THESIS - 185413

PHYSICAL AND MECHANICAL CHARACTERIZATION OF PYKRETE WITH VARIOUS MATERIAL COMPOSITION AND IT'S POSSIBLE APPLICATION

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INSTITUT TEKNOLOGI SEPULUH NOPEMBER
SURABAYA
2021

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THESIS APPROVAL SHEET

This thesis is prepared and written to fullfil one of the requirements

in order to obtain a degree

MAGISTER TEKNIK (MT)

in:

Institut Teknologi Sepuluh Nopember

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ABSTRACT

Vacuum-based insulation system has been widely used in daily lives to maintain low temperature for storage purposes. While this method of insulation is widely available and easy to make, it has one major shortcoming in the form of it's fragility. The system cannot be exposed to concussive shocks since it could break the outer shell of the containment and removes the vaccuum, causing a containment breach. If this happen, the system will rapidly lose insulation and the contents inside is no longer stored in low-temperature environment. Ice could be used to preserve the low temperature environment, but not for long.

Pykrete is an ice-composite material made from a mixture of water and cellulose-based reinforce material (either wood or paper) with very high resistance against concussive shocks and very resistant against melting compared to the regular ice. Pykrete has a potential to be used as protective insulation material, with the aim to keep the temperature inside low even in containment breach situation much longer than regular ice.

This research has shown that pykrete, in general has a much longer cooling duration compared with regular ice (roughly up to 2 to 3 hours more) as well as better mechanical properties based from the calculations performed on it's theoretical tensile strength, depending on the contents of it's reinforce material. However, this also comes with a cost of slightly lower cooling temperature compared to regular ice (1 to 2 degrees Celcius higher). This properties makes pykrete well-suited for low-cost insulative protection for cold storage application, concept of application can be in the form of spaced armor protection.

Keyword: Pykrete, Insulation, Temperature, Ice, Humidity

KARAKTERISASI FISIK DAN MEKANIK DARI MATERIAL PYKRETE DENGAN BERBAGAI KOMPOSISI MATERIAL DAN POTENSI APLIKASINYA

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ABSTRAK

Sistem insulasi berbasis vakum telah digunakan secara luas dalam kehidupan sehari-hari untuk mempertahankan suhu rendah dalam penyimpanan dingin. Walaupun sistem insulasi ini dipergunakan secara luas dan mudah untuk dibuat, sistem ini rentan terhadap benturan dan goncangan. Jika system insulasi berbasis vakum terkena benturan dan goncangan, maka ada kemungkinan terjadinya kebocoran yang akan menghilangkan kondisi vakum didalam sistem. Hal ini mengakibatkan hilangnya kemampuan insulasi dan temperatur didalam sistem tidak lagi dalam kondisi dingin. Es dapat digunakan untuk menjaga agar temperature tetap dingin, namun tidak dalam waktu yang lama.

Pykrete adalah material komposit es yang dibuat dengan mencampurkan air dan reinforce material berbasis selulosa (dalam bentuk kayu atau kertas). Pykrete memiliki keunggulan yaitu ketahanan yang tinggi terhadap benturan dan goncangan serta lebih tahan terhadap proses pelelehan dibandingkan dengan es biasa. Pykrete memiliki potensi untuk digunakan sebagai insulasi protektif untuk mempertahankan suhu rendah pada sistem insulasi berbasis vakum jika terjadi kebocoran, dalam durasi yang lebih lama dibandingkan es biasa.

Penelitian ini telah menunjukkan bahwa secara umum, pykrete memiliki durasi pendinginan yang lebih lama dibandingkan es biasa (sekitar 2-3 jam lebih lama) dan juga memiliki karakteristik material yang lebih baik berdasarkan perhitungan kekuatan tarik teoretikal pykrete, (dipengaruhi oleh reinforce material). Hal ini membuat pykrete cocok untuk dipakai sebagai perlindungan insulatif dalam aplikasi cold storage. Konsep untuk aplikasi dapat dipakai dalam bentuk perlindungan berlapis.

Kata kunci: Pykrete, Insulasi, Temperatur, Es, Kelembaban

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CHAPTER 1
INTRODUCTION

1.1 Background

The usage of vacuum-based insulation has been widely used in order to maintain low temperature for extended duration. It relies on a buffer space of vaccuum that separates the inner wall of the containment with it's outer wall. The inner surface of this system is usually made from reflective surface in order to maximize insulation.. It's used in a wide array of application in daily lives, from portable ice box, thermos, cold storage, to a large refrigeration unit. However, this method of insulation has a weakness: It's fragile, and it cannot be exposed towards impact shocks, since they are prone to cracking, which will severely reduce their insulative capabilities. At this point, other means of cooling must be used in order to preserve the low temperature inside, especially if the content inside requires constant cooling or starts to decompose at warmer temperature.

Ice is a common cooling agent to be used in this situation due to it's availability, it's cheap and readily available. However, while ice provides good cooling capacity, it does not last very long when exposed in room temperature. Aside from that, even if ice is packed inside the vacuum storage as a precaution for backup cooling in case of impact shocks, the impact itself is likely shattering the ice into smaller pieces, which, owing to it's fragility, makes it melt faster.

Today, vaccuum-based storage are used in a variety of commercial applications with some of them are dealing with delicate materials, such as organ storage box for transplantation or chemical cold storage box, where any containment breach in these applications could be catastrophic. More durable and longer-lasting cooling agent is certainly very useful in these apllication. It must be strong enough to resist external impact, cheap enough to be mass produced, and still able to cool the content inside the storage box for a limited time after there's a containment breach.

Figure 1.1: A block of wood-based pykrete (Tan, 2014)

During World War II, Geoffrey Pyke proposed a special ice-based composite material called pykrete (as seen on figure 1.1. above) as a substitute material for a huge, unsinkable aircraft carrier for the British Royal Navy, which at that time having limited steel reserves to build warships. Pykrete is an ice composite made from water mixed with cellulose-based reinforce material, and it has some interesting properties including it's high resistance towards impact shocks and relatively slow melting rate because of low thermal conductivity. This properties makes pykrete suitable for protective insulation material for cold storage application since it can still provide cooling effect in the event of containment breach while being highly resistant to impact makes it less likely to be shattered into pieces, increasing the survivability of the contents inside the storage. The cellulose-based reinforce material inside the pykrete usually consists of wood/ sawdust (particulate) or paper pulp (fiber). These two materials are usually selected due to their availability. Unlike ice, which breaks easily when exposed to impact shocks, pykrete is much more resistant due to the reinforce material acting as a dampener towards external force while holding the ice structure together. In addition, the reinforce material's low thermal conductivity also makes pykrete much more resistant towards natural melting at room temperature by inhibiting the heat propagation into deeper layer of pykrete.

Figure 1.2: Materials used for Pykrete: Paper (left) and wood (right) (Siddiqui, 2010)

Pykrete is created by combining water and cellulose-based reinforce material such as wood or paper, as seen on fig 1.2, before freezing it. In low-temperature environment, pykrete is extremely durable, easily shrugging off impact that would otherwise shatters regular ice. In fact, one of the first demonstration of pykrete's durability is by shooting it with a handgun. It's low thermal conductivity and slow melting rate makes it ideal for long-lasting cooling agent. By applying a layer of pre-fabricated pykrete, or stacking pykrete bricks to surround the inner wall of vacuum-based cold storage, a backup cooling system for containment breach could be devised. Essentially, whenever there's a containment breach when the cold storage being subjected to external impact, the vacuum will lose it's insulative capability, but the pykrete layer inside will maintain the inner temperature of the cold storage in order to keep the content inside at low temperature while the high impact resistance also makes it less likely to be shattered on impact, increasing the effective cooling duration post-containment breach even further. The combination of slow melting rate, durability and cold nature of the pykrete keeps the content refrigerated far longer than regular ice cooling could achieve.

This research aims to study the physical characteristic of pykrete in the form of it's cooling performance with various composition ratio. A special test will be carried out to investigate the cooling effect based from the correlation between ambient air humidity and cooling effect provided by pykrete samples and plot the results into a graphical curve that also shows the time it takes for the sample to melt and the fluctuations of absolute humidity in surrounding area. This test is also performed on regular ice for comparison. This study also investigates the theoretical tensile strength of pykrete with various composition. In addition, a review of existing experiments in the past will be conducted in order to investigate pykrete's viability for protective insulation material.

1.2 Formulation of Problems

1. How pykrete cooling performance compares with regular ice in terms of temperature and cooling duration.
2. How pykrete affects the value of absolute and specific humidity of the ambient air compared to regular ice.
3. How the theoretical tensile strength of pykrete compares with regular ice.
4. What kind of application pykrete could be used for in cold storage application.

1.3 Aims of Research

1. In general

In general, this research investigates the physical characteristic of pykrete based on it's cooling performance, which is derived from the cooling duration, fluctuations of temperature, specific and absolute humidity by comparing it with regular ice as well as it's theoretical mechanical characteristic.

2. Specific aim

Specifically, this research aims to:

a. Study the effect of different types of composition of pykrete's material content towards it's cooling performance.
b. Study the fluctuation of specific and absolute humidity value as well as the temperature of ambient air over fixed intervals during the effective cooling duration and plotting the results into the graphical curve format before comparing it with regular ice.
c. Calculate the theoretical tensile strength of pykrete with various composition.
d. Determine pykrete viability for protective insulation material for cold storage application.
e. Devise a concept of pykrete application in cold storage application as protective insulation material.

1.4 Benefits of Research

From this research, it's expected to yield these benefits :

1. A graphical curve that shows pykrete's physical characteristic in terms of temperature based from the fluctuations of specific and absolute air humidity and air temperature during the effective cooling duration from the moment the cooling is started until the complete melting of each specimen that can be compared with regular ice.
2. An analysis of mechanical characteristic of pykrete by calculating it's theoretical tensile strength with different composition.
3. An analysis of each sample's results that can provide a final verdict of pykrete's viability as a protective insulation material as well as the effect of different composition contained in each sample.

1.5 The Limitations of the Problem

Pykrete needs a cold temperature to form, and a brief exposure towards room temperature during the process of cooling performance test (Moving the sample from storage into the containment) before the commencing the test itself might slightly impact the cooling performance data obtained from testing (But this should be small enough to be insignificant in the overall result).

The size of all samples needs to be large in order to yield an accurate result and for the cooling effect to be noticeable enough to be used for analysis. This makes the sample takes a very long time to melt (but also yield more data for more accurate results).

Since ice (and by extension, pykrete) does not last very long outside at room temperature, especially when formed into a sample suitable for tensile strength test, since the small size of the sample, especially the middle breaking point is highly susceptible of weakening due to melting when exposed with room temperature, leading to an incorrect reading unless the temperature of the testing room is around -15°C, the same temperature used to make the sample in the first place. For this reason, only theoretical tensile strength will be calculated.

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CHAPTER 2
LITERATURE AND THEORETICAL STUDY

2.1 The History of Pykrete

In the year of 1942, during the World War 2, the German submarine fleet initiated a naval blockade on Atlantic Ocean in order to hamper Great Britain's supply lines. As an island nation, Great Britain relies heavily on constant supply from naval routes in order to keep the country running. The presence of German submarine fleet has a substantial impact on Great Britain's supply lines, mainly due to the naval convoy from United States being constantly sunk, preventing large amount of supply from reaching the Great Britain. An attempt to assign a fleet of warships in order to provide escort for the convoy was rather ineffective, anti-submarine tactics has little effect, owing to the primitive sonar and countermeasures at that time to deal with German submarine fleet, which tend to operate as coordinated fleet (known as "Wolf Pack", where if a single submarine finds a target, the others will converge upon it, ensuring a kill).

A decisive plan was made to reduce the threat of German submarine fleet and open the naval blockade in order to ensure the supply convoy from United States reaches Great Britain. This plan, however, calls for a bombing raid towards the German submarine pens, which is located on the German territory. No British bombers at that time has range, endurance and bombload in order to fly from Great Britain into German, bomb the target for appreciable damage, and return back to base, much less for fighters escorting them. It had been a common experience that the carrier-based aircraft of the Allies were inferior in armament and speed to the land-based planes of the enemy. It was feared, therefore, that in an invasion of a distant shore the allied armies would be handicapped by lack of air support until they had actually succeeded in establishing their own airfields there

It is possible to do this if the airbase is located closer to the German territory. An aircraft carrier can be used to "extend" the range of British aircraft by launching them closer to the target. Unfortunately, Great Britain was critically low on steel for manufacturing ships, and after the major loss of HMS *Hood*, HMS *Repulse*, and HMS *Prince of Wales* during the early stages of the war (all sunk during 1941), the British cannot risk to deploy large fleet operation such as one involving an aircraft carrier for this mission, especially on submarine-infested water on hostile territory. It was only natural, that a proposal for the apparently cheap construction of gigantic

aircraft carriers, capable of operating land-based aircraft hundreds of kilometers away from their base, was seriously considered.

It was during this time that a man named Geoffrey Pyke has a bright idea to create a substitute material for steel. In October 1942, Geoffrey Pyke submitted a proposal to the military in which he proposed that an iceberg, either natural or artificial, should be hollowed out to house hangar facility for aircraft and levelled to provide an adequate flat runway sufficient to conduct flight operation. It must have a mobility of at least a few knots, sufficient maneuverability and be resistant against melting, if not indefinitely at least until it had fulfilled it's strategic purpose. Pyke pointed out that all strategic materials such as metals, wood and concrete were already being used to the fullest for the war effort and that ice, requiring for it's manufacture only 1% of the energy needed for an equivalent weight of steel, would be an ideal material for structural component in the construction of large aircraft carrier. Ice, he considered, possessed many advantages as substitute material; it was difficult to break up with explosives, as shown by the tenacious resistance of icebergs to shellfire, and it melted very slowly when sufficiently insulated. However, the greatest attraction of a floating air-base made of ice was the fact that it could not be sunk, no matter what, since ice always floats.

In December 1942 Prime Minister Winston Churchill issued a directive that research on the project should be pressed forward at the highest priority, with the project known as "Project Habbakuk". However, he expressed the opinion that it would be better to "let nature do the job" (In other words, letting the ambient cold temperature of the sea low enough to maintain the ship's structural integrity) of making this ship, as otherwise the technical difficulties would prove insurmountable in order to keep the ship sufficiently cooled. He also suggested that floating ice floes on the Arctic Seas might be towed into the Atlantic ocean and used as a floating airfield until they were broken up by melting.

It soon became apparent, however, that neither natural icebergs nor floating ice floes were suitable as floating air-bases, the former because their surface above the water was too small, rendering any ocean waves splashing directly on the runway, making the surface slippery and hazardous for flight operation, and the latter because they were too thin to withstand the waves of the Atlantic. The Russian North Pole Expedition under Papanin, for instance, had revealed that the average thickness of floating ice floes, even at the North Pole was less than 3 meters, far too thin to be used as a runway as it would easily breaks when a multi-ton bomber runs on top of it. Moreover, the experts of the Fleet Air Arm considered a ship free board specifications of at least

15 meters, the minimum specification required for continuous operation of aircraft from the deck of an aircraft carrier. The minimum length of runway required for land-based heavy bombers at that time was 600 meters, with the width of at least 60 meters, which is considered the most desirable. Thus the engineers and physicists were given the task of building a vessel of these gigantic dimensions, made basically of ice and satisfying a number of essential requirements sufficient to allow the flight operations of land-based heavy bombers safely. The vessel must be sufficiently seaworthy and stable to withstand the waves of the Atlantic and Pacific oceans; it must be self-propelled; it must have a speed at least sufficient to prevent it drifting aimlessly in the wind; and it must be difficult to sink.

In order to design this massive ship, the British naval engineers, in cooperation with Canadian researchers, need accurate information and data on the mechanical strength of ice. A search of the research literature revealed a mass of conflicting data which is contradictory with their theory and offers little to no assistance. It soon became clear that most of the physical constants for ice's mechanical properties would have to be determined from scratch. A variety of mechanical strength tests for ice were made, but the results were extremely disappointing. The average modulus of rupture of ice beams in bending, for instance, was found to be about 22,5 kg/cm^2, but individual ice beams sometimes failed at stresses as low as 4,9 kg/cm^2. For comparison, Pine wood has a far higher modulus of rupture of about 800 kg/cm^2. As a structural material, ice was found to be too brittle and unreliable and ice's resistance to explosives quite unpredictable. Owing to ice's brittleness it was dangerous to regard any reasonable stresses as safe for constructional purposes, especially for naval vessel.

In 1943, the project did not look very good, with the absence of relevant data and a lack of progress. But then, they were suddenly fascinated by the discovery that the inclusion of a small percentage of wood pulp improved the mechanical properties of ice in a spectacular manner. The discovery was made by Mark and Hohenstein, working at the Brooklyn Polytechnic, who thought that ice could be strengthened like composite by adding reinforce material before freezing it. In view of the similarity to concrete and in honor of the originator of the Project Habakkuk, the frozen wood pulp was given the code name of Pykrete (Pyke's concrete).

Geoffrey Pyke managed to convince Lord Mountbatten, chief of British combined operation, the potential of pykrete as building material for Project Habakkuk. A block of Pykrete was prepared by a Canadian engineering company and it was taken to the Quebec Conference in the fall of 1943. As it appeared that Project Habbakuk would run into supply and technical

problems, owing to the Great Britain's supply situation back then, it was Mountbatten's aim to get the Americans to take the project, since United States has far better industrial and manpower capability to complete the project within an appreciable amount of time, and what a better way to do that than to set up a live demonstration for them? It is reported that Mountbatten took out his own personal revolver and fired at a block of ordinary ice, which immediately shattered. He then fired at a similar block of Pykrete which was so strong that the bullet ricocheted on impact.

a. *b.* *c.*

Figure 2.1: The wooden frame of the prototype (a), deck area of the prototype (b), the prototype with roof for simulated weight aboard the ship (George, 2001)

The demonstration managed to impress the Americans and convince them to take the project. A mockup prototype, as seen on figure 2.1, was constructed in order to study pykrete's application as structural component of a large ship. The dimension of the prototype, 18 meters long, 9 meters wide and 6 meters high was constructed on a lake in the Canadian Rocky Mountains, specifically on Patricia Lake in Jasper, Alberta. The structure was a wooden frame construction, filled with ice cut directly from the lake itself. The structure was insulated and contains 3 Freon compressors to maintain sufficiently low temperature. Cold air was distributed throughout the entire structure by a network of cooling pipes. A further experiment was conducted simultaneously in the Chateau Lake Louise, near Banff, Alberta. The main focus of this project was to determine ways to reinforce large ice units. The work at Lake Louise indicated that the ship needs a hull at least 9 meters thick, which would be needed to withstand damage from aerial bombs and submarine torpedoes.

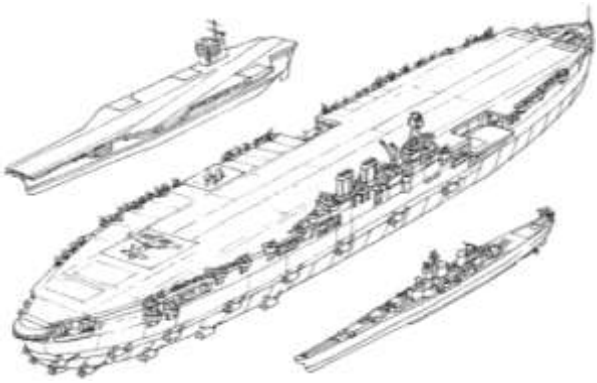

Figure 2.2: HMS Habakkuk (middle) compared to modern warships (Perutz, 1948)

With a runway of 600 x 60 m, a free board of 15 m and an all-round wall thickness of 9 m, it was found that this collosal ship would have an estimated draught of 45 m and a projected displacement of 2,200,000 tons. To build a ship 26 times heavier than the HMS *Queen Elizabeth* from a material which had never been used before was a formidable proposition for the researchers and engineers involved in this project. To be fair though, regular aircraft carriers are not designed to allow flight operations of land-based heavy bombers, which is what makes the dimension of Project Habakkuk ridiculously large in the first place.

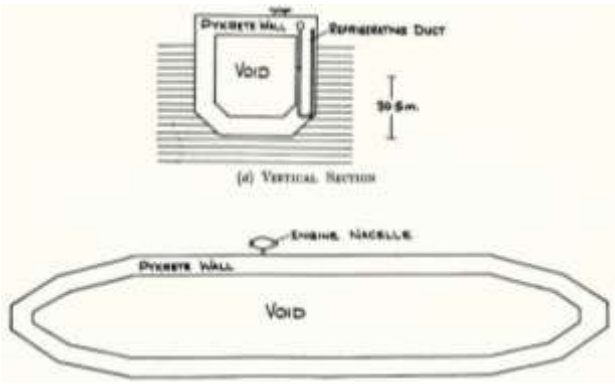

Figure 2.3: HMS Habakkuk's simplified pykrete hull design (Perutz, 1948)

For the sake of simplifying the construction, it was decided to give the ship the shape of a hollow square beam, with bevelled edges to reduce the drag underwater as the ship moves. The outside walls were to be surrounded by waterproof insulating skin and the pykrete inside was to be kept at a constant temperature of -15°C with the help of artificial refrigeration system inside the ship. U-shaped refrigerating ducts were to be built into the inner side of insulating skin, buried deep inside the pykrete structure itself. These ducts were to be placed about 1,2 meters away from

the outer surface of the pykrete and regulates a network of cooling pipes circulating compressed air at -30°C.

