Demi water	0,8 L	NaCl	8	10	M003	-70	-2°C/min	23,5
freezing: 31/10/2017 - testing: 01/10/2022	C0.006	B0.010	Demi water	0,8 L	NaCl	8	10	M003	-70	-2°C/min	23,5
31/10/2017 - testing: 01/10/2023	C0.007	B0.011	Demi water	0,8 L	NaCl	12	15	M003	-70	-2°C/min	23,5
31/10/2017 - testing: 01/10/2024	C0.008	B0.012	Demi water	0,8 L	NaCl	12	15	M003	-70	-2°C/min	23,5
freezing: 31/10/2017 - testing: 01/10/2025	C0.009	none	Demi water	0,8 L	NaCl	12	15	M003	-70	-2°C/min	23,5

Test nr	Ice formation	Strength test	
	[visual]	[test type]	[observations]
C0.001	lots of cracks form after taking it out of the coolbox but first nice longitudinal bubble formation (crystals?) - ice is clear	compression at -70°C (1mm/min)	broke in the short direction in lots of little pieces
C0.002	lots of cracks (really clear) form after taking it out of the coolbox but first nice longitudinal bubble formation (crystals?) - ice is clear	compression at -70°C (1mm/min)	a corner broke off with different little pieces
C0.003	lots of cracks (lots of small ones) form after taking it out of the coolbox but first nice longitudinal bubble formation (crystals?) - ice is clear	compression at -70°C (1mm/min)	Specimen broke upon demoulding, therefore not tested.
C0.004	ice is white - one or two vertical cracks	compression at -70°C (1mm/min)	corner broke off in one piece
C0.005	ice is white - one nerve like vertical crack	compression at -70°C (1mm/min)	smooth cut in the middle in longitudinal direction with small pieces in the cut
C0.006	ice is white - one nerve like vertical crack	compression at -50°C (1mm/min)	Liquid N2 tank went empty - smooth cut in the middle in longitudinal direction - one half broke into many pieces when deposing it in the box
C0.007	ice is white - one small crack formation (Y)	compression at -20°C (1mm/min)	smooth cut in the middle in longitudinal direction - keeps its original shape
C0.008	ice is white - no visible cracks	compression at -20°C (1mm/min)	smooth cut in the middle in longitudinal direction with little broke off pieces
C0.009	ice is white - no visible cracks	compression at -20°C (1mm/min)	smooth 2 cuts in the middle in longitudinal direction - keeps its original shape