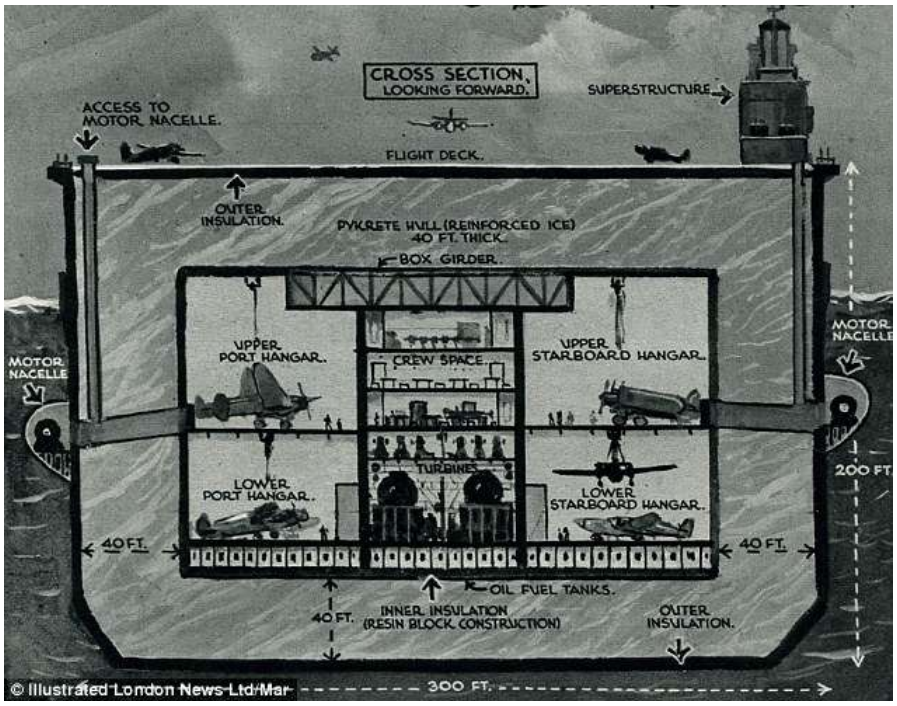

Figure 2.4: Habakkuk's cross section, note the 40 ft (12 m) thick pykrete on the hull (Perutz, 1948)

Sixteen refrigerating plants, each with it's own circulating system for redundancy in case of failure, were to supply cold air to keep the whole structure cooled. The ship was to be propelled by over twenty electric motors housed in streamlined hydrodynamic pressure hulls and distributed evenly across the ship's hull for safety and redundancy. It was decided that 7 knots (1 knot = 1.8 km/h) was the absolute minimum speed necessary to keep the ship from drifting aimlessly in the wind; for this, turbo-electric generators would be installed in order to provide power for rotating the propeller shafts. Steering such a massive ship presented a particularly difficult problem to the naval engineers. The proposal to alter course by changing the relative speed of the propellers (like steering tank treads) was rejected by the experts in favour of a conventional fin and rudder system. This would have added several hundred tons of weight, presenting a hazard of making the ship's center of gravity being shifted to aft instead of evenly distributed around the ship and the problem was never satisfactorily settled.

Another problem was presented by the huge void, 884 m x 43 m x 43 m, in the centre of the ship. This would be the hangar for the aircraft. If it were to be left empty after all aircraft has

taken off, the walls would be liable to bend inwards by creep, so a structural reinforcement or some sort of pressurized hull system is necessary, and despite pykrete being easier to manufacture and repair than steel, if a crack occurred, due to frequent torpedo hits, there's still a danger of flooding, which, while it won't sink the ship, the same cannot be said to the aircraft stored inside that hangar. Despite all of the difficulties, subsequent tests showed the feasibility of pykrete as a material to build this ship. It was projected that this ship will be built within a year, starting during winter season in order to kickstart the project by accelerating initial stage of construction by providing low ambient temperature in order to assist the production of large amount of pykrete.

However, in 1944, the project was cancelled. As the scientists worked to build the ship, the war keeps progressing, and technology marches on. United States' strong naval industry makes extensive use of standardized blueprints of cargo ships, leading to instances where their ship could be replaced faster than the rate they sunk. In addition, World War 2 was the era where aviation industry saw a massive development in aircraft technology. The introduction of long-range fuel tanks allows extra patrol time for British-based aircraft over the Atlantic. Aircraft engine has become much more powerful, allowing them to carry much heavier bombload over longer distance, while British also received permission from Portugal to use airfields in the Azores, which facilitated the hunting of U-boats in the Atlantic. In addition, United States also successfully tried the new concept of escort carriers (Which is a scaled-down aircraft carrier made for high speed and maneuverability for escorting convoys. It's not as sophisticated as full-fledged aircraft carriers, but also much cheaper and still gets the job done for launching aircraft). With the *Operation Overlord* imminent, where US and Great Britain pushing the German from west while Soviet Union pushing from the East, such huge aircraft carrier becomes unnecessary and with the arrival of US naval convoy on Britain, the British can build actual, full-fledged warship. All of these signs the end of Project Habakkuk, with the project being abandoned during early 1944.

2.2.Comparison Between Ice and Pykrete's Physical Characteristics

There are significant difference between regular ice and pykrete. Fundamentally, the basis of the freezing process comes from the fact that if two objects with different temperature comes into contact with each other, one of them start taking energy from the other, and that will continue until some sort of equilibrium is achieved. An object that gives up energy is hotter than the object that receives energy which means heat always moves from system of higher temperature into system of lower temperature until an equilibrium is achieved between the two.

Normally, the freezing process happens when the temperature of the ambient air around the liquid water drops into freezing point. The freezer works by isolating a pocket of ambient air inside an insulated chamber and channel the heat away from the chamber. This allows liquid to freeze into solid. As the temperature of ambient air decreases, the movement of water molecules slows down before finally hooking with each other, creating hydrogen bonds and forming solid crystals (figure 2.5). This is how water freezes into ice.

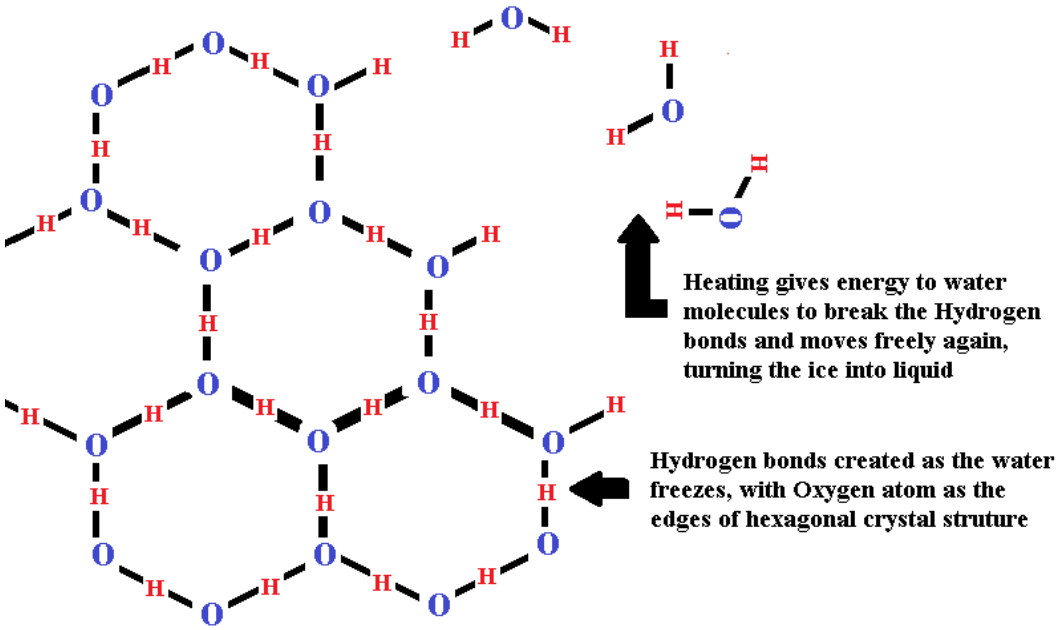

Figure 2.5: Hexagonal Crystal structure of ice

When the temperature of ambient air around the ice increases, heat from higher temperature flows from ambient air into the ice, giving the water molecules energy to move again and breaking the hydrogen bonds. As the hydrogen bonds breaks, the water changes state from solid to liquid. This is how ice melts into water. The melting process always starts from the edge of ice structure since that's where there's the least amount of hydrogen bond. However, pykrete has significantly different physical properties compared to regular ice due to the physical characteristic characteristic of it’s reinforce material.

Pykrete has different melting mechanic compared to regular ice. Normally, in regular ice, the melting process occurs continuously where heat from ambient air steadily breaks the hydrogen bonds of ice structure from the outside and gradually moves inside. The rate of melting process is

generally uniform across the ice structure. However, in pykrete, the melting process is significantly different. Instead of continuous melting like regular ice, pykrete has what can be described as layered melting process. The way pykrete melts is that, the ice on the outer portion melts first and leaves the reinforcement material intact, which forms a “shell” that inhibits heat propagation from ambient air outside to penetrate into the ice beneath the shell layer. The shell of leftover reinforce material does not prevent the heat from propagating deeper, only slowing it. As such, eventually, the ice beneath the shell layer will eventually melts too and the resulting liquid water seeping from the inside will crumble the outer shell, but also leaves another shell behind that will repeat the process over and over again until the whole pykrete completely melts.

When water freezes into ice, it has significantly more thermal conductivity in solid form than it’s liquid form since ice is far from the state of equilibrium compared to water. Ice has about 2.22 W/m-k thermal conductivity, compared to water’s (at 20ºC) thermal conductivity of 0.6 W/m-k. This means that ice will receive heat more easily than liquid water. Pykrete has a much slower melting rate compared to regular ice due to the effect of it’s reinforce material’ thermal conductivity. For example, in this experiment, the paper reinforcement material has thermal conductivity of 0.06 W/m-k while teak wood reinforcement material has thermal conductivity of 0.08 W/mk, both are much lower than ice’s thermal conductivity of 2.22 W/m-k. The concept behind pykrete is to introduce a reinforcement material inside the ice matrix with lower thermal conductivity to inhibit the heat propagation inside the ice’s structure in order to slow down the melting rate.

This, in turn determine the melting rate of pykrete depending on the heat conductivity of the added reinforcement material. As mentioned before, when the ice portion of the surface of pykrete melts, it leaves behind the reinforcement material, which formed a shell that inhibit the heat propagation into deeper layer of pykrete, which still has frozen ice. The shell does not completely block the heat, only slowing it down based from the thermal conductivity of the reinforcement material itself. As such, after the shell is formed, the heat from the outside propagates using the thermal conductivity of the reinforce material, not the thermal conductivity of ice, which means, the ice in the deeper layer will eventually melts. When the ice in the deeper layer melts, the shell outside can no longer support it’s own weight, causing it to crumbles, which leaves another shell from the leftover reinforce material in the deeper layer, and thus the process starts all over again.

2.3. Entropy Changes Associated With Ice Melting

The melting of ice induce a change of entropy based from the thermodynamic process between ice and the heat on the surrounding air. To understand this process, let's make an example. Let's say a 100 grams of regular ice (at 0ºC) is exposed at ambient temperature of 25ºC, causing it to melt into water before the water temperature ends up at 25ºC temperature, equalizing with ambient air. Now in this situation, we can identify the system and surrounding as well as their temperature, which is ice (the system, initially solid, which later turns into liquid), with the temperature of 0ºC and the ambient air (the surrounding) with the temperature of 25ºC. The whole process can be simplified into the following diagram:

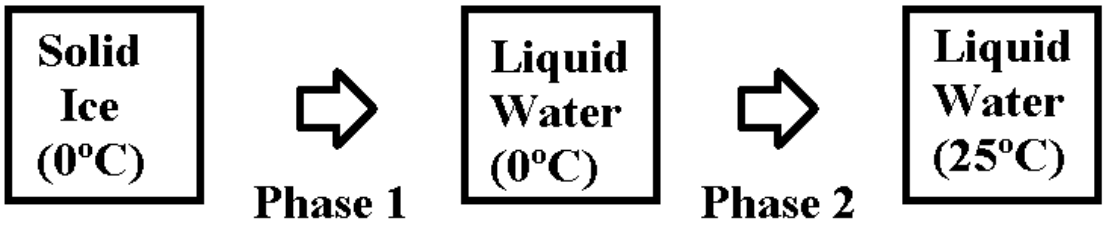

Figure 2.6: Simplified diagram of melting ice

In the process of ice melting until the liquid water warmed up into 25ºC, we can identify the initial and final state of the system. As shown on figure 2.6, this composed of 2 phases, the first phase is when the solid ice (0ºC) melted by the surrounding temperature into water (0ºC), the second phase is when the liquid water (0ºC) warmed up by the surrounding into 25ºC temperature. Both of these phases has different thermodynamic process that we can analyze.

In both phases there's a change of energy between the system. In the first phase, the energy flows from the surrounding (25ºC) into the system at lower temperature (solid phase at 0ºC) causing a phase transition from solid to liquid, while in the second phase the energy flows from the surrounding (25ºC) into the system (liquid phase at 0ºC) until an equilibrium is achieved when liquid water's temperature is at 25ºC. In both phases, the energy always flows from the surrounding into the system and this happen in the form of heat.

In order to understand how much heat that's involved, calculations can be made for both phases separately. The heat related for both phases is related with change in enthalpy, for phase 1, when the heat from surrounding flows into the system and cause a phase transition from solid ice to liquid water, the following formula is can be applied:

$$\Delta H_1 = \Delta H_{\circ fus}\ x\ M_{water}\ x\ m_{ice}$$

Where: ΔH_1 = Heat flow from surrounding to the system (KJ)

$\Delta H_{\circ fus}$ = Enthalpy of fusion of water (6.02 kJ mol^{-1})

M_{water} = Molecular mass of water (18 g/mol)

m_{ice} = Mass of ice (100 g)

Which, by inputting the values of known parameter in the system and surrounding yields the following result for ΔH_1:

$$\Delta H_1 = \frac{6.02kj}{mol} \text{ x } \frac{1\ mol}{18\ g} \text{ x } 100 \text{ g} = \mathbf{33.4\ kJ}$$

For the second phase (warming of water from 0ºC to 25ºC, the following formula can be used:

$$\Delta H_2 = C \text{ x } m \text{ x } \Delta T$$

Where: ΔH_2 = Heat flow from surrounding to the system (KJ)

C = Heat capacity of water (4.184 J g^{-1} $^{\circ}C^{-1}$)

m = Mass of water (100 g)

ΔT = Change of temperature (25 ºC)

Which, by inputting the values of known parameter in the system and surrounding yields the following result for ΔH_2:

$$\Delta H_2 = \frac{4.184\ J}{g\ ^{\circ}C} \text{ x } 100g \text{ x } 25^{\circ}C = 10460 \text{ J} = \mathbf{10{,}460\ kJ}$$

Thus, the total enthalpy for both phases are:

$$\Delta H_1 + \Delta H_2 = 33.4 \text{ kJ} + 10{,}460 \text{ kJ} = \mathbf{43.86\ kJ}$$

The melting phase and the warming phase also induce a change in entropy. This changes can also be calculated separately between 2 phases. For the first phase where the ice (0ºC) undergoes a phase transition into water (0ºC), the following formula could be used:

$$\Delta S_1 = \frac{\Delta H}{T} = \frac{\Delta H_{fus} \text{ x mol}}{T_{fus}}$$

Where: ΔS_1 = Entropy change of melting ice (J K^{-1})

ΔH_{fus} = Enthalpy of fusion of water (6020 J mol^{-1})

mol = Number of moles in 100 grams of water (5.5 mol)

T_{fus} = Temperature of fusion (melting temperature) (273.15 K)

By inputting the values of known parameter in the system and surrounding yields the following result for ΔH_2:

$$\Delta S_1 = \frac{(6020 \text{ J } mol^{-1}) \times (5.5\ mol)}{273.15\ K} = \mathbf{121.2\ J\ K^{-1}}$$

For the change of entropy in the second phase (the warming of water from 0ºC to 25ºC, we can use the following formula:

$$\Delta S_2 = C \ln\left(\frac{T_f}{T_i}\right)$$

Where: ΔS_2 = Entropy change of warming the water (J K^{-1})

C = Heat capacity of water (4.184 J K^{-1} g^{-1})

T_f = Final temperature (298.15 K)

T_i = Initial temperature (273.15 K)

Inputting the values of known parameter in the system and surrounding yields the following result for ΔH_2:

$$\Delta S_2 = (4.184 \text{ J } K^{-1} g^{-1}) \text{ x } (100 \text{ g}) \ln\left(\frac{298.15\ K}{273.15\ K}\right) = \mathbf{+36.6\ J\ K^{-1}}$$

Thus, the total change of entropy in the system is:

$$\Delta S_{system} = \Delta S_1 + \Delta S_2 = 121.2 + 36.6 = \mathbf{+157.8\ J\ K^{-1}}$$

Note that the above calculation is based from the system's persepective. When viewed from the surrounding's perspective, the change of entropy is different. The change of entropy of the surrounding is related to heat. From the perspective of the surrounding, the energy, in the form of heat is leaving the surrounding and flows into the system, in both phases, so in other words the change of entropy of the surrounding is going down ($\Delta S_{surrounding} < 0$). How much the entropy changes for the surrounding can be calculated by using the following formula:

$$\Delta S_{surr} = \frac{-q}{Tsurr}$$

Where: ΔS_{surr} = Entropy change of the surrounding (J K^{-1})

$-q$ = Negative heat (surrounding perspective) (-43860 J)

T_{surr} = Temperature of the surrounding (298.15 K)

By inputting the values from previous calculations, the result for ΔS_{surr} is:

$$\Delta S_{surr} = \frac{-q}{Tsurr} = \frac{-43860\ J}{298.15\ K} = \mathbf{-147.1\ J\ K^{-1}}$$

Note that since heat leaves the surroundings and enters the system to melt the ice, the value of q is negative for the surroundings, therefore ΔS is also negative. With both the change of entropy of the system and the surroundings known, we can now calculate the change of entropy for the universe in the whole process using the following formula:

$$\Delta S_{total} = \Delta S_{system} + \Delta S_{surrounding}$$

Where: ΔS_{total} = Entropy change of the universe (J K^{-1})

ΔS_{system} = Entropy change of the system (+157.8 J K^{-1})

$\Delta S_{surrounding}$ = Entropy change of the surrounding (-147.1 J K^{-1})

Since both the entropy change of the system and the surrounding has been calculated before, we can simply input the numbers into the equation:

$$\Delta S_{total} = +157.8 - 147.1 = \mathbf{10.7\ J\ K^{-1}}$$

In theory, the change of entropy in pykrete should be less less than ice (given the same volume) simply because there are less ice portion in pykrete. The ice portion is only 85-86% of the total volume of pykrete, with the rest being reinforce material.

2.4.Relative, Specific and Absolute Humidity

In general, humidity is a measure of moisture content of the atmosphere, or how much water vapor there is in the air. There are relative humidity, specific humidity and absolute humidity. Relative humidity (Rh) is the ratio of the partial pressure of water vapor to the equilibrium vapor pressure of water at a given temperature and it's represented as percentage, which is a measure of of current absolute humidity value relative to the maximum possible value for that temperature. Relative humidity depends on temperature and the pressure of the system of interest. Relative humidity have no unit of measurement, and usually just being represented as a percentage, which is not very useful in measuring the precise value of ambient air humidity.

Specific humidity (Sh) is the ratio of the mass of water vapor to the total mass of the air in current temperature. The specific humidity is represented as grams of water vapor per grams of air. This value fluctuates as the temperature changes, with low air temperature yielding lower specific humidity value as the water vapor condensates into liquid phase. Like relative humidity, this value also depends on temperature and the pressure of the system of interest. In other words, the Specific humidity represents the intensity of cooling effect of the sample based from the ratio of amount of water vapor with the amount of air around the sample.

Absolute humidity (Ah) is the ratio of the mass of water vapor to the volume of air in current temperature. The absolute humidity is represented as grams of water vapor per a meter cubic of air. This value fluctuates as the temperature changes, with low air temperature yielding lower absolute humidity value as the water vapor condensates into liquid phase. Like relative humidity, this value also depends on temperature and the pressure of the system of interest. Thus, the Absolute humidity could be viewed as the intensity of cooling effect of the sample based from the amount of water vapor in the surrounding area of air around the sample.

Both specific and absolute humidity might look similar, but they actually quite different in that they represent the moisture content in the air on a specific temperature over different unit of measurement (mass and volume). In general, the lower the air temperature, the lower the value of specific and absolute humidity is, due to cooler air holds lower amount of water vapor as it condenses into dew.

In addition to that, the specific and absolute humidity could be viewed as the "strength" of cooling intensity, based on the mass of water vapor and volume of area affected by cooling. In specific humidity, the air holds less water vapor as the temperature drops. The lower the value, the better the cooling effect is. As for absolute humidity, the value represents the intensity of cooling

effect within a fixed volume around the sample. The lower the value, the higher the intensity of cooling effect within that area.

2.5.Application of Pykrete

It is known that the application of ice as a building material has some limitations. Ice is a relatively weak and brittle material and shows an extreme creep behavior compared to conventional building materials. Mechanical properties of ice are strongly temperature-dependent and anti-melt protection is necessary even in the coldest areas. At present, there are only three types of ice composite such as pykrete, cryogel ice-soil composite and ice reinforced by geomaterials, that has been applied successfully in engineering of structure in various projects. Pykrete still has use, even today. It's commonly used as a substitute for asphalt and concrete to build aircraft runway or roads in cold regions. It's also useful as structural component in low-temperature environment. Below is a table of notable engineering projects with ice-based materials:

Table 2.1: Historical events involving pykrete

№	Time	Reinforced material or method	Structure	The place
1	Ancient times	Lichen	Igloo	The northern regions of Canada, USA and Russia (Eskimos, Chukchi)
2	During the Second World War	Logs, branches and twigs	Ice road and ice ferries	Ladoga Lake 'Life Road" USSR (ice ferries,1943) Ice railway bridge over the Dnieper (Ukraine, winter 1941-1942
3		Wood pulp (pykrete)	Aircraft carrier	Project Habakkuk, Canada, Great Britain,1942-1943. (Gold,1989)
4	During the Cold War	Fiberglass	Ice airstrip	Arctic region, USA,1966. (DeGoes, Neal, 1998)
5		Sawdust (pykrete)	Ice roads crossing swamps	Siberian region, USSR, 1960-1968. (Borshchuk, 1968)
6		Wooden covering	Ice working space	Siberian region, rivers, USSR,1966. (Marchuk,1973)
7	Nowadays	Geonets from fiberglass	Ice roads crossing rivers	Arkhangelsk region, Russia (2010-2012)www/ador.ru/data/files/does/innovations_01.pdf
8		The method of cryotropic gel formation	Watertight elements in dams	Irelyah hydrosystem, Siberia, Russia,2005. (Altunina et al., 2010)
9		Pykrete	Ice Dome, Sagrada Familia in Ice	Juuka, Finland, 2014 (Pronk, 2014) Nunnanlahti,Juuka, Finland, 2015

Source: Vasiliev, 2015

2.5 Previous Researches

Several research about pykrete has been conducted in the past, mainly to utilize pykrete's very low thermal conductivity and durability. Dr. M.F Perutz (1946), one of the researcher involved in the Project Habakkuk itself has written an extensive detail about mechanical properties of wood-based pykrete for it's application in ship construction. He expressed the advantage and disadvantage of Pykrete's mechanical properties. A lot of this problem stemmed from the extremely demanding specifications presented by the project itself, creating a lot of structural problems due to the sheer scale of dimension involved, especially the problem about creep. However, testing for small-scale application still provides a feasible result, which makes the application of pykrete for protective insulation liner possible.

Vasiliev, N. K., & Pronk, A. D. C. (2015) has investigated the application of pykrete as construction materials in projects involving ice structures. They studied the potential application of pykrete to build large structure and finding the best mixture of ingredients for this purpose. It was found that a pykrete with 10% of reinforce material by weight provides the best result for structural components for large object. A large project conducted to investigate this result culminates in construction of a massive pykrete dome with a diameter of 29 m and height of nearly 10 m. It was the largest pykrete-based structure ever built, excluding the proposed size of the original Project Habakkuk. The second project involves a group of scientists from Eindhoven University of Technology, cooperating with other research institutes and the local community of Juuka (Finland) to build a 1:5 scale model of the *Sagrada Familia in Ice* - the world's highest ice dome of pykrete with a height of 30 meters. These projects might represent the currently reasonable size for pykrete-based construction.

Tan E-Liang (2014) has studied the rate of sublimation of pykrete based on the exposed area of the material itself. It was apparent that there's a relationship between mass loss phenomenon and the surface area of the specimen. He concluded that pykrete is a feasible material for construction as long as there's a negative relationship between mass loss and exposed surface area. However, if the structure has positive relationship between mass loss and exposed surface, a coating or shielding is recommended to slow the rate of mass loss or stop it altogether. It's especially useful for this purpose if there's a scarcity of electricity and manpower but there's an immediate need for strong construction material.

Andreas Bastian, & Siddiqui (2010) has been investigating the mechanical properties of pykrete augmented with emulsifier in uniaxial compression. They investigated the mechanical

properties of paper-based and wood-based pykrete. It was revealed that paper-based pykrete has better mechanical properties than wood-based pykrete, not to mention that pykrete materials require significantly less processing than concrete. Additionally, pykrete with 14% paper dust has shown to be just as strong as some concrete, with strength to weight ratio up to four times compared to concrete. Pykrete has also been revealed to not fail explosively, unlike concrete, giving pykrete a potential for application where safety and warning of failure is important. Aside from that, when an emulsifier is added to low-ingredient percentage pykrete, it was discovered that it allows a much higher ultimate strength compared to pykrete made with water.

Alisha Vijay Supekar, Divyashree Prasad Deore & Sarthak Sharma(2016) Investigated the application of pykrete as thermal energy storage system, by studying the cooling system performance through a simple air conditioning prototype using the Pykrete as thermal storage capacity for an alternative method in air conditioning system. They aimed this research to reduce the pollution and global warming by reducing the usage of fossil fuel for producing electricity. With global warming, extremely hot weather may become more common, so, the ice thermal storage can provide potential solution for hot weather cooling issue and avoid forced shutdown during hot weather as well as lowering power consumption during night time. The results obtained from this research is intriguing: it was found that performance of using the Pykrete based Thermal Energy Storage System is effective in which the coefficient of performance (COP) is comparable to a conventional Ice based Thermal Energy Storage System. The results showed that the COP for higher air flow rate is lower than the COP for lower air flow rate due to lower power consumed by the system. And the outlet temperature for the higher air flow rate is higher than the outlet temperature for the lower air flow rate due to the more time of contact between the air and the Pykrete block. Since the Pykrete block melts at a very slow rate as compared to ice, a sustained cooling can be achieved for a longer duration as compared to ice based systems. The mass Pykrete required to attain a given amount of cooling effect is more than ice, but the time required for the same mass to melt is very high for Pykrete. Hence, a given amount of cooling can be achieved without refreezing the Pykrete block as is the case with ice.

Pykrete is a rarely explored material in scientific community. The first research paper was published at 1946 by one of the researcher of the pykrete itself. After the World War 2, research about pykrete stagnates and being a secret project, the material fades into obscurity until it's revealed again during the early 20th century.

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CHAPTER 3
RESEARCH METHODOLOGY

3.1 Materials, Tools and Methods

3.1.1 Materials:

1. Water as a basis for pykrete material structure. Frozen as a matrix for cellulose-based reinforcement. The water used in this experiment is regular water. Aside for being used as primary ingredient for pykrete, it's also used to make regular ice for testing in order to make a comparison between pykrete and regular ice.
2. Paper powder: A4 70 GSM (ISO 9001, 14001) supplied by Pindo Deli pulp and paper mills. Ltd (Indonesia). The papers are cut into 1000 strips with the size of 2.8cm x 10cm before being shredded.
3. Blocks of 2.8cm x 10cm teak wood (Grade B) supplied by UD Wahyu (Indonesia). Finely shredded for use as reinforce material. The size of wood particles used in this experiment has a texture close to powdered wood, with particle size of around 1-2 mm.

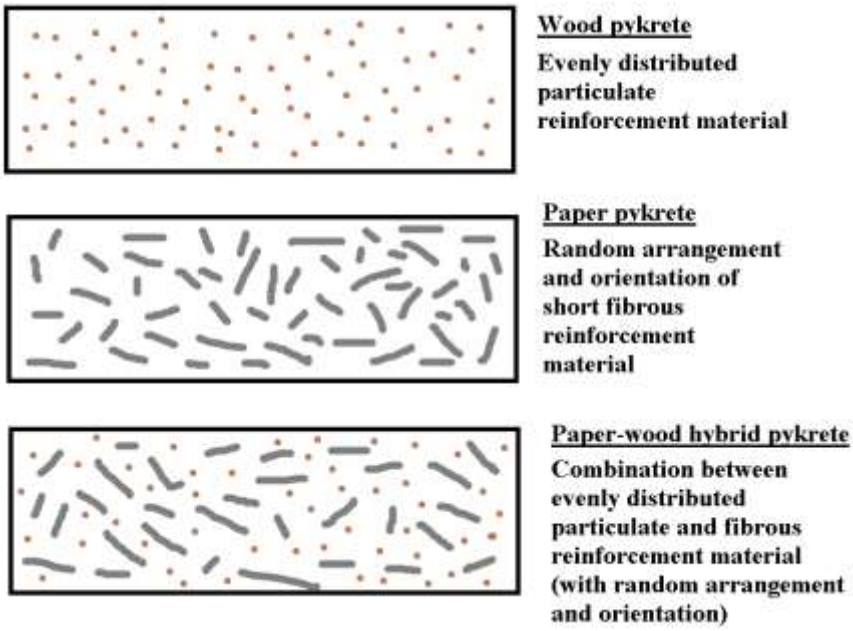


Figure 3.1: Detailed reinforcement material's characteristic for pykrete samples

3.1.2 Tools:

1. Open-topped cold storage: Commercially available medium-sized insulated storage box made from EPS (Expanded Polystyrene), with KGS standard size of 30cm x 25cm x 20cm (internal volume) and the wall thickness of 2cm. This box is open on top during cooling performance test in order to simulate exposure of the specimen inside towards room temperature as well as localizing the cooling effect in one place in order to obtain accurate readings on measurement data.
2. Digital thermometer-hygrometer: TP-40 Model Digital room thermometer/ hygrometer (ISO 17714) is used to measure the relative humidity and temperature of surrounding air during testing. This small device has three sensor slits on it's rear that samples the surrounding air and updates it's reading every 2 seconds. It's accuracy is ±0.1°C for temperature readings and ±1% for relative humidity readings. Two of these devices will be used, one placed inside the box, the other is placed outside the box. All readings from both devices will be recorded with interval of 15 minutes.
3. Mold: A 20cm x 10cm x 10cm mold is used to manufacture the specimens used in this experiment. The mold is made from aluminium sheet with a thickness of 1 mm.
4. Ice maker machine (VEVOR ADT Type 110V, Commercial Ice Maker Model 350LBS/24H) for freezing the sample in a controlled -15ºC environment.

Table 3.1: Details of ingredients of specimens used for testing

Sample	Reinforcement material
1 (1st Test)	Regular ice, no reinforcement material
2 (1st Test)	Regular ice infused with paper pulp around 14% of total volume
3 (1st Test)	Regular ice infused with sawdust around 14% of total volume
4 (1st Test)	Regular ice infused with 7% paper pulp and 7% sawdust of total volume
5 (2nd Test)	Regular ice with added salt around 1% of total volume
6 (2nd Test)	Regular ice with 14% paper pulp and 1% salt of total volume
7 (2nd Test)	Regular ice with 14% sawdust and 1% salt of total volume
8 (2nd Test)	Regular ice infused with 7% paper pulp, 7%, sawdust, 1 % salt of total volume

3.1.3 Sample Preparation:

A ratio of 14% reinforce material and 86% water is chosen since it has been tested in previous research to have the best material composition ratio to maximize the mechanical characteristic (Siddiqui, 2010). A deviation tolerance of 1% of this content is possible without significantly affecting pykrete's cooling and mechanical properties. With a specimen size of 2000 cm^3 , it's roughly 1720 cm^3 of water and 280 cm^3 of reinforce material. Due to the difficulty of getting an accurate measurement of paper and wood reinforcement, mainly because of their shredded nature used in this experiment, the way the reinforce material measured for this experiment is by taking 280 cm^3 (140 cm^3 for sample 4 and 8) of solid block/ stack of material before shredding them into powdered form, while minimizing any loss of materials during the shredding process as much as possible.

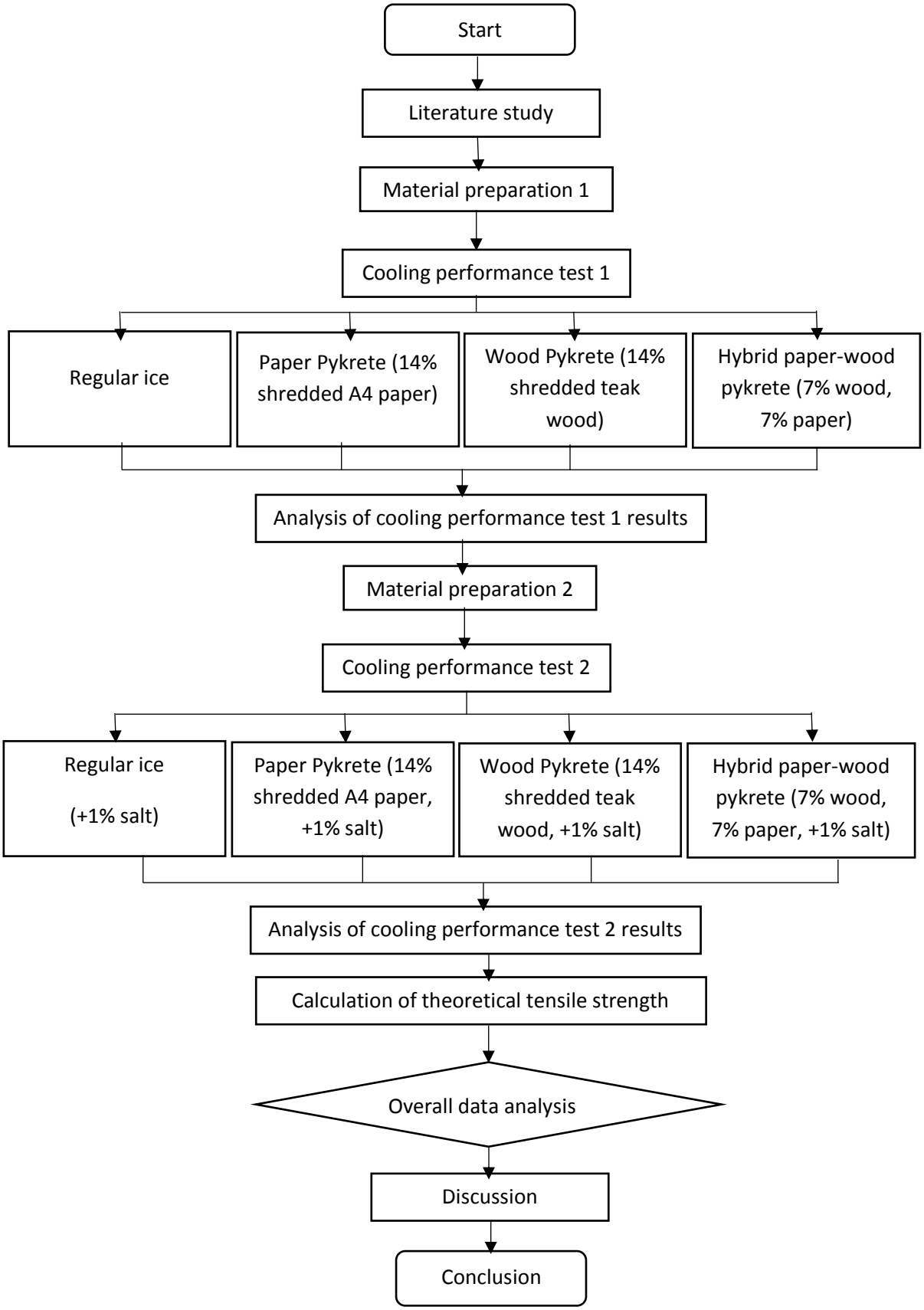
For creating a sample, a mold with dimensions of 20cm x 10cm x 10cm is prepared to create a pykrete sample, which consists of 14% reinforce material and 86% water. Since pykrete is based from ice, it'll expand as it freezes. The mold is open on top to provide pykrete expansion space during the freezing process. The sample is frozen in ice maker machine (VEVOR ADT Type 110V) in -15ºC temperature for approximately 5 hours. After the pykrete freezes, the excess part on the expansion space will be discarded.

After the freezing process is completed, the sample is moved into an ice box for storage. The box will be filled with dry ice in order to keep the temperature low enough to preserve the specimens' condition until the time of testing. The dry ice will be refilled as necessary. Since pykrete must remain in low temperature to maintain it's material properties, the tests will be conducted as soon as the specimens are taken out of ice box in order to minimize the change in material's properties due to rising temperature.

Figure 3.2: TP-40 digital thermometer with integrated hygrometer

Two TP-40 digital thermometer with integrated hygrometer will be used to measure the value of ambient temperature and relative humidity of ambient air around the sample.

3.2 Research Plan



3.3 Measuring Specific and Absolute Humidity

The relative humidity is the ratio of the partial pressure of water vapor to the equilibrium vapor pressure of water at a given temperature and it's represented as percentage, which is a measure of of current absolute humidity value relative to the maximum possible value for that temperature. Normally, it's around 70%-90% saturation, which fluctuates as the temperature changes. When ice cools the ambient air, it changes the relative humidity value as water vapor begin to condense at low temperature. However, using only the relative humidity does not provide any meaningful information about the cooling performance since the relative humidity changes very slightly for several degrees of change in ambient air temperature, as such it's not a very accurate indicator for cooling performance. In order to observe the cooling performance accurately, we need to look into the specific humidity **(Sh)** absolute humidity **(Ah)**.

Specific humidity **(Sh)** is the ratio of the mass of water vapor to the total mass of the dry air in current temperature. The specific humidity is represented as grams of water vapor per grams of dry air. This value fluctuates as the temperature changes, with low air temperature yielding lower specific humidity value as the water vapor condensates into liquid phase. Like relative humidity, this value also depends on temperature and the pressure of the system of interest. Absolute humidity **(Ah)** is the actual measure of water vapor in the air regardless of ambient air temperature. The value changes for even a very slight change in ambient air temperature, which is far more accurate than relative humidity for observing the cooling performance. The lower the specific and absolute humidity value, the better the cooling is. In order to find the values of specific and absolute humidity, first, **T** (current temperature) will be used alongside with **Rh**. The formula for Rh is shown in the equation 3.1 below:

$$Rh = \frac{Pw}{Psat(T)} x100 \qquad (3.1)$$

Where: Rh = Relative humidity (in %)

Pw = Partial pressure of water vapor (mmHg)

Psat (T) = Saturation pressure of water vapor at T (mmHg)

We can look the value of **Psat(T)** value from the table of correlation between the partial water vapor pressure and ambient air temperature using the following table 3.1:

Table 3.2: Saturation pressure of water vapor at specific temperature

	T(°C)	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
↓	0	4.579	4.613	4.647	4.681	4.715	4.750	4.785	4.820	4.855	4.890
	1	4.926	4.962	4.998	5.034	5.070	5.107	5.144	5.181	5.219	5.256
Liquid	2	5.294	5.332	5.370	5.408	5.447	5.486	5.525	5.565	5.605	5.645
water	3	5.685	5.725	5.766	5.807	5.848	5.889	5.931	5.973	6.015	6.058
	4	6.101	6.144	6.187	6.230	6.274	6.318	6.363	6.408	6.453	6.498
	5	6.543	6.589	6.635	6.681	6.728	6.775	6.822	6.869	6.917	6.965
	6	7.013	7.062	7.111	7.160	7.209	7.259	7.309	7.360	7.411	7.462
	7	7.513	7.565	7.617	7.669	7.722	7.775	7.828	7.882	7.936	7.990
	8	8.045	8.100	8.155	8.211	8.267	8.323	8.380	8.437	8.494	8.551
	9	8.609	8.668	8.727	8.786	8.845	8.905	8.965	9.025	9.086	9.147
	10	9.209	9.271	9.333	9.395	9.458	9.521	9.585	9.649	9.714	9.779
	11	9.844	9.910	9.976	10.042	10.109	10.176	10.244	10.312	10.380	10.449
	12	10.518	10.588	10.658	10.728	10.799	10.870	10.941	11.013	11.085	11.158
	13	11.231	11.305	11.379	11.453	11.528	11.604	11.680	11.756	11.833	11.910
	14	11.987	12.065	12.144	12.223	12.302	12.382	12.462	12.543	12.624	12.706
	15	12.788	12.870	12.953	13.037	13.121	13.205	13.290	13.375	13.461	13.547
	16	13.634	13.721	13.809	13.898	13.987	14.076	14.166	14.256	14.347	14.438
	17	14.530	14.622	14.715	14.809	14.903	14.997	15.092	15.188	15.284	15.380
	18	15.477	15.575	15.673	15.772	15.871	15.971	16.771	16.171	16.272	16.374
	19	16.477	16.581	16.685	16.789	16.894	16.999	17.105	17.212	17.319	17.427
	20	17.535	17.644	17.753	17.863	17.974	18.085	18.197	18.309	18.422	18.536
	21	18.650	18.765	18.880	18.996	19.113	19.231	19.349	19.468	19.587	19.707
	22	19.827	19.948	20.070	20.193	20.316	20.440	20.565	20.690	20.815	20.941
	23	21.068	21.196	21.324	21.453	21.583	21.714	21.845	21.977	22.110	22.243
	24	22.377	22.512	22.648	22.785	22.922	23.060	23.198	23.337	23.476	23.616
	25	23.756	23.897	24.039	24.182	24.326	24.471	24.617	24.764	24.912	25.060
	26	25.209	25.359	25.509	25.660	25.812	25.964	26.117	26.271	26.426	26.582
	27	26.739	26.897	27.055	27.214	27.374	27.535	27.696	27.858	28.021	28.185
	28	28.349	28.514	28.680	28.847	29.015	29.184	29.354	29.525	29.697	29.870
	29	30.043	30.217	30.392	30.568	30.745	30.923	31.102	31.281	31.461	31.642
	30	31.824	32.007	32.191	32.376	32.561	32.747	32.934	33.122	33.312	33.503
	31	33.695	33.888	34.082	34.276	34.471	34.667	34.864	35.062	35.261	35.462
	32	35.663	35.865	36.068	36.272	36.477	36.683	36.891	37.099	37.308	37.518
	33	37.729	37.942	38.155	38.369	33.584	38.801	38.018	39.237	39.457	39.677
	34	39.898	40.121	40.344	40.569	40.796	41.023	41.251	41.480	41.710	41.942
	35	42.175	42.409	42.644	42.880	43.117	43.355	43.595	43.836	44.078	44.320
	36	44.563	44.808	45.054	45.301	45.549	45.799	46.050	46.302	46.556	46.811
	37	47.067	47.324	47.582	47.841	48.102	48.364	48.627	48.891	49.157	49.424
	38	49.692	49.961	50.231	50.502	50.774	51.048	51.323	51.600	51.879	52.160
	39	52.442	52.725	53.009	53.294	53.580	53.867	54.156	54.446	54.737	55.030
	40	55.324	55.61	55.91	56.21	56.51	56.81	57.11	57.41	57.72	58.03
	41	58.34	58.65	58.96	59.27	59.58	59.90	60.22	60.54	60.86	61.18
	42	61.50	61.82	62.14	62.47	62.80	63.13	63.46	63.79	64.12	64.46
	43	64.80	65.14	65.48	65.82	66.16	66.51	66.86	67.21	67.56	67.91
	44	68.26	68.61	68.97	69.33	69.69	70.05	70.41	70.77	71.14	71.51
	45	71.88	72.25	72.62	72.99	73.36	73.74	74.12	74.50	74.88	75.26
	46	75.65	76.04	76.43	76.82	77.21	77.60	78.00	78.40	78.80	79.20
	47	79.60	80.00	80.41	80.82	81.23	81.64	82.05	82.46	82.87	83.29
	48	83.71	84.13	84.56	84.99	85.42	85.85	86.28	86.71	87.14	87.58
	49	88.02	88.46	88.90	89.34	89.79	90.24	90.69	91.14	91.59	92.05

Ambient air temperature

1/10 of current temperature

Source: Richard, 2005

Thus, by using the equation (3.1), we can extrapolate it to get the equation 3.2:

$$Pw = \frac{Rh}{100} x Psat(T) \tag{3.2}$$

By obtaining the value of Pw in equation (3.2), we can now calculate the Absolute humidity **(Sh)** of the ambient air by using the following formula:

$$Specific\ humidity = \frac{Mass\ of\ vapor}{Mass\ of\ dry\ air}$$

Which could be written as equation 3.3:

$$Sh = \frac{Pw\ x\ Mw}{(TP - Pw) x\ Md} \tag{3.3}$$

Where	: Sh	= Specific humidity ($g_{\text{ of water}}/1g_{\text{ of air}}$)
	Pw	= Partial pressure of water vapor (mmHg)
	Mw	= Molecular mass of water (18 g/mol)
	TP	= Total pressure of dry air (average 760mmHg)
	Md	= Molecular weight of dry air (29 g/mol)

As the ice cools the surrounding ambient air, the value of **Sh** decreases from it's initial value as water vapor condenses while temperature drops (cooler air holds less water). As the time passes, heat from ambient, non-cooled air outside the cooling range will begin to affect the cooled air by raising the ambient air temperature, which will raise the **Sh** value of cooled air. When ice has completely melted, it'll no longer be able to provide any cooling as the ambient air temperature now equalizes with room temperature and **Sh** returns to it's initial value.

In order to find the value of Absolute Humidity **(Ah)**, we can use the following equation:

$$Ah = \frac{6.112 \times e\text{^}[(17.67 \times T)/(T+243.5)] \times Rh \times 18.02}{(273.15+T)} \quad (3.4)$$

Where : Ah = Specific humidity ($g_{\text{ of water}}/1m^3_{\text{ of air}}$)

T = Air temperature (°C)

Rh = Relative humidity

If the resulting line chart of Sh and Ah of the sample similar, then the calculation is correct, since both specific and absolute humidity is the measure of humidity in ambient air, albeit at different units of measurement (mass and volume respectively). Of course, by changing the sample used (not just ice), the value could be very different. Being able to withstand melting better than ice, pykrete could theoretically be used to provide cooling over much longer duration than regular ice, and being resistant towards impact shocks also lessens the chance it'll break apart when exposed to external force, allowing it to provide cooling longer than ice that has been broken up into smaller chunks

3.4 Measuring the Theoretical Tensile Strength

Measuring the tensile test of ice/ pykrete is quite difficult. The main difficulty comes from the fact that the shape needed for the tensile test sample is quite small, and if tested at room temperature, the readings from the test won't be accurate since if exposed at room temperature, the melting process of ice/ pykrete will weaken it's structure, especially the middle point of the sample (the predicted breaking point for tensile test) where it's small cross-section makes it highly susceptible to weakening effect caused by the melting process at room temperature.

It's rather difficult to get an accurate reading of actual tensile strength of ice and pykrete from tensile test since it requires the ambient temperature inside the testing room to be equal to the temperature of pykrete manufacturing process (-15°C) so that there's no compromise to the sample's material properties. In this case, a purely mathematical calculation method will be used to determine the theoretical tensile strength of ice/ pykrete. Theoretical tensile strength is a theoretical value of a material's tensile strength based on the properties of interatomic bonds in the crystal lattice of the material.

Although this method can be used, there is one limitations on it's usage: In real crystals, destruction is associated with the presence and movement of dislocations and other defects/ imperfections of the crystal structure, cracks, etc. When calculating the theoretical limit, it is assumed that the destruction is caused by the breaking of interatomic bonds in the crystal due to heat and it's always assumed that the crystal has ideal structure with no defects or imperfections, it doesn't take account for any chemical additives added into the mixture and the reinforcement material is represented separately as a portion of it's tensile strength, depending on the percentage of reinforcement material inside the pykrete.

Since ice is made from water, it's solid crystal lattice is made from the hydrogen bonds of water molecules. As temperature drops, the water molecules are slowed down and slowly bond with each other into solid ice crystal (freezing process) due to the change of energy of the surrounding area. When the temperature increases, it gives water molecules energy to move, breaking the bond between them and changes the phase of water from solid to liquid (melting process). Thus, the breaking of interatomic bonds in the crystal due to heat played a more significant role than other materials.

The first thing to do to use this method to find theoretical tensile strength is to find the number of crystal structure nodes (CSn) of the ice portion of the sample.

$$CSn = \frac{mass}{molar\ mass\ x\ Avogadro\ constant} \tag{3.5}$$

Where : CSn : Number of crystal structure nodes per Kg of the sample (Atom/Kg)

Mass : Mass of the sample (1 Kg)

Molar mass : Molar mass of the sample (Kg/mol)

Avogadro constant : 6.022×10^{23} mol^{-1}

We can now use the CSn value to determine the energy needed to break one bond in a 1 Kg ice by using the following equation:

$$ERn = \frac{\triangle Hvap}{CSn} \tag{3.6}$$

Where : ERn : Energy required to break one crystal node (J/node)

$\triangle H_{vap}$: Enthalpy of Vaporization of the sample (J/Kg)

CSn : The number of crystal structure nodes per Kg of the sample

Next, we need to find the average distance between the nodes of ice crystal structures inside the sample. We can use these equation to find out:

$$ADn = \left(\frac{V}{(mass{:}(molar\ mass\ x\ Avogadro\ constant)}\right)^{\frac{1}{3}} \tag{3.7}$$

Where :	ADn	: Average distance of nodes (m)
	V	: Volume of the sample (1 m^3)
	Mass	: Mass of the sample (Kg)
	Molar mass	: Molar mass of the sample (Kg/mol)
	Avogadro constant	: 6.022×10^{23} mol^{-1}

This way, we've acquired the value of energy needed to break one ice crystal node, the amount of ice crystal nodes and the average distance between ice crystal nodes. To break the ice sample apart in two halves we need to take away from each other at least two neighboring layers of the crystal structure. So we need to find the average number of ice crystal nodes per cross-sectional area. Since we will be simulating the breaking of the sample in a tensile test, we will use the simulated size for the testing sample (ASTM D3500) in figure 3.2 below:

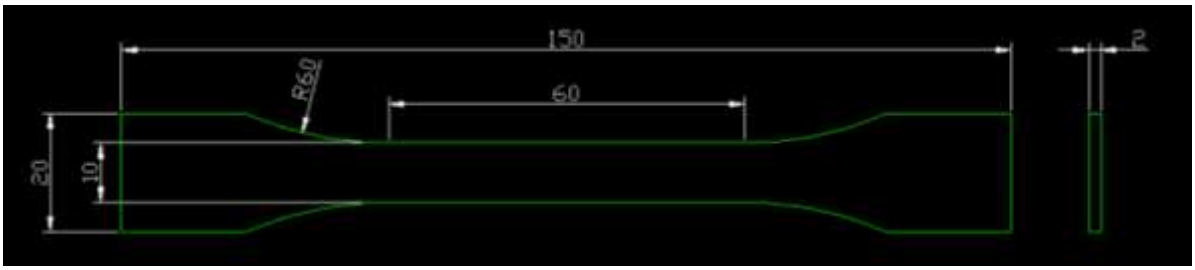


Figure 3.3: Sample size for simulated theoretical tensile test calculation

Note that we are only looking for the amount of nodes in a cross section area of the breaking point of the sample, which is assumed in the middle of the sample. We will take the middle portion of the sample with 10 mm x 10 mm size. Since the thickness of the sample is 2 mm, a stack of 5 sample means a thickness of 10 mm. This is used to simplify the calculation by making the volume calculated for cross-sectional area as a 10 mm x 10 mm x 10 mm cube. The result will be divided by 5 to obtain the value of the slab with 2 mm thickness.

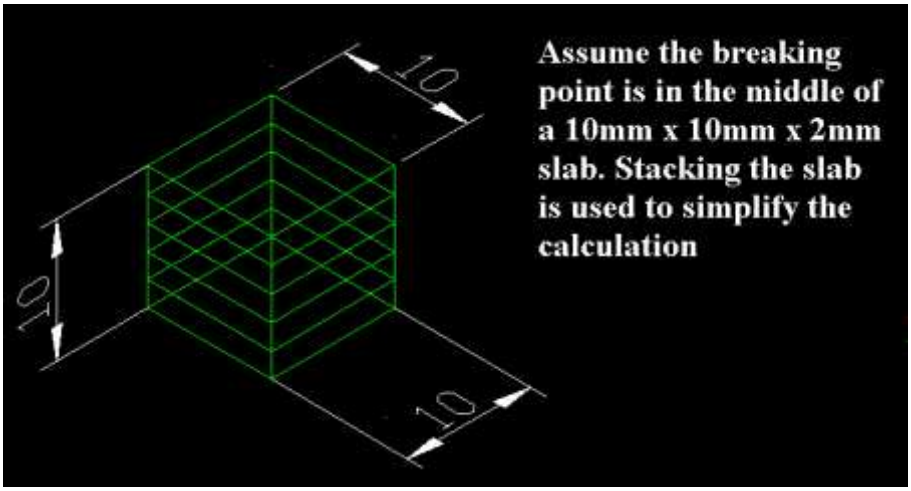


Figure 3.4: Simplification of calculation by stacking 5 slabs of predicted breaking point

$$NCs = (\frac{V}{(ADn)^2})/5 \tag{3.8}$$

Where: V : Volume of the stacked slabs (m^3)

NCs : Average nodes per cross-sectional area (nodes/ m^2)

ADn : Average distance of nodes (m)

By obtaining the amount of nodes per cross-sectional area, we can now use the ERn from equation (3.6) to determine the amount of energy needed to break all nodes in a cross-sectional area of the sample. Since (Work = force x distance), so (Force = work : distance). The distance is nearly the same as the distance between the nodes:

$$TTs = \frac{(ERn\ x\ NCs)}{ADn} \tag{3.9}$$

Where: TTs : Theoretical tensile strength (J/m^2) (convert to N/m^2 then to GPa)

ERn : Energy required to break one crystal node (J/node)

ADn : Average distance of nodes (m)

For calculating TTs of pykrete, we need to multiply the TTs of ice by 0.86 (the percentage of ice portion) then add the tensile strength of it's reinforce material multiplied by 0.14 (the percentage of reinforce material portion, 0.07 for hybrid pykrete's reinforce material, calculated separately). Note that the results will most likely lean towards the tensile strength of the reinforce material itself since ice's tensile strength is pretty weak by itself.

3.5 Execution

Cooling performance test will be conducted for all 8 samples. This test are roughly based from the setup used by Tan E-Liang (2014) except it uses larger sample size and the box used to confine the ambient air. This is done to give space for the thermometers as well as making the sensor readout more noticeable (smaller sample has been tested, but it turns out the fluctuations is too faint to be readable by sensor). The setup for the test is shown in figure 3.4 below:

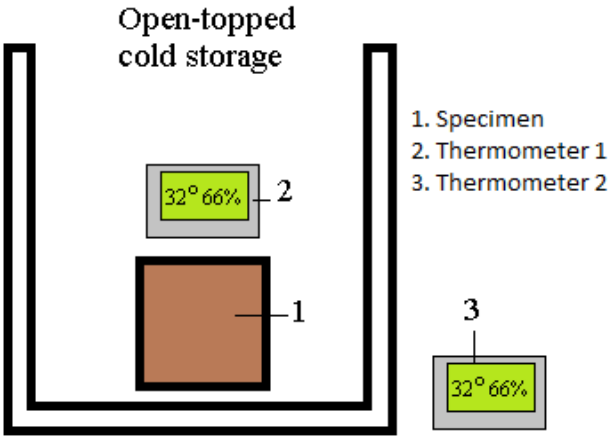


Figure 3.5: Concept for cooling performance test

This test will investigate pykrete's melting rate and cooling performance in room temperature until it's unable to provide any cooling for ambient air (The temperature of testing is same with room temperature). The procedure is as follows:

1. The sample will be put inside the open-topped cold storage (The reason for open top is that it simulates the condition of broken cold storage box that's exposed to outside temperature, and allows the cooling effect to be confined in a single area so a more accurate measurement could be taken)
2. The timer is started, and the initial value of relative humidity and the temperature from digital thermometer 1 is taken. Every 15 minutes, another value will be taken. These values is then inserted into the specific and absolute humidity equation.
3. The timer will stop the moment the temperature value of digital thermometer 1 matches the value of digital thermometer 2 (Meaning that the specimen no longer provides any cooling). At this point, the sample should have completely melted.
4. The data of **Ts** and **Rh** obtained from the moment the test started until the specimen's complete melt over 5-minutes interval is used to calculate the value of **Sh**,and **Ah** which is then plotted into line charts.

5. After all specimens in cooling performance test has been tested, the data obtained from the readings of 4 samples will be analyzed before comparing them together to provide the final verdict of pykrete's viability as a protective insulation for cold storage application. The experiment will be repeated 2 to 3 times to verify the results if there's any error in the sensor readings or unnatural temperature spike/ drop.

3.6 Observed Variables

The main variable of this experiment is the composition ratio of the specimens. The data that's being collected is the ambient air temperature, relative humidity and the time until the specimen's complete melt. The temperature and relative humidity value is used to calculate the absolute humidity of ambient air temperature, which is then plotted into the line chart that shows the relation between the fluctuation of absolute humidity value and the elapsed time to completely melt the specimen. From data obtained from test results, we can compare the plotted charts in order to determine the final conclusion of the cooling performance of each pykrete sample compared with regular ice, which is used as the primary benchmark for overall cooling duration, lowest air temperature attained, as well as lowest specific and absolute humidity values. Although there are several variables that's being measured from the samples, which is, temperature , cooling duration, relative, specific and absolute humidity, all of it goes through similar chart phases like on figure 3.5 below:

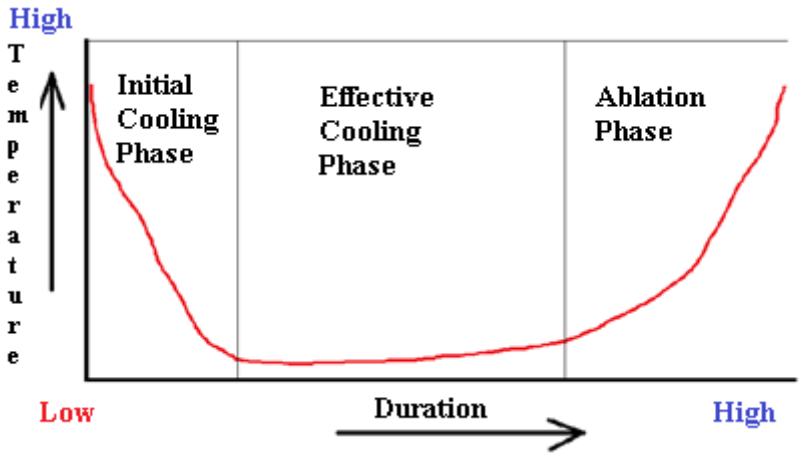


Figure 3.6: Phases of chart of the cooling performance test

As shown on figure 3.5, there are 3 phases that occurs throughout the testing:

1. **Initial cooling phase:** This phase occurs during the initial phase cooling where the temperature of ambient air around the sample drops into the lowest possible value for that sample. This phase stops at the lowest temperature reading attained by sensor. The vertical portion represents the degree of how far the temperature drops while the horizontal portion represents how fast the temperature reached the lowest possible value.
2. **Effective cooling phase:** This phase occurs after the temperature reached the lowest possible value for that sample. During this phase, ambient air temperature more or less stagnates, with little fluctuations that doesn't drastically increase the overall temperature, staying between slightly higher or lower than a fixed temperature value that defines this phase. The vertical portion represents the degree of cooling stability during this phase (more fluctuations means less stability) while the horizontal portion represents how long this phase lasts.
3. **Ablation phase:** Also known as meltdown phase, this phase occurs when the temperature during effective cooling phase keep increasing with little to no drop of temperature until the sample has been completely melted. Only the horizontal portion that represents any useful information here, which is how fast the ablation phase lasts, since the vertical portion will eventually back to the normal room temperature level anyway.

For the theoretical tensile strength, only the force needed to(theoretically) break the sample apart will be observed.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Physical Characteristics From Cooling Peformance Test 1 Samples

4.1.1 Sample 1: Regular Ice

Figure 4.1: Regular ice, 10cm x 10cm x 20cm size

Meltdown : 13 Hours 17 Minutes 54 Seconds

Min. temperature attained (°C) : 10.6

Min. absolute humidity value (g of water vapor/ 1m^3 of air) : 5.5966

Min. specific humidity value (g of water vapor/ 1g of air) : 0.00452

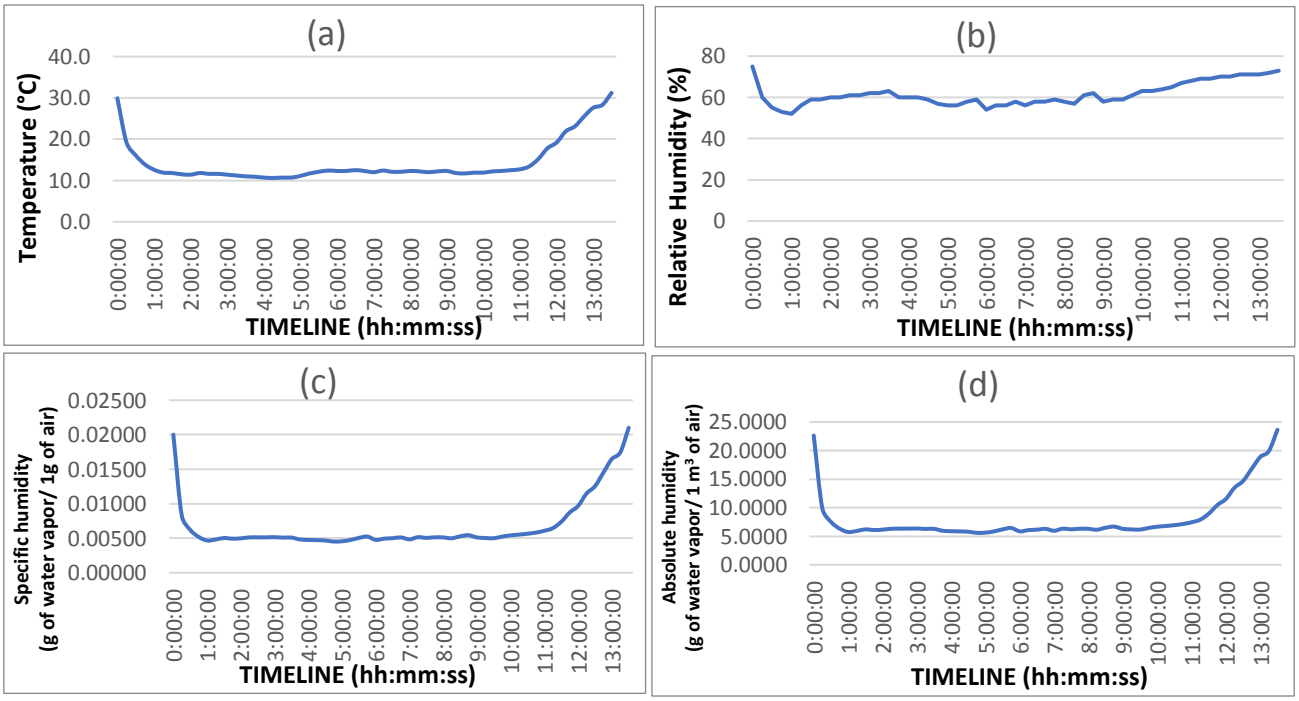


Figure 4.2: Influence of time on temperature (a), relative humidity (b), specific humidity (c) and absolute humidity (d) of regular ice

The first sample is completed and tested on 16th January 2020. It is a block of plain ice without any reinforce material, measuring 10cm x 10cm x 20cm, frozen in -15°C temperature. The first sample provides 13 hours, 17 minutes and 54 seconds of cooling duration before the air temperature inside the box equalizes with air temperature outside the box. The lowest temperature attained by the first sample is 10.6°C.

If we look at the first sample's charts, ice already provides good cooling temperature and duration. The chart for temperature shows that during the initial phase of cooling, ice tend to cool the surrounding air quickly (show by a steep dive on the curve) before the cooling effect becomes stable (shown by a more or less flat line of the curve), but the moment ice began to lose it's cooling effect, there's a sudden spike on surrounding air temperature (shown by a sharp increase of curve at the end of the chart).

In terms of specific and absolute humidity, there are surprisingly very little fluctuations both charts, along with near-flat line that suggests a highly stable cooling temperature during the effective cooling duration before the temperature starts to increase. This also suggest that the cooling intensity of ice over a fixed area around the sample is more or less constant throughout the cooling duration. The amount of water in the air around the sample rarely changes except during the initial cooling phase where a sudden drop of water level occurred from normal water level at room temperature and during the end of effective cooling phase where the amount of water level experienced a sudden spike as ambient temperature around the sample increases.

The results from testing the first sample will be used as a benchmark to measure the cooling performance of subsequent samples.

4.1.2 Sample 2: Paper-based Pykrete

Figure 4.3: Paper-based pykrete, 10cm x 10cm x 20cm size

Meltdown : 16 Hours 42 Minutes 35 Seconds

Min. temperature attained (°C) : 9.7

Min. absolute humidity value (g of water vapor/ 1 m^3 of air): 4.7003

Min. specific humidity value (g of water vapor/ 1g of air) : 0.00378

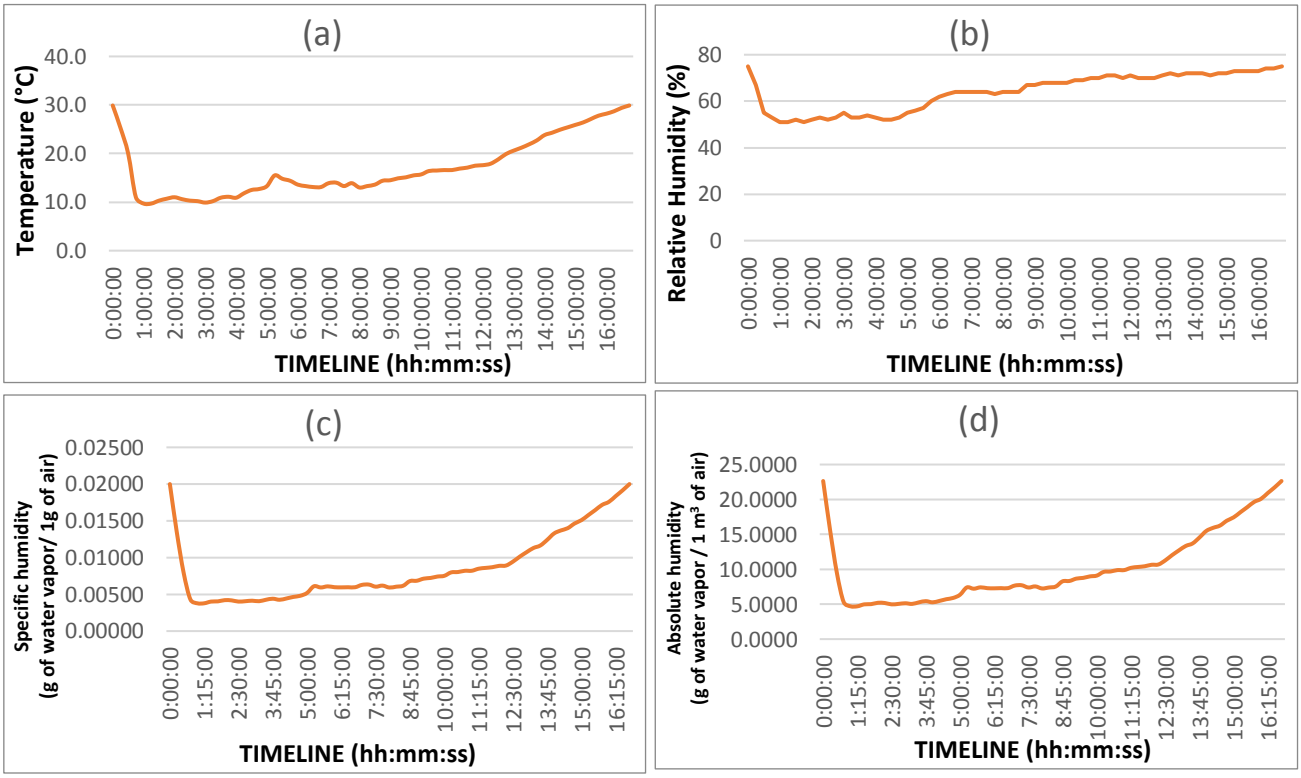


Figure 4.4: Influence of time on temperature (a), relative humidity (b), specific humidity (c) and absolute humidity (d) of paper-based pykrete

The second sample is completed and tested on 24th January 2020. It is a block of paper-based pykrete with 14% reinforce material, measuring 10cm x 10cm x 20cm, frozen in -15°C temperature. The second sample provides 16 hours, 42 minutes and 35 seconds of cooling duration before the air temperature inside the box equalizes with air temperature outside the box, a massive improvement of 3 hours, 24 minutes and 41 seconds compared to the first sample. The lowest temperature attained by the first sample is 9.7°C, which is 0.9°C lower than the first sample.

. In terms of absolute and specific humidity, it's quite stable due to the small amount of fluctuations encountered (however, regular ice is still better). After the temperature drops into effective cooling range, it's noticeably more inclined than regular ice, suggesting that it's less capable of maintaining constant cooling at stable pace during effective cooling duration.

As observed on the charts, the paper-based pykrete shows a much longer cooling duration than regular ice, at the cost of less stable cooling, judging from less-than flat lines. The sample shows a smooth curve of increasing air temperature when it starts to be unable to provide cooling (ambient air temperature returns to normal over long period of time), compared to the regular ice, which shows sudden increase in air temperature chart (ambient air temperature returns to normal over short period of time). During testing, it's found that the sample melts differently than regular ice, which, instead of continuous melting at uniform pace on all surfaces, the sample exhibits a unique characteristic where the melted portion of the sample leaves behind the reinforce material as a "blanket" that insulates the deeper ice layer, yet still allows the cooling of surrounding air to continue. As predicted, these blanket of reinforce material crumbles as the time passes, exposing the layer beneath it and repeating the process all over again. This might explain why there's a lot of erratic fluctuations on all 4 charts due to the ever-changing nature of cooling and melting in pykrete. It's predicted that all subsequent pykrete samples will exhibit these behavior during the melting process.

4.1.3 Sample 3: Wood-based Pykrete

Figure 4.5: Wood-based pykrete, 10cm x 10cm x 20cm size

Meltdown : 15 Hours 27 Minutes 15 Seconds

Min. temperature attained (°C) : 10.5

Min. absolute humidity value (g of water vapor/ 1 m^3 of air): 5.3032

Min. specific humidity value (g of water vapor/ 1g of air) : 0.00429

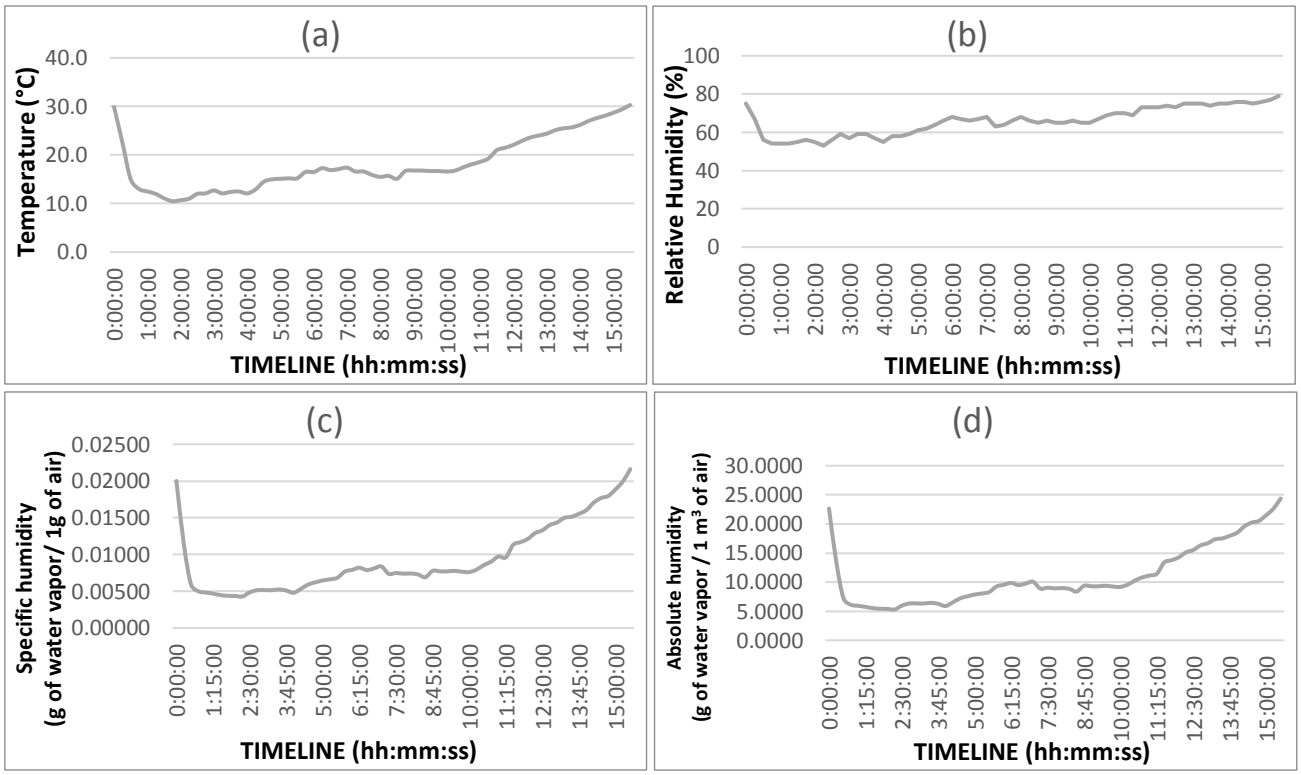


Figure 4.6: Influence of time on temperature (a), relative humidity (b), specific humidity (c) and absolute humidity (d) of wood-based pykrete

The third sample is completed and tested on 28th January 2020. It is a block of wood-based pykrete with 14% reinforce material (made from teak wood), measuring 10cm x 10cm x 20cm, frozen in -15°C temperature. The third sample provides 16 hours, 42 minutes and 35 seconds of cooling duration before the air temperature inside the box equalizes with air temperature outside the box, which is higher than regular ice (+2 hours, 9 minutes and 21 seconds) but slightly lower than paper-based pykrete (-1 hour, 15 minutes and 20 seconds). The lowest temperature attained is 10.5°C, which is a very small improvement compared to regular ice (0.1°C lower than regular ice) but still worse than paper-based pykrete (0.8°C higher than paper-based pykrete)

The wood-based pykrete has lower cooling duration and lower cooling temperature than paper-based pykrete (although still better than regular ice). During testing, it's discovered that, although wood-based pykrete exhibit similar cooling phase like paper-based pykrete, it's a bit different in that the blanket of reinforce material crumbles bit-by-bit by a small amount, which might explain the lack of sharp points of fluctuations of temperature, and explain the lower cooling duration. On paper-based pykrete, the blanket of reinforce material stays for some time after the ice that bonds them together has melted, protecting the ice layer beneath it from the exposure of external temperature. However, when it came off, it crumbles in a large chunks, which might explain the sudden fluctuation of change in temperature as the now-exposed layer of ice underneath when it's exposed all at once. On the other hand, the crumbling of wood-based pykrete's reinforce material exposes the ice layer underneath bit-by-bit, explaining the more "rounded" peaks and smaller fluctuations on the chart. Like paper-based pykrete, wood-based pykrete also shows smooth curve of increasing air temperature over long period of time when it returns to normal.

In terms of specific and absolute humidity however, the chart shows significantly more fluctuations that results in more "jagged" peaks over inclined line when compared with paper-based pykrete and regular ice, suggesting that it is even more unstable than paper-based pykrete in terms of maintaining constant cooling during effective cooling duration. The highly fluctuating chart of specific and absolute humidity of wood-based pykrete means that the water content in the ambient air changes wildly due to the cooling instability (which is assumed to be caused by uneven cooling by the variable nature of pykrete mixture where it's surface isn't always 100% ice, but there's some reinforce material on the surface). Despite this, wood-based pykrete is still superior than ice in terms of cooling temperature and cooling duration.

4.1.4 Sample 4: Hybrid Paper-Wood-based Pykrete

Figure 4.7: Hybrid paper-wood-based pykrete, 10cm x 10cm x 20cm size

Meltdown : 14 Hours 42 Minutes 14 Seconds

Min. temperature attained (°C) : 8.3

Min. absolute humidity value (g of water vapor/ 1 m^3 of air): 4.4103

Min. specific humidity value (g of water vapor/ 1g of air) : 0.00353

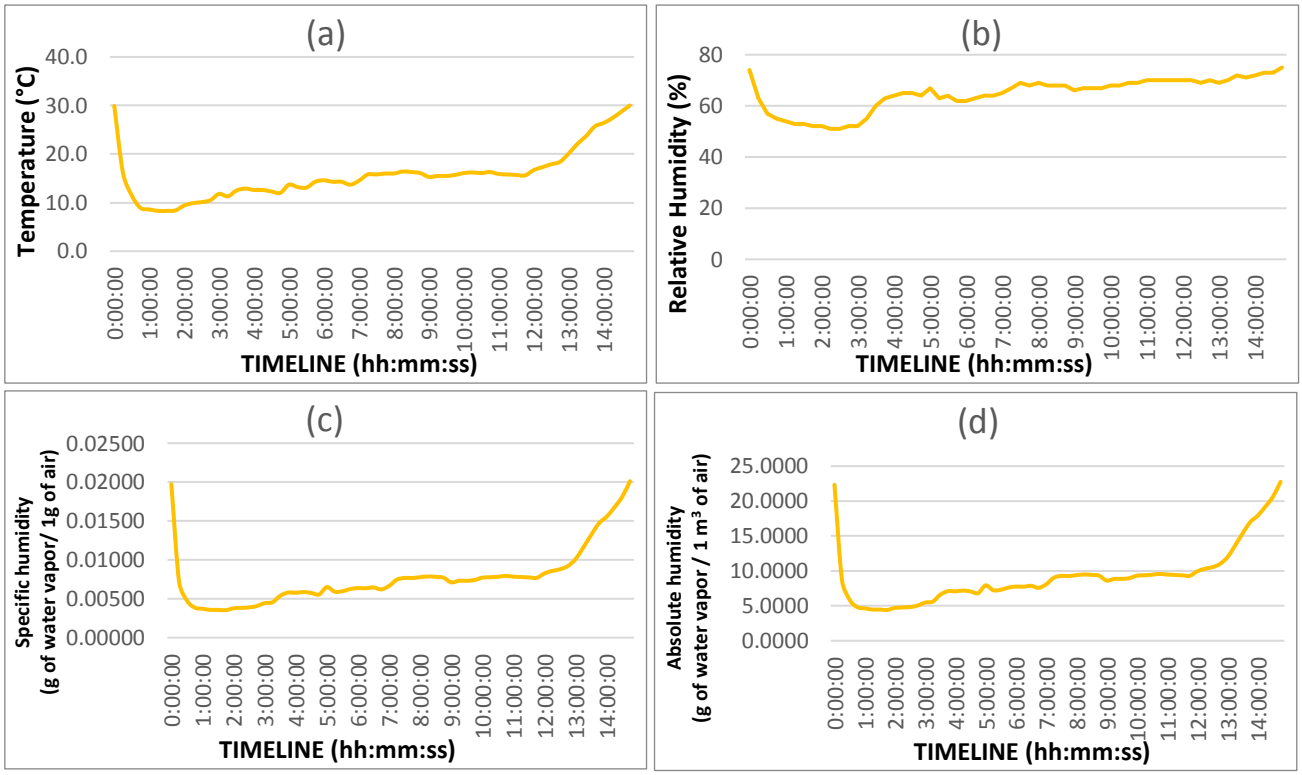


Figure 4.8: Influence of time on temperature (a), relative humidity (b), specific humidity (c) and absolute humidity (d) of hybrid paper-wood-based pykrete

The fourth sample is completed and tested on 3rd March 2020. It is a block of hybrid paper-wood-based pykrete with 14% reinforce material (7% made from teak wood, and 7% made from shredded paper), measuring 10cm x 10cm x 20cm, frozen in -15°C temperature. The fourth sample provides 14 hours, 42 minutes and 14 seconds of cooling duration before the air temperature inside the box equalizes with air temperature outside the box, which is slightly longer than regular ice (+1 hour, 24 minutes and 20 seconds) but shorter than paper-based (-2 hours and 21 seconds) and wood-based pykrete (45 minutes and 1 second). However, the lowest temperature attained by hybrid paper-wood pykrete is by far the best of all samples, 8.3°C, which is a very big improvement compared to regular ice (2.3°C lower), paper-based pykrete (1.4°C lower) and wood-based pykrete (2.2°C lower). The fourth sample managed to maintain this low temperature for about 90 minutes (based from sensor readings between 07:30 AM – 09:00 AM).

The hybrid paper-wood pykrete has the lowest cooling duration compared to paper and wood-based pykrete, although it's still better than regular ice. During testing, the combination of paper and wood as reinforce material for the fourth sample make it's melting process different when compared with previous samples where the blanket of reinforce material that has lost it's ice content crumbles in medium-sized chunks, which is smaller than wood-based pykrete, but larger than paper-based pykrete. The fourth sample also exhibit the lowest cooling temperature at 8.3°C, the best of all samples. By observing the charts, the hybrid paper-wood pykrete is the only pykrete which doesn't have the characteristic long duration of increasing temperature curve after the cooling starts to cease, which makes the fourth sample's temperature chart resembles regular ice (albeit with lower temperature and slightly longer duration).

In terms of absolute and specific humidity, the fourth sample provides a chart that resembles regular ice (albeit with more "inclined" base). suggesting that it's still less stable than ice in terms of maintaining air humidity (judging from the fluctuations in water content in ambient air), though it's far more stable than paper and wood-based pykrete). Overall, the paper-wood pykrete sacrifices the cooling duration for lower cooling temperature (and stability)

4.1.5 Analysis of First Cooling Performance Test's Physical Characteristics

The results from the line charts of the 4 samples can be compared between each other to observe their cooling performance characteristics by overlaying the 4 line charts together into the line charts below:

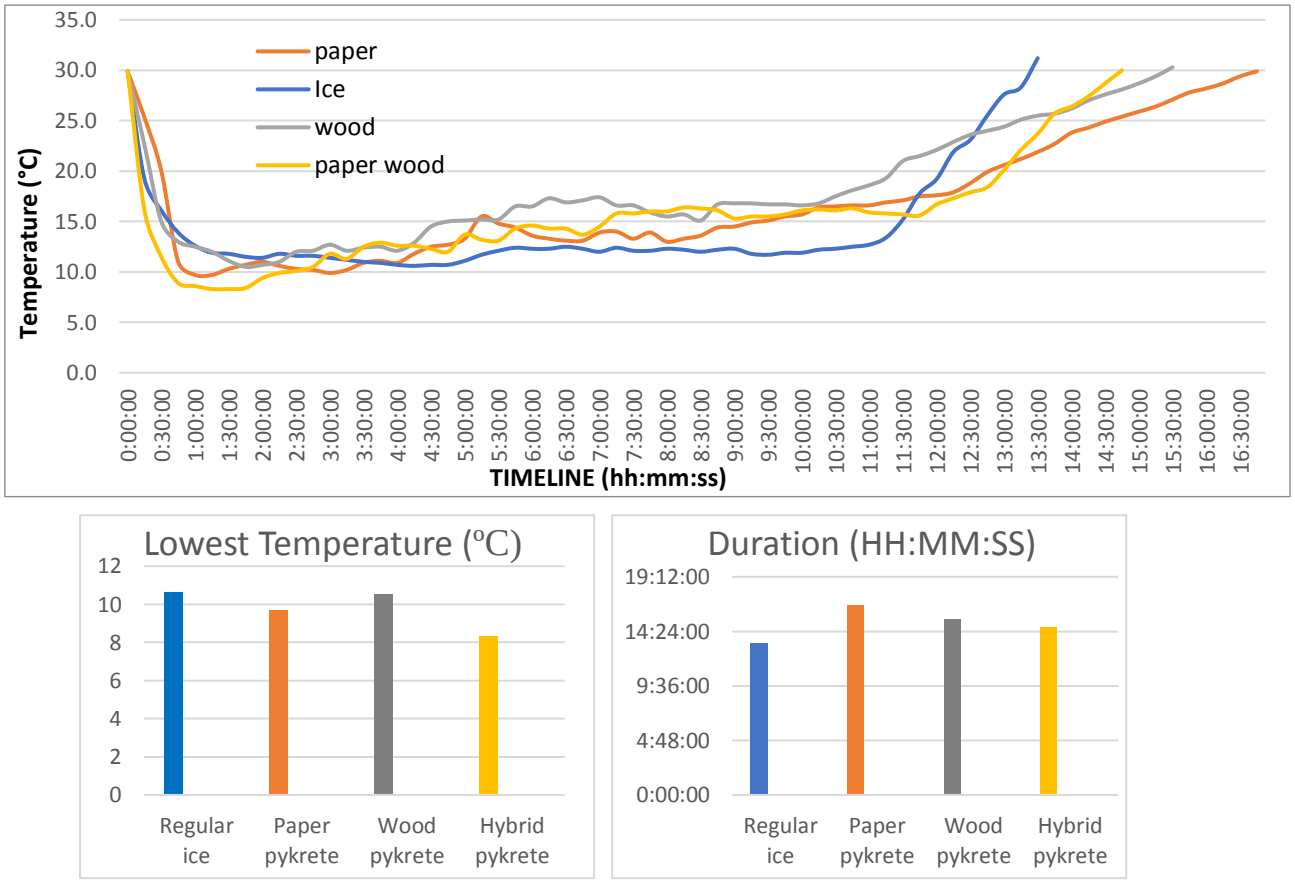


Figure 4.9: Influence of time on temperature of cooling performance test 1 samples

Based from line chart above, it can be summarized for the first cooling performance test that, in general, pykrete boasts a better cooling duration than regular ice, even when it's exposed to room temperature, with paper pykrete having the longest cooling duration of all pykrete samples while ice having the shortest cooling duration. Paper wood pykrete has been observed to possess the lowest cooling temperature and the fastest cooling speed of all pykrete samples. However, this comes at a cost of having the worst cooling duration of all pykrete samples (although it's still better than regular ice) From the chart, we can observe that pykrete samples has a lot more fluctuations than ice. This is probably because of the unstable cooling on pykrete caused by the layer being peeled off during it's melting process.

Observing the absolute and specific humidity of the samples is a bit unique. Since both has same line chart results (only differing in units being measured), the only thing that matters from it is the cooling stability (how much fluctuations occurred) and it's lowest value (indicating lower cooling temperature). By overlaying the absolute and specific humidity line charts from 4 samples together, the resulting line chart is as follows:

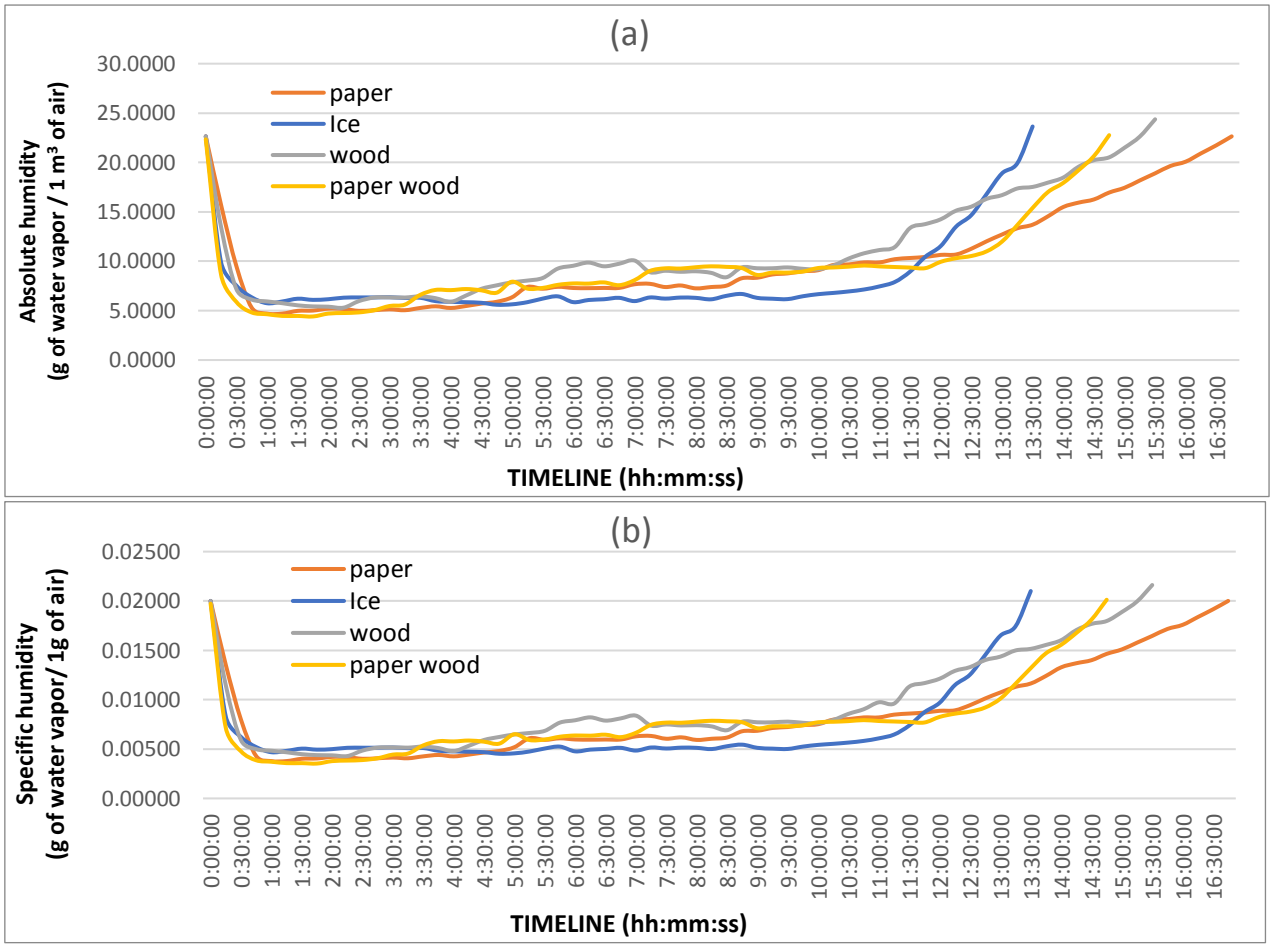


Figure 4.10: Influence of time on absolute humidity (a) and specific humidity (b) of cooling performance test 1 samples

Ice provides the most stable chart (it's near-flat during it's effective cooling duration), this means the surrounding water vapor content in the ambient air around the ice changes very little throughout it's cooling duration. Compared to the 3 pykrete samples where there's a lot of instability where the chart goes up and down erratically until the very end of it's effective cooling duration where it increases steadily. This might be caused by the layered nature of pykrete's melting process where the process is layer-by-layer instead of continuously like ice.

By extrapolating data from 4 samples, the overall results of cooling performance 1 can be summarized as follows, with red highlight means the lowest (worst) and green highlight means the highest (best):

Table 4.1: Overall analysis of first cooling performance test

Cooling Performance Test 1 results				
Sample	Meltdown (hh/mm/ss)	Lowest temperature attained (°C)	Lowest absolute humidity value (g of water vapor / 1 m^3 of air)	Lowest specific humidity value (g of water vapor/ 1g of air)
1 (regular ice)	13:17:54	10.6	5.5966	0.00452
2 (paper pykrete)	16:42:35	9.7	4.7003	0.00378
3 (wood pykrete)	15:27:15	10.5	5.3032	0.00429
4 (hybrid pykrete)	14:42:14	8.3	4.4103	0.00353

The long cooling duration of pykrete samples compared to regular ice might be attributed to the reinforcement material inside, which slows the heat propagation, making the sample melts slower and lasts longer compared to regular ice. In addition, the high fluctuations observed on pykrete samples' temperature and humidity level matches the prediction on how the sample cools the surrounding air. On regular ice, since the ice portion is always in contact with ambient air, the temperature is always stable. However, on pykrete, the way pykrete melts affects the temperature and humidity level of ambient air. Unlike regular ice, initially, when the ice portion of pykrete is in contact with ambient air, the temperature decreases. When the ice portion melted, the reinforce material left formed a shell that shields the lower layer of pykrete from heat outside, making it melt slower, but since the shell has no ice component in contact with ambient air, the temperature now increases. After the shell crumbles away, the now exposed ice portion on the new layer cools the ambient air again, lowering the temperature again. This repeats until pykrete sample completely melted.

The second cooling performance test will be conducted in order to improve the cooling performance of all samples by adding 1% salt concentration of total volume into the mixture. In theory, lowering the freezing point of the sample would make it last longer by increasing the temperature needed to melt the sample, as well as improving the lowest possible cooling temperature of all samples.

4.2 Physical Characteristics of Cooling Peformance Test 2 Samples

4.2.1 Sample 5: Regular Ice (with salt)

Figure 4.11: Regular ice with 1% salt, 10cm x 10cm x 20cm size

Meltdown : 17 Hours 5 Minutes 57 Seconds

Min. temperature attained (°C) : 5.9

Min. absolute humidity value (g of water vapor/ 1 m^3 of air): 3.8460

Min. specific humidity value (g of water vapor/ 1g of air) : 0.00306

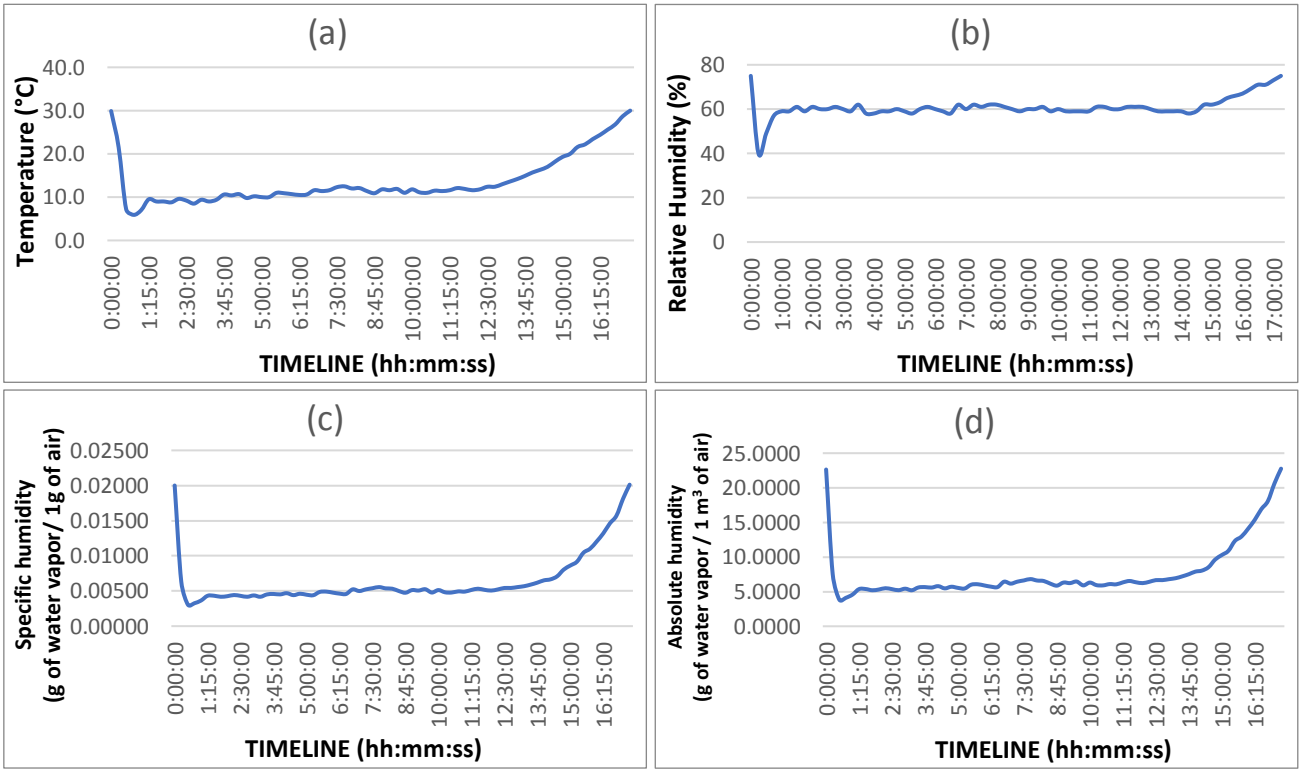


Figure 4.12: Influence of time on temperature (a), relative humidity (b), specific humidity (c) and absolute humidity (d) of salted regular ice

The fifth sample is completed and tested on 11th June 2020. It is a block of plain ice without any reinforce material, but with an additional content of salt (1% by volume). The sample, measuring 10cm x 10cm x 20cm is frozen in -15°C temperature. The fifth sample provides 17 hours, 5 minutes and 7 seconds of cooling duration before the air temperature inside the box equalizes with air temperature outside the box, a massive improvement of 3 hours 47 minutes and 13 seconds compared to regular ice. The lowest temperature attained by the fifth sample is 5.9°C (4.7°C lower than regular ice), which is reached at 07:45AM, much faster compared to the regular ice's lowest attainable temperature of 10.6°C which is reached at 11:15AM. This means the addition of salt additive makes the sample capable of cooling the ambient air to it's lowest possible temperature much faster than regular ice.

The salt-infused ice provides an even better cooling temperature and duration. The chart for temperature isn't really different than regular ice (with the exception of lower temperature and longer duration). However, with faster cooling effect, the water content in the ambient air around the sample drops much more quickly than regular ice. As Absolute Humidity parameter is the amount of water per cubic meter of air, this means the sample cools the ambient air of the same area as regular ice with cooling intensity strong enough to lower the temperature even further.

The addition of salt decreases freezing point of water, which, in effect makes the sample froze slower. The time required to completely freeze the sample is approximately double than regular ice, although it also provides a substantially better cooling temperature and duration. The cooling duration is enough to surpass all previous pykrete samples except paper-based pykrete (which is 1 hour, 37 minutes and 28 seconds longer than salted ice).

4.2.2 Sample 6: Paper-based Pykrete (with salt)

Figure 4.13: Paper-based pykrete with 1% salt, 10cm x 10cm x 20cm size

Meltdown : 17 Hours 2 Minutes 11 Seconds

Min. temperature attained (°C) : 9.9

Min. absolute humidity value (g of water vapor/ 1 m^3 of air): 5.2271

Min. specific humidity value (g of water vapor/ 1g of air) : 0.00421

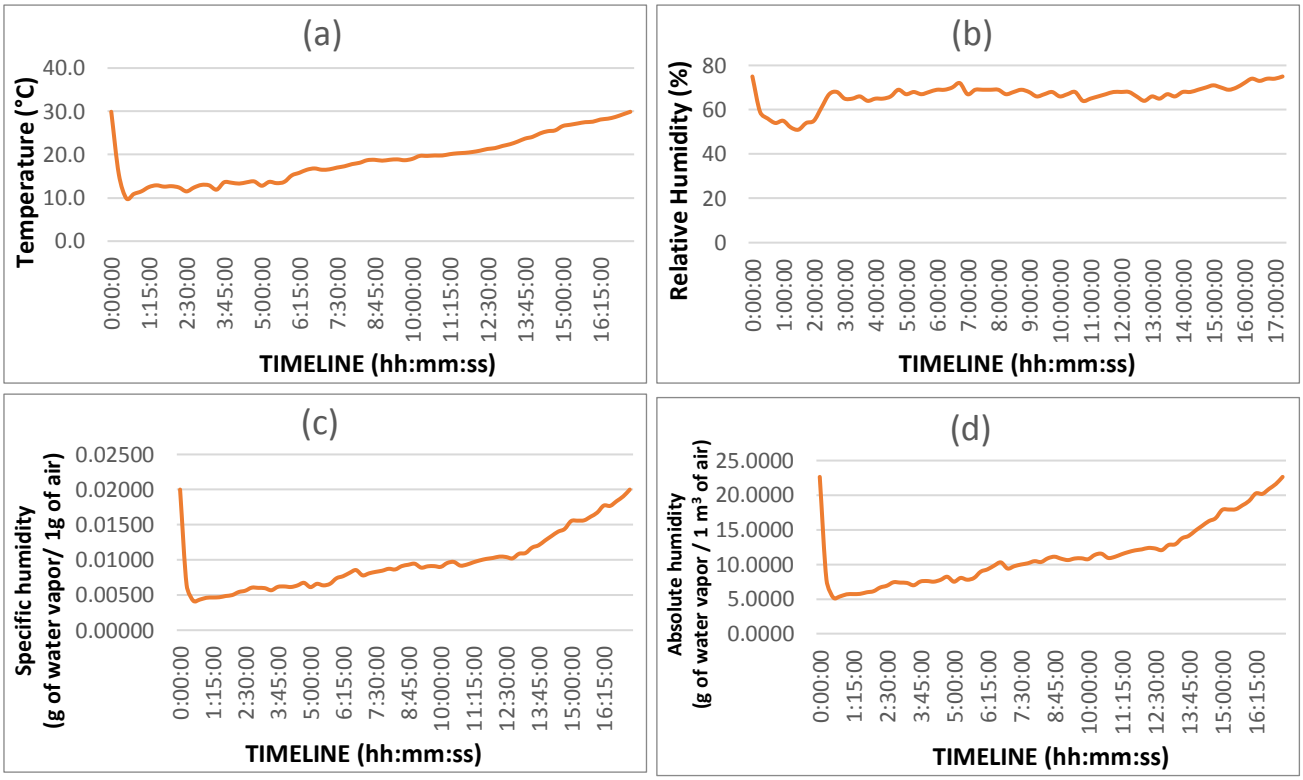


Figure 4.14: Influence of time on temperature (a), relative humidity (b), specific humidity (c) and absolute humidity (d) of salted paper-based pykrete

The sixth sample is completed and tested on 18th June 2020. It is a block of paper-based pykrete with an additional content of salt (1% by volume). The sample, measuring 10cm x 10cm x 20cm is frozen in -15°C temperature. The sixth sample provides 17 hours, 2 minutes and 11 seconds of cooling duration before the air temperature inside the box equalizes with air temperature outside the box, which is a very small improvement compared with regular paper-based pykrete (only adding 19 minutes and 36 seconds for total cooling duration). Although it provides higher lowest attainable temperature at 9.9°C, this is also a very small difference compared to the regular paper-based pykrete's lowest attainable temperature of 9.7°C.

If we look at the sixth sample's charts, the salt-infusion seems to provide stability for pykrete, judging from the lack of fluctuations in temperature, relative, absolute and specific humidity. This makes the salt-infused paper pykrete far more stable allowing it to maintain temperature and humidity level of ambient air with very little fluctuations as the chart slowly moves upward as the cooling effect slowly dissipates.

Like the salt-infused ice, the cooling effect of ambient air around the sixth sample also takes effect much faster (reaching lowest temperature reading of 9.9°C at 07:30AM compared to the regular wood-based pykrete's 9.7°C at 08:00AM), which is a highly desirable trait in cooling application. It's predicted that the subsequent salt-infused sample will also exhibit this characteristic that allows it to cool the ambient air much faster than regular version.

4.2.3 Sample 7: Wood-based Pykrete (with salt)

Figure 4.15: Wood-based pykrete with 1% salt, 10cm x 10cm x 20cm size

Meltdown : 15 Hours 6 Minutes 42 Seconds

Min. temperature attained (°C) : 13.0

Min. absolute humidity value (g of water vapor/ 1 m^3 of air): 6.6883

Min. specific humidity value (g of water vapor/ 1 g of air) : 0.00546

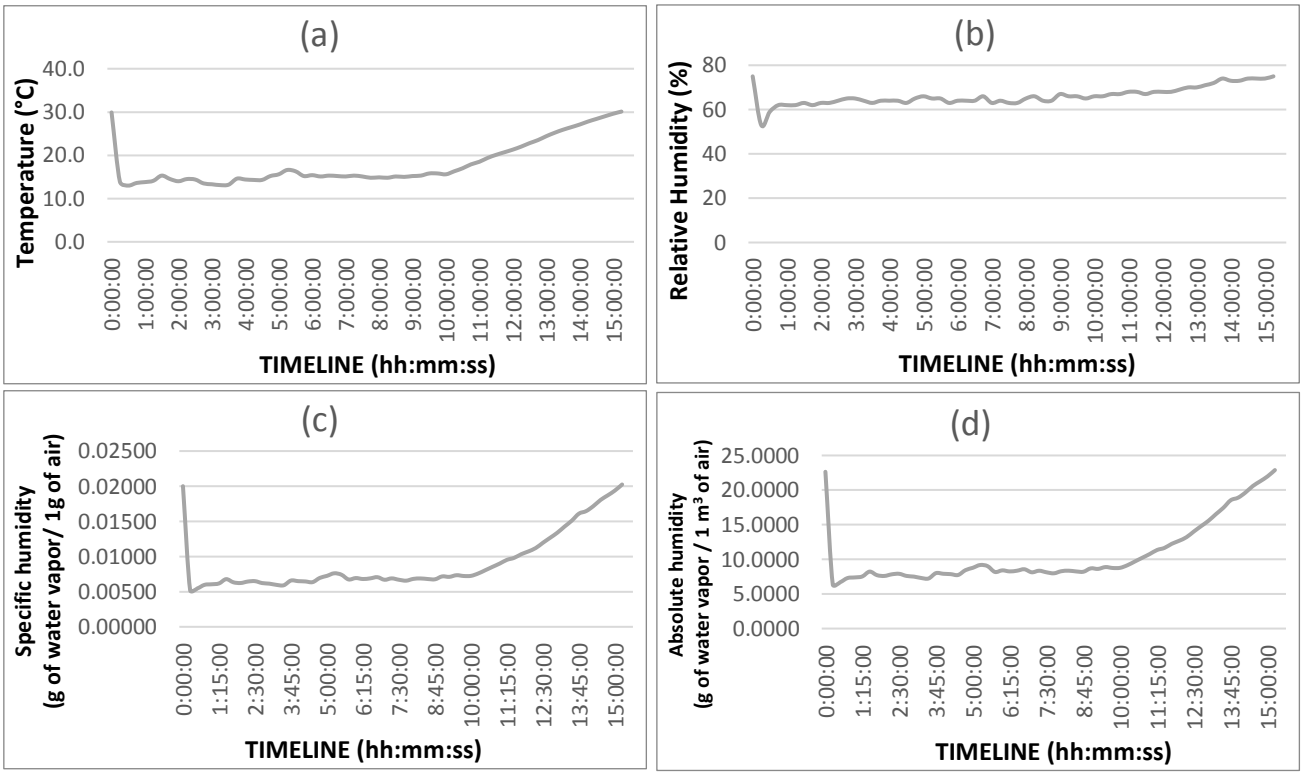


Figure 4.16: Influence of time on temperature (a), relative humidity (b), specific humidity (c) and absolute humidity (d) of salted wood-based pykrete

The seventh sample is completed and tested on 16th July 2020. It is a block of wood-based pykrete with an additional content of salt (1% by volume). The sample, measuring 10cm x 10cm x 20cm is frozen in -15°C temperature. The seventh sample provides 15 hours, 6 minutes and 42 seconds of cooling duration before the air temperature inside the box equalizes with air temperature outside the box. This is slightly lower than regular wood-based pykrete (20 minutes and 33 seconds lower). The seventh sample also has higher lowest temperature attainable, at 13°C, which is higher than regular wood-based pykrete by 2.5°C, although it also reached this temperature faster than regular wood-based pykrete (Reached the temperature of 13°C at 07:30AM compared to regular wood-based pykrete's 10.5°C at 08:45 AM).

If we look at the seventh sample's charts, it has a lot less fluctuations in temperature, relative, absolute and specific humidity than regular wood-based pykrete, suggesting that the addition of salt is indeed makes pykrete's cooling effect more stable, judging from the same effect observed on fifth and sixth sample.

4.2.4 Sample 8: Hybrid Paper Wood-based Pykrete (with salt)

Figure 4.17: Hybrid paper-wood-based pykrete with 1% salt, 10cm x 10cm x 20cm size

Meltdown : 13 Hours 49 Minutes 31 Seconds

Min. temperature attained (°C) : 10.1

Min. absolute humidity value (g of water vapor/ 1 m^3 of air): 5.8610

Min. specific humidity value (g of water vapor/ 1 g of air) : 0.00473

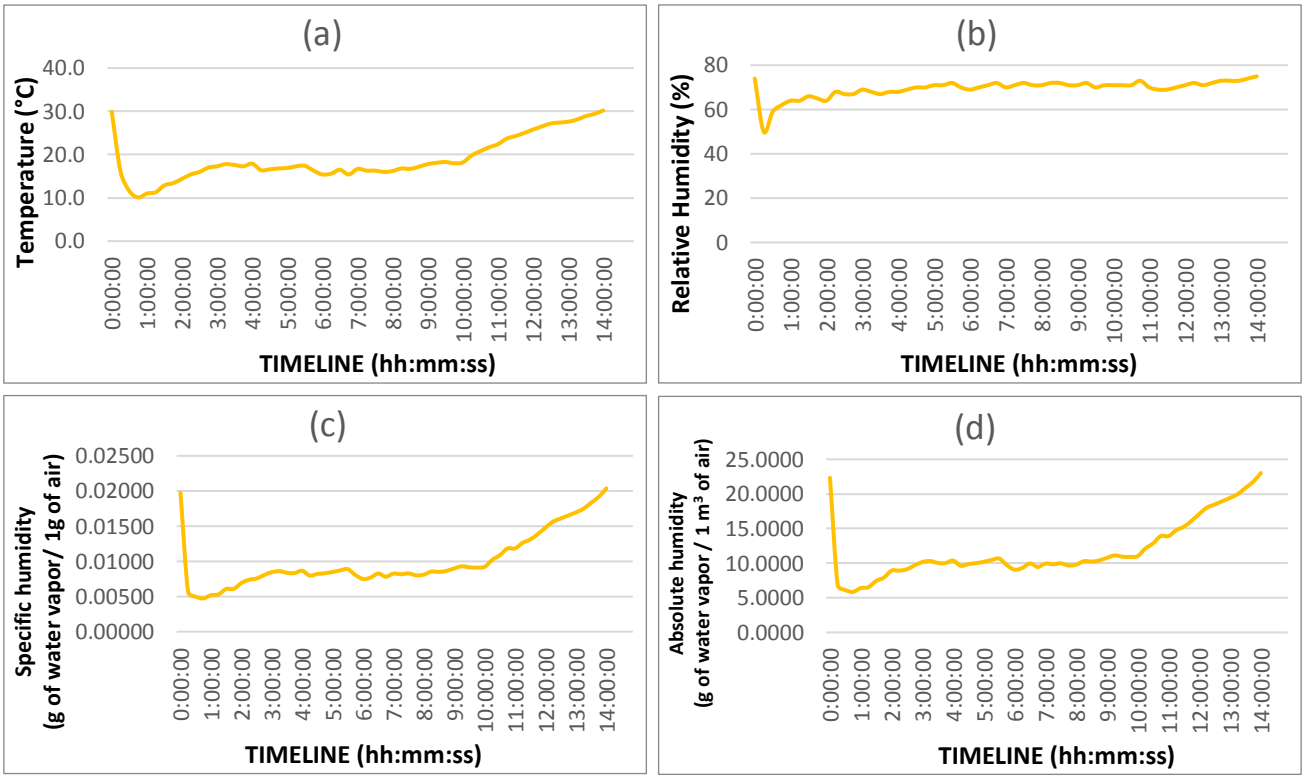


Figure 4.18: Influence of time on temperature (a), relative humidity (b), specific humidity (c) and absolute humidity (d) of salted hybrid paper-wood-based pykrete

The eighth sample is completed and tested on 23rd July 2020. It is a block of hybrid paper-wood-based pykrete with an additional content of salt (1% by volume). The sample, measuring 10cm x 10cm x 20cm is frozen in -15°C temperature. The eighth sample provides 13 hours, 49 minutes and 31 seconds of cooling duration before the air temperature inside the box equalizes with air temperature outside the box.

Compared to regular hybrid paper-wood-based pykrete, the salt infusion stabilizes the eighth sample's cooling performance, shown by the lack of fluctuation on it's temperature, relative, absolute and specific humidity charts. However, it also has lower cooling duration compared to the regular hybrid paper-wood-based pykrete (52 minutes and 43 seconds shorter) as well as higher lowest attainable temperature (1.8 °C higher). This means that the addition provides cooling stability at the cost of cooling duration and temperature. The cooling of ambient air around the eighth sample also takes effect much faster (reaching lowest temperature reading 10.1°C at 07:45 AM, compared to the regular hybrid paper-wood-based pykrete, which reached it's lowest temperature reading of 8.3°C at 08:15 AM).

4.2.5 Analysis of Second Cooling Performance Test's Physical Characteristics

The results from the line charts of the next 4 samples can be compared between each other to observe their cooling performance characteristics. In terms of cooling temperature, the results from overlaying the next 4 line charts together would result in the following line chart:

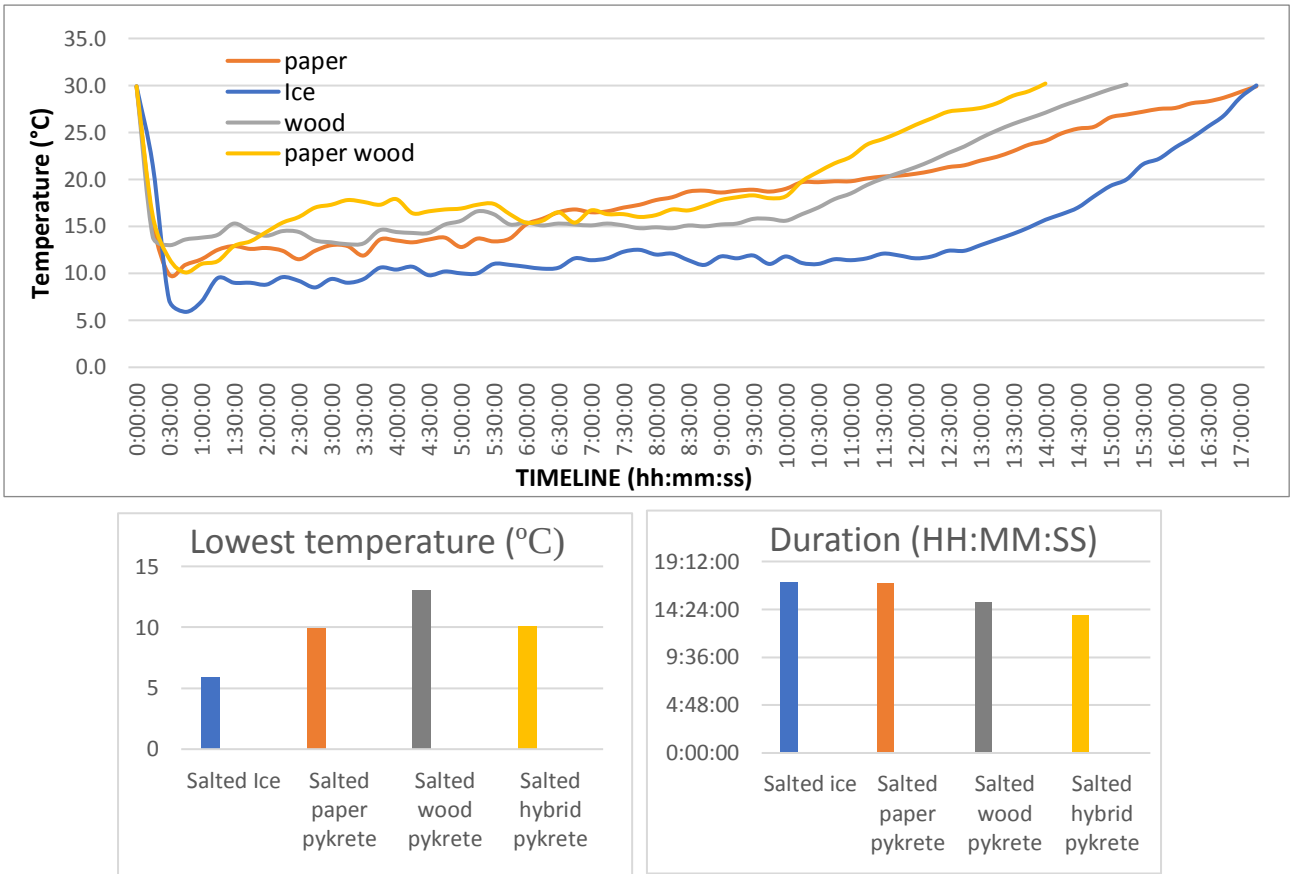


Figure 4.19: Influence of time on temperature of cooling performance test 2 samples

The addition of salt additives into the sample dramatically increases the cooling duration of regular ice to surpass most pykrete samples, except salted paper pykrete (which barely within the same level of cooling duration), while other types of salted pykrete sample seems getting worse than regular version. Compared with regular samples, the salted samples cools the surrounding air much faster, judging from how the line chart of all 4 samples reached the lowest possible temperature much earlier. The lowest temperature attainable is also far lower than regular sample. Although this came with a cost of rather unstable cooling and the longer time it takes to create the salted sample compared to regular sample (roughly double the amount of time needed to freeze it).

Observing the absolute and specific humidity of the second cooling performance test will give insight how it turns out compared to the regular version of the samples. By overlaying the absolute and specific humidity line charts from the next 4 samples together, the resulting line chart is as follows:

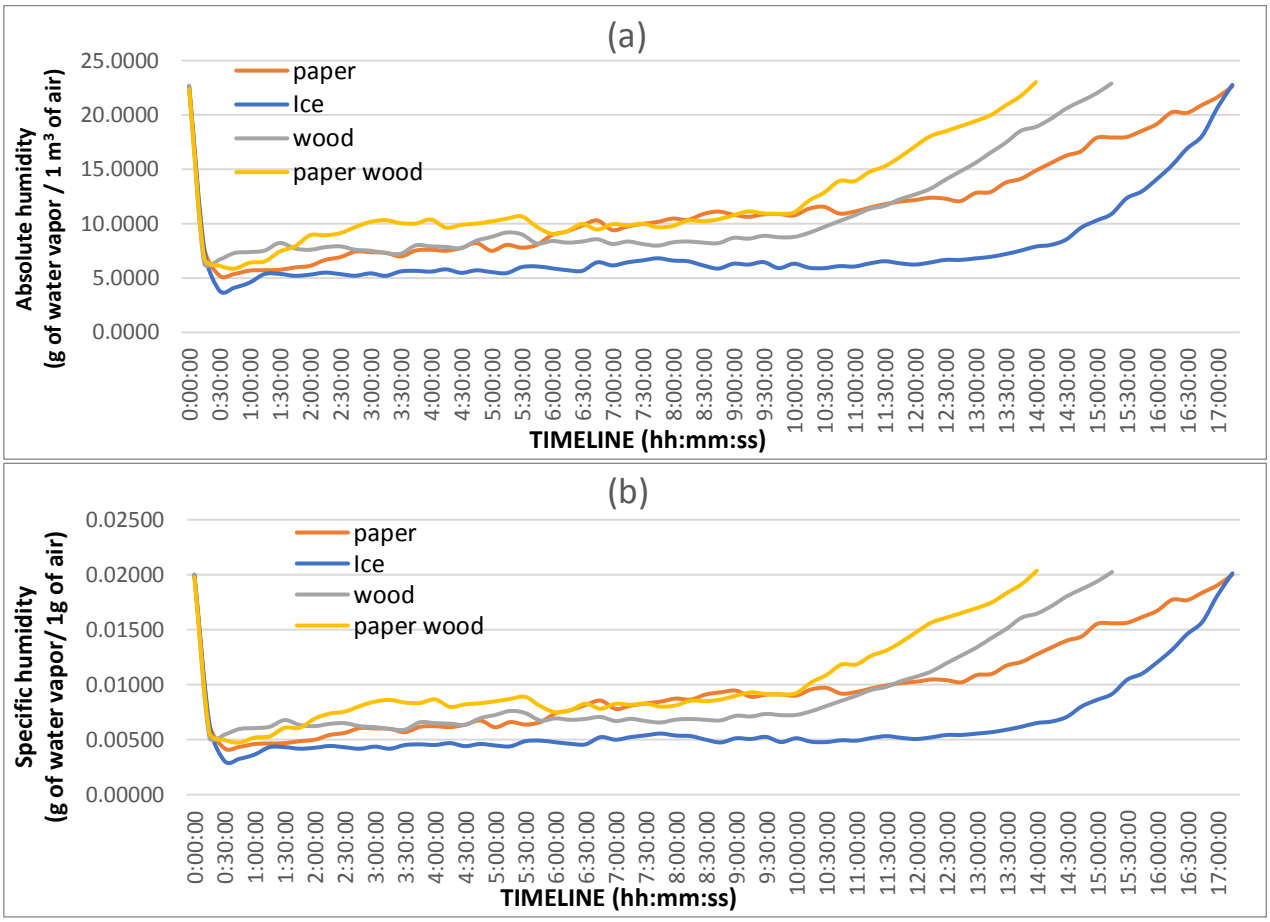


Figure 4.20: Influence of time on absolute humidity (a) and specific humidity (b) of cooling performance test 2 samples

We can see that the absolute and specific humidity charts for the salted pykrete samples are much more stable than the regular version. There are very little fluctuations that occurred pykrete samples after the addition of salt additives. This means that the amount of water vapor content on the ambient air changes very little throughout the effective cooling duration. The improved cooling stability of the salted pykrete actually puts it on par with regular ice, both regular and salted. Although this cooling stability also comes with a cost of overall lower cooling duration compared to the regular version of the sample.

Based from the results of the second cooling performance tests, it can be summarized that, the addition of salt has an effect of stabilizing the cooling effect for pykrete. By extrapolating line chart data from the next 4 samples, the results can be summarized as follows, with red highlight means the lowest and green highlight means the highest:

Table 4.2: Overall analysis of second cooling performance test

Cooling Performance Test 2 results				
Sample	Meltdown (hh/mm/ss)	Lowest temperature attained (°C)	Lowest absolute humidity value (g of water vapor / 1 m^3 of air)	Lowest specific humidity value (g of water vapor/ 1g of air)
5 (salted ice)	17:05:57	5.9	3.8460	0.00306
6 (salted paper pykrete)	17:02:11	9.9	5.2271	0.00421
7 (salted wood pykrete)	15:06:42	13.0	6.6883	0.00546
8 (salted hybrid pykrete)	13:49:31	10.1	5.8610	0.00473

The addition of salt additive has an effect of intensifying the cooling effect of the samples, allowing the ambient air temperature to reach lowest possible temperature much faster than regular version of the sample. Normally, water molecules are composed of hydrogen and water molecules and they have bonded together into ordered crystalline structure of ice. When added, salt (NaCl) dissolves into its ions in water, Na+ and Cl-. The ions diffuse throughout the water and block the water molecules from getting close enough together and in the right orientation to organize into the ordered crystalline structure. This caused the sample to take longer to freeze than it's regular version, but also intensifies the cooling effect since the sample now has the freezing point below 0 ºC, which is represented by the overall lower temperature of ambient air compared with the regular version of the samples. The addition of salt improves the cooling stability, cooling speed, and cooling temperature, at the cost of lower cooling duration and longer freezing time for the salted sample compared with regular version.

4.3 Theoretical Tensile Strength

$\triangle H_{vap}$ of ice : 3.3 MJ/Kg >>> 3.3 MJ/Kg to break all crystal nodes in a 1 Kg ice

V of 1 Kg ice : 1 m^3

Molar mass of ice : 0.018 Kg/mol

Number of crystal structure nodes in 1 Kg ice:

$$CSn = \frac{mass}{molar\ mass\ x\ Avogadro\ constant} = \frac{1}{0.018\ x\ 6.022\ x\ 10^{23}} = \mathbf{3.3\ x\ 10^{25}}\ \textbf{atom/Kg}$$

Energy required to break one ice crystal node:

$$ERn = \frac{\Delta Hvap}{CSn} = \frac{3\ x\ 10^{6}}{3.3\ x\ 10^{25}} = \mathbf{9\ x\ 10^{-20}\ J/Node}$$

Average distance of ice crystal nodes:

$$ADn = \left(\frac{V}{(mass/(molar\ mass\ x\ Avogadro\ constant)}\right)^{1/3} = \left(\frac{1}{(1000/(0.018\ x\ 6.022\ x\ 10^{23}))}\right)^{1/3} = \mathbf{3.1\ x\ 10^{-10}m}$$

Average ice crystal nodes per cross-sectional area:

$$NCs = \left(\frac{V}{(ADn)^2}\right)/5 = \left(\frac{1\ x\ 10^{-6}}{(3.1\ x\ 10^{-10})^2}\right)/5 = (1\ x\ 10^{13})/5 = \mathbf{0.2\ x\ 10^{13}}\ \textbf{nodes/ m}^2$$

Theoretical tensile strength of ice:

$$TTs = \frac{9\ x\ 10^{-20}\ x\ 0.2\ x\ 10^{13}}{3.1\ x\ 10^{-10}} = 5.8\ x\ 10^{-18}\ J/m^2 = 5.8\ x\ 10^{-18}\ N/m^2 = \mathbf{5.8\ x\ 10^{-27}\ GPa}$$

Theoretical Tensile Strength of the Samples (Adjusted for material percentage):

Tensile strength of teak wood of similar sample size : 4.1 x 10^{-4} GPa

Tensile strength of A4 paper of similar sample size : 22.8 x 10^{-3} GPa

Sample 1 (ice) **=5.8 x 10^{-27} GPa**

Sample 2 (paper pykrete) **=(**0.86 x 5.8 x 10^{-27})+ (0.14 x 22.8 x 10^{-3})

=(4.9 × 10^{-28}) + (3.19 × 10^{-3})

=**3.192 × 10^{-3} GPa**

Sample 1 (wood pykrete) **=(**0.86 x 5.8 x 10^{-27})+(0.14 x 4.1 x 10^{-4})

=(4.9 × 10^{-28}) + (5.74 × 10^{-6})

=**5.74 × 10^{-6} GPa**

Sample 1 (hybrid pykrete) **=(**0.86 x 5.8 x 10^{-27})+(0.07 x 4.1 x 10^{-4})+ (0.07 x 22.8 x 10^{-3})

=(4.9 × 10^{-28}) + (2.87 x 10^{-6}) + (1.59 x 10^{-3})

=**1.59 x 10^{-3} GPa**

As we can see in the theoretical calculation of tensile strength of the samples, the paper pykrete yields the strongest theoretical tensile strength while regular ice yields the lowest (which isn't surprising since it has no reinforce material at all). However the resulting theoretical tensile strength of the pykrete samples are greatly influenced by the tensile strength of it's reinforce material while it's ice constituents contributes extremely little with the overall theoretical tensile strength value.

The calculation of theoretical tensile strength of ice can be applied on any material as long as the H_{vap} value of the material is known. However, it should be noted that it does not factor any chemical additives for improving the mechanical characteristic of the material (which is why the next 4 samples that has salt additives added isn't calculated) as well as any material imperfections, uneven reinforce material distribution and and defect on crystal matrix. The theoretical tensile strength from this calculations is only based on the properties of molecular bonds inside the material. In practice, the actual tensile strength of the material might be higher or lower, roughly on a factor of 50% higher or lower depending on the interaction of reinforce material with the primary matrix or any defects and imperfections.

Regardless, although the theoretical tensile strength of the pykrete are heavily affected by it's reinforce material contents, in the end, the primary use for these reinforce materials is to inhibit the heat propagation inside pykrete's ice structure in order to slow down pykrete's melting rate and stopping any crack propagation inside pykrete's structure, which cannot be determined purely using mathematical calculations.

4.4 Overall Analysis and Discussion

Based from the observations from cooling performance test 1 and 2, we can conclude that pykrete is more or less equal in terms of cooling performance compared to ice. The addition of salt somewhat even out the cooling performance across all samples. Although the addition of salt on regular ice improves it's cooling to be more or less better than all pykrete samples, as a composite of ice, pykrete is still much stronger than regular ice and can resist impact shock better than regular ice. As such, for insulation and protection purpose of a portable containment, pykrete is better suited for this application. In order to provide effective protection and insulation during containment breach, there must be a way to apply pykrete's cooling ability while also make it economical to be used for this purpose. A concept of application on figure 4.9 could be used:

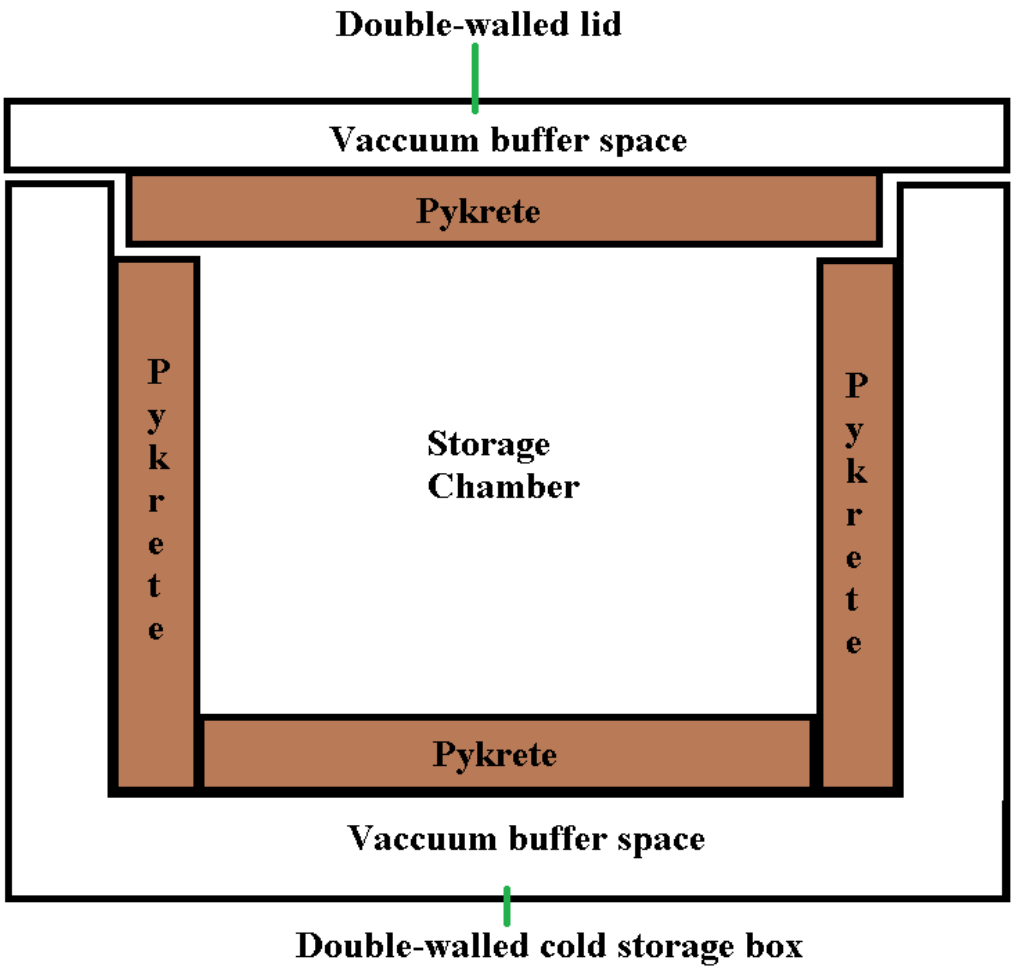


Figure 4.21: Concept for pykrete application as protective insulation material

The pykrete is placed as slabs covering the inner wall of the containment chamber. For this application and ease of placement, pykrete mixture can be packed inside plastic packs. This allows the pykrete to stay at relatively desired shape while also allows it to be refreezed again if it melts. Pykrete has minimal expansion than regular ice due to the lower water content of pykrete compared with regular ice in the same volume, so plastic works quite well to hold the pykrete mixture and freeze it to fit the inner wall of the storage box.

The double-walled storage box, with vaccuum buffer space is a standard feature of commercially available cold storage box. Mostly, these are made from hard plastic. The vaccuum inhibit the heat propagation from the outside, allowing the box to maintain the low temperature inside. However, by adding slabs of pykrete inside the box and placing it behind the inner wall, it creates a whipple shield effect. Essentially, the vaccuum buffer space between the inner wall and outer wall now serves additional purpose as spaced armor. On normal storage box, an impact that's powerful enough to break through the outer and inner wall will rapidly cause a temperature spike that quickly compromise the low temperature condition of the cold storage. In spaced armor, two armor plates of different thickness is layered on top of each other, separated by empty space, with the main purpose of minimizing the effect of impact by forcing the majority of impact force expended on thinner outer wall and the buffer space while the thicker inner wall resist the rest. In this case, the outer wall acts as the thin armor while the inner wall, supplanted by pykrete slabs acts as a thicker armor while the vaccuum buffer space acts as an empty space inbetween. Even if a penetration on outer wall causes loss of refrigeration effect of the cold storage, the pykrete itself is able to provide cooling comparable to ice for a long time.

Regarding the potential application that's suitable for pykrete, depending on the condition of operating environment, pykrete is best for self-contained cooling system that could maintain the low temperature condition by itself while requires longer duration backup cooling in case of containment breach. Potential application includes impact protection and backup cooling for cold storage designed for transplant organs, meat and fish whrere the temperature range for such application is within the range of pykrete cooling temperature observed in the cooling performance test 1 and 2, which is around 4°C-8°C, which if we factor the packaging and insulation applied on the object in question, the ambient temperature around the object should be around that range. Smaller scale application such as strengthening commercially available cold storage boxes by providing increased protection against external impact is also possible.

There are some correlations with the previous researches conducted on pykrete material, mainly with those that involves temperature of ambient air and total cooling duration. According to Tan E-Liang (2004), who studied the correlation between mass loss rate of pykrete with the exposed surface area, he concluded that there is a correlation between both aspects. In particular, if pykrete is used on area with fluctuating temperature which cycles regularly between above and below freezing point of water (there is a short but regular interval of thawing period that allows pykrete to melt), there is a positive and negative correlation.

A positive correlation is when pykrete is exposed towards ambient temperature above freezing point of water, causing it to melt, but the remaining wet shell created from leftover reinforce material on pykrete's surface is enough to protect the frozen portion of ice in the deeeper layer long enough for the ambient temperature to return below freezing point of water, causing the liquid water contained in the shell to refreeze, essentially returning pykrete to a state before the melting takes place. In this positive correlation, little to no mass loss occur as long as the outer shell formed by initial melting does not crumble too much to expose the lower layer and the damage on the outer layer caused by melting phase is counteracted by refreezing process that occur later, essentially allowing pykrete to self-repair as long as the ambient temperature does not increase too much during the melting phase, allowing the mass of refreezed pykrete stays relatively the same with little to no mass loss compared with mass before the melting process takes place. However, if the ambient temperature does increase substantially enough during the melting phase to cause part of pykrete to break off, then this is a negative correlation, meaning when pykrete finally refreezes, there's a mass loss that the total mass of refreezed pykrete is lower than the initial mass before the melting process takes place. He also concluded that the area of pykrete that's being exposed towards ambient temperature also affects how much mass loss that will occur when melting process takes place.

In the research conducted here, we can see that various reinforce material composition offers different melting rate on resulting pykrete. Ideally, for positive correlation to occur, pykrete with longest cooling duration is the best to use, which in this case is paper pykrete (In his research, Tan E-Liang used newspaper as reinforce material, so there might be a little difference in results, depending on the type of paper being used). However, the slower melting rate also means that the reinforce material itself has low heat condutivity, which, in turn also makes refreezing process slower. Thus, a positive correlation might be achieved if the ice portion that melts isn't too much to offset the slow refreezing process to replenish the outer surface during the freezing phase.

Previous research done by Alisha Vijay Supekar, Divyashree Prasad Deore and Sarthak Sharma (2016), who investigated the possible application of pykrete as thermal energy storage, using pykrete for low-cost cooling material for cooling fan that lasts longer than regular ice. By exposing the airflow from cooling fan towards a block of pykrete inside cooling chamber, a low-cost cooling system could be devised. The results from the research is quite intriguing, although pykrete is indeed have longer cooling duration than regular ice with cooling temperature comparable wih regular ice, it was also found that the speed of airflow entering the cooling chamber inlet also affects the temperature of ambient air from the outletof the cooling chamber. Ths could happen because at low airspeed, the ambient air has more time to be exposed towards pykrete, allowing it to be cooled for longer compared at higher airspeed. In theory, at low airspeed, the ambient air temperature using pykrete could be much lower compared when using regular ice, although obviously this came at a cost of lower amount of total volume of cooled air.

In the research conducted here, the salted version of pykrete could be used for a much better cooling performance. The low ambient air temperature combined with much faster cooling rate is very beneficial. In theory, this could allow a comparable cooling temperature like ambient air at low airspeed, but conducted at higher airspeed, which in turn allows a much larger volume of air being cooled. That said, the same could be said with regular pykrete, which although it has a slower cooling speed, it also has lower cooling temperature compared with salted pykrete. Essentially, when using regular pykrete, ambient air could be cooled at much lower temperature, albeit at low airspeed, while if using salted pykrete, although the cooling temperature isn't as good as regular pykrete, it also allows cooling at higher airspeed due to it's faster cooling.

CHAPTER 5
CONCLUSIONS

5.1 CONCLUSION

Based from the 1st and 2nd cooling performance test as well as the theoretical tensile strength calculation, it can be summarized that pykerete has a special properties that differentiates it from regular ice when being used as a cooling material, which could be summarized as follows:

1. Pykrete has a much better cooling duration compared to regular ice, with paper pykrete having the longest cooling duration of all samples. This is due to the bad heat conductivity of pykrete's reinforce material and the melting process that's different compared to regular ice, which, instead of melting progressively as the solid portion of the material turned into liquid, the reinforce material in pykrete's structure delays the melting process layer by layer by forming a blanket that inhibits further heat propagation, protecting the layer beneath it before crumbling away.
2. Generally, pykrete also have lower cooling temperature compared to regular ice. With hybrid pykrete providing the best cooling temperature, although it has the lowest cooling duration of all pykrete samples. The generally low temperature provided by pykrete, combined with it's long cooling duration makes it better for keeping the temperature low in case of containment breach in cold storage application.
3. Unlike regular ice, which has a noticeable flat line area on the cooling performance chart upon hitting the lowest attainable cooling temperature where the cooling is near-constant before suddenly there's a temperature spike as it's near the end of it's cooling duration, pykrete behaves differently, where upon reaching the lowest attainable cooling temperature, it steadily rises continuously until it hits the room temperature.
4. Pykrete's cooling performance is less stable than regular ice, judging from numerous fluctuations on cooling performance chart (Temperature, relative, specific and absolute humidity) compared to smooth line on regular ice's cooling performance chart. Despite being unstable, the effect is small enough that it doesn't have any substantial effect that would directly impact the cooling process provided by pykrete.

5. The addition of salt additive on pykrete samples stabilizes the cooling process, lessening the fluctuations on the cooling performance chart, however, it causes an unpredictable changes on cooling duration, either making the overall performance better or worse. Though on the other hand, it also equalizes the overall performance of all samples.
6. The theoretical tensile strength of pykrete are highly dependent on it's reinforce material constituent. The ice portion of the pykrete contributes very little to pykrete's overall theoretical tensile strength. Out of all 3 reinforcement variables, the paper pykrete boasts the highest theoretical tensile strength.

For further research, it is advisable to add another variable of reinforcement material's size (either the paper fibers or wood particles) to observe it's effect on the cooling performance. Some other fields that's worthy to be researched is the material properties of different types of pykrete as it's relatively unexplored and may yield an interesting results that can be applied on application in low-temperature environments.

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ATTACHMENTS

REGULAR ICE

Time	Temperature inside the box (°C)	Relative humidity inside the box (%)	Temperature outside the box (°C)	Relative humidity outside the box (%)	Saturation pressure of water vapor (mmHg)	Partial pressure of water vapor (mmHg)	Specific humidity (g of water/ 1g of air)	Absolute humidity (g of water/ 1 m3 of air)
0:00:00	29.9	75	29.9	75	31.642	23.7315	0.02001	22.6425
0:15:00	19.2	60	29.9	76	16.685	10.0110	0.00829	9.8910
0:30:00	16.1	55	29.7	74	13.721	7.5466	0.00623	7.5360
0:45:00	13.9	53	30.6	76	11.910	6.3123	0.00520	6.3511
1:00:00	12.6	52	30.3	75	10.941	5.6893	0.00468	5.7504
1:15:00	11.9	56	30.3	77	10.449	5.8514	0.00482	5.9285
1:30:00	11.8	59	30.4	78	10.380	6.1242	0.00504	6.2072
1:45:00	11.5	59	30.4	77	10.176	6.0038	0.00494	6.0918
2:00:00	11.4	60	30.5	78	10.109	6.0654	0.00499	6.1563
2:15:00	11.8	60	30.6	79	10.380	6.2280	0.00513	6.3124
2:30:00	11.6	61	30.6	80	10.224	6.2366	0.00514	6.3379
2:45:00	11.6	61	30.8	80	10.224	6.2366	0.00514	6.3379
3:00:00	11.4	62	30.9	79	10.109	6.2676	0.00516	6.3615
3:15:00	11.2	62	31.1	78	9.976	6.1851	0.00509	6.2822
3:30:00	11.0	63	31.1	79	9.844	6.2017	0.00511	6.3038
3:45:00	10.9	60	31.1	79	9.779	5.8674	0.00483	5.9659
4:00:00	10.7	60	31.3	77	9.649	5.7894	0.00476	5.8912
4:15:00	10.6	60	31.4	79	9.585	5.7510	0.00473	5.8542
4:30:00	10.7	59	31.5	77	9.649	5.6929	0.00468	5.7930
4:45:00	10.7	57	31.6	76	9.649	5.4999	0.00452	5.5966
5:00:00	11.1	56	31.7	75	9.910	5.5496	0.00457	5.6387
5:15:00	11.7	56	31.7	75	10.312	5.7747	0.00475	5.8549
5:30:00	12.1	58	31.9	75	10.588	6.1410	0.00506	6.2174
5:45:00	12.4	59	31.9	76	10.799	6.3714	0.00525	6.4439
6:00:00	12.3	54	31.9	77	10.728	5.7931	0.00477	5.8612
6:15:00	12.3	56	32.0	75	10.728	6.0077	0.00495	6.0783
6:30:00	12.5	56	32.1	75	10.870	6.0872	0.00501	6.1544
6:45:00	12.3	58	32.3	76	10.728	6.2222	0.00512	6.2953
7:00:00	12.0	56	32.2	75	10.518	5.8901	0.00485	5.9657
7:15:00	12.4	58	32.2	74	10.799	6.2634	0.00516	6.3346
7:30:00	12.1	58	32.0	75	10.588	6.1410	0.00506	6.2174
7:45:00	12.1	59	32.3	77	10.588	6.2469	0.00514	6.3246
8:00:00	12.3	58	32.2	76	10.728	6.2222	0.00512	6.2953
8:15:00	12.2	57	32.2	75	10.658	6.0751	0.00500	6.1484
8:30:00	12.0	61	32.3	75	10.518	6.4160	0.00528	6.4983
8:45:00	12.2	62	32.3	74	10.658	6.6080	0.00544	6.6877
9:00:00	12.3	58	32.1	73	10.728	6.2222	0.00512	6.2953
9:15:00	11.8	59	31.9	75	10.380	6.1242	0.00504	6.2072
9:30:00	11.7	59	31.9	77	10.312	6.0841	0.00501	6.1685
9:45:00	11.9	61	30.8	78	10.449	6.3739	0.00525	6.4579
10:00:00	11.9	63	30.7	73	10.449	6.5829	0.00542	6.6696
10:15:00	12.2	63	30.6	73	10.658	6.7145	0.00553	6.7956
10:30:00	12.3	64	30.7	72	10.728	6.8659	0.00566	6.9466
10:45:00	12.5	65	30.6	73	10.870	7.0655	0.00582	7.1434
11:00:00	12.7	67	30.5	73	11.013	7.3787	0.00609	7.4553
11:15:00	13.4	68	31.0	72	11.528	7.8390	0.00647	7.9015
11:30:00	15.2	69	30.3	73	12.953	8.9376	0.00739	8.9524
11:45:00	17.8	69	30.1	73	15.284	10.5460	0.00873	10.4692
12:00:00	19.2	70	30.8	72	16.685	11.6795	0.00969	11.5395
12:15:00	21.9	70	30.2	72	19.707	13.7949	0.01147	13.5070
12:30:00	23.1	71	30.6	73	21.196	15.0492	0.01254	14.6773
12:45:00	25.5	71	30.7	72	24.471	17.3744	0.01452	16.8143
13:00:00	27.6	71	31.4	73	27.696	19.6642	0.01649	18.8992
13:15:00	28.3	72	31.2	73	28.847	20.7698	0.01744	19.9187
13:15:54	31.2	73	31.2	73	34.082	24.8799	0.02101	23.6413

PAPER PYKRETE

Time	Temperature inside the box (°C)	Relative humidity inside the box (%)	Temperature outside the box (°C)	Relative humidity outside the box (%)	Saturation pressure of water vapor (mmHg)	Partial pressure of water vapor (mmHg)	Specific humidity (g of water/ 1g of air)	Absolute humidity (g of water/ 1 m3 of air)
0:00:00	29.9	75	29.9	75	31.642	23.7315	0.02001	22.6425
0:15:00	25.3	67	29.9	74	24.182	16.2019	0.01352	15.6898
0:30:00	20.0	55	29.7	75	17.535	9.6443	0.00798	9.5030
0:45:00	11.0	53	30.2	76	9.844	5.2173	0.00429	5.3032
1:00:00	9.7	51	30.3	75	9.025	4.6028	0.00378	4.7003
1:15:00	9.7	51	30.3	77	9.025	4.6028	0.00378	4.7003
1:30:00	10.3	52	30.4	78	9.395	4.8854	0.00402	4.9783
1:45:00	10.7	51	30.4	77	9.649	4.9210	0.00405	5.0075
2:00:00	11.0	52	30.5	79	9.844	5.1189	0.00421	5.2031
2:15:00	10.6	53	30.6	78	9.585	5.0801	0.00418	5.1712
2:30:00	10.3	52	30.6	79	9.395	4.8854	0.00402	4.9783
2:45:00	10.2	53	30.8	79	9.333	4.9465	0.00407	5.0421
3:00:00	9.9	55	30.9	79	9.147	5.0309	0.00414	5.1337
3:15:00	10.2	53	31.1	79	9.333	4.9465	0.00407	5.0421
3:30:00	10.9	53	31.1	77	9.779	5.1829	0.00426	5.2699
3:45:00	11.1	54	31.1	78	9.910	5.3514	0.00440	5.4373
4:00:00	10.9	53	31.3	79	9.779	5.1829	0.00426	5.2699
4:15:00	11.8	52	31.4	79	10.380	5.3976	0.00444	5.4708
4:30:00	12.5	52	31.5	78	10.870	5.6524	0.00465	5.7148
4:45:00	12.7	53	31.6	78	11.013	5.8369	0.00480	5.8975
5:00:00	13.3	55	31.7	79	11.453	6.2992	0.00519	6.3516
5:15:00	15.5	56	31.7	80	13.205	7.3948	0.00610	7.3993
5:30:00	14.8	57	31.9	79	12.624	7.1957	0.00593	7.2174
5:45:00	14.4	60	31.9	81	12.302	7.3812	0.00609	7.4138
6:00:00	13.6	62	31.9	80	11.680	7.2416	0.00597	7.2937
6:15:00	13.3	63	32.0	80	11.453	7.2154	0.00595	7.2754
6:30:00	13.1	64	32.0	79	11.305	7.2352	0.00597	7.3001
6:45:00	13.1	64	31.2	78	11.305	7.2352	0.00597	7.3001
7:00:00	13.9	64	31.0	79	11.910	7.6224	0.00629	7.6692
7:15:00	14.0	64	31.1	79	11.987	7.6717	0.00633	7.7165
7:30:00	13.3	64	31.3	78	11.453	7.3299	0.00604	7.3909
7:45:00	13.9	63	31.2	77	11.910	7.5033	0.00619	7.5494
8:00:00	13.0	64	31.2	80	11.231	7.1878	0.00593	7.2551
8:15:00	13.3	64	31.2	80	11.453	7.3299	0.00604	7.3909
8:30:00	13.6	64	30.9	79	11.680	7.4752	0.00617	7.5290
8:45:00	14.4	67	31.1	78	12.302	8.2423	0.00681	8.2788
9:00:00	14.5	67	30.7	78	12.382	8.2959	0.00685	8.3296
9:15:00	14.9	68	30.8	79	12.706	8.6401	0.00714	8.6629
9:30:00	15.1	68	30.9	78	12.870	8.7516	0.00723	8.7691
9:45:00	15.5	68	31.0	77	13.205	8.9794	0.00742	8.9849
10:00:00	15.7	68	31.4	78	13.375	9.0950	0.00752	9.0945
10:15:00	16.4	69	31.3	79	13.987	9.6510	0.00798	9.6269
10:30:00	16.5	69	30.9	79	14.076	9.7124	0.00803	9.6850
10:45:00	16.6	70	31.3	78	14.166	9.9162	0.00821	9.8847
11:00:00	16.6	70	30.9	77	14.166	9.9162	0.00821	9.8847
11:15:00	16.9	71	30.5	79	14.438	10.2510	0.00849	10.2082
11:30:00	17.1	71	30.1	77	14.622	10.3816	0.00860	10.3314
11:45:00	17.5	70	30.3	79	14.997	10.4979	0.00869	10.4325
12:00:00	17.6	71	30.2	78	15.092	10.7153	0.00888	10.6449
12:15:00	17.9	70	30.5	77	15.380	10.7660	0.00892	10.6843
12:30:00	18.8	70	29.9	79	16.272	11.3904	0.00944	11.2703
12:45:00	19.9	70	29.8	78	17.427	12.1989	0.01013	12.0241
13:00:00	20.6	71	29.8	77	18.197	12.9199	0.01073	12.7051
13:15:00	21.2	72	30.1	79	18.880	13.5936	0.01130	13.3415
13:30:00	21.9	71	30.1	78	19.707	13.9920	0.01164	13.6999
13:45:00	22.7	72	30.4	78	20.690	14.8968	0.01241	14.5471
14:00:00	23.8	72	30.2	79	22.110	15.9192	0.01328	15.4900
14:15:00	24.3	72	30.1	78	22.785	16.4052	0.01369	15.9358
14:30:00	24.9	71	30.0	77	23.616	16.7674	0.01400	16.2563
14:45:00	25.4	72	29.9	75	24.326	17.5147	0.01464	16.9556
15:00:00	25.9	72	29.7	77	25.060	18.0432	0.01509	17.4375
15:15:00	26.4	73	30.1	78	25.812	18.8428	0.01578	18.1802
15:30:00	27.1	73	30.3	77	26.897	19.6348	0.01646	18.9014
15:45:00	27.8	73	29.9	76	28.021	20.4553	0.01717	19.6472
16:00:00	28.2	73	30.2	76	28.680	20.9364	0.01758	20.0846
16:15:00	28.7	74	29.9	76	29.525	21.8485	0.01837	20.9260
16:30:00	29.4	74	29.9	77	30.745	22.7513	0.01915	21.7415
16:42:35	29.9	75	29.9	75	31.642	23.7315	0.02001	22.6425

WOOD PYKRETE

Time	Temperature inside the box (°C)	Relative humidity inside the box (%)	Temperature outside the box (°C)	Relative humidity outside the box (%)	Saturation pressure of water vapor (mmHg)	Partial pressure of water vapor (mmHg)	Specific humidity (g of water/ 1g of air)	Absolute humidity (g of water/ 1 m3 of air)
0:00:00	29.9	75	29.9	75	31.642	23.7315	0.02001	22.6425
0:15:00	22.6	67	29.9	74	20.565	13.7786	0.01146	13.4595
0:30:00	15.0	56	29.7	75	12.788	7.1613	0.00590	7.1778
0:45:00	13.0	54	30.2	76	11.231	6.0647	0.00499	6.1215
1:00:00	12.5	54	30.3	75	10.870	5.8698	0.00483	5.9346
1:15:00	12.0	54	30.3	77	10.518	5.6797	0.00467	5.7526
1:30:00	11.1	55	30.4	78	9.910	5.4505	0.00448	5.5380
1:45:00	10.5	56	30.4	77	9.521	5.3318	0.00439	5.4295
2:00:00	10.7	55	30.5	79	9.649	5.3070	0.00436	5.4003
2:15:00	11.0	53	30.6	78	9.844	5.2173	0.00429	5.3032
2:30:00	12.0	56	30.6	79	10.518	5.8901	0.00485	5.9657
2:45:00	12.1	59	30.8	79	10.588	6.2469	0.00514	6.3246
3:00:00	12.7	57	30.9	79	11.013	6.2774	0.00517	6.3425
3:15:00	12.1	59	31.1	79	10.588	6.2469	0.00514	6.3246
3:30:00	12.4	59	31.1	77	10.799	6.3714	0.00525	6.4439
3:45:00	12.5	57	31.1	78	10.870	6.1959	0.00510	6.2643
4:00:00	12.1	55	31.3	79	10.588	5.8234	0.00479	5.8958
4:15:00	12.9	58	31.4	79	11.158	6.4716	0.00533	6.5343
4:30:00	14.5	58	31.5	78	12.382	7.1816	0.00592	7.2107
4:45:00	15.0	59	31.6	78	12.788	7.5449	0.00622	7.5623
5:00:00	15.1	61	31.7	79	12.870	7.8507	0.00648	7.8664
5:15:00	15.2	62	31.7	80	12.953	8.0309	0.00663	8.0442
5:30:00	15.2	64	31.9	79	12.953	8.2899	0.00685	8.3037
5:45:00	16.5	66	31.9	81	14.076	9.2902	0.00768	9.2639
6:00:00	16.5	68	31.9	80	14.076	9.5717	0.00792	9.5447
6:15:00	17.3	67	32.0	80	14.809	9.9220	0.00821	9.8668
6:30:00	16.9	66	32.0	79	14.438	9.5291	0.00788	9.4893
6:45:00	17.1	67	31.2	78	14.622	9.7967	0.00811	9.7493
7:00:00	17.4	68	31.0	79	14.903	10.1340	0.00839	10.0741
7:15:00	16.6	63	31.1	79	14.166	8.9246	0.00738	8.8962
7:30:00	16.6	64	31.3	78	14.166	9.0662	0.00749	9.0374
7:45:00	15.9	66	31.2	77	13.547	8.9410	0.00739	8.9345
8:00:00	15.5	68	31.2	80	13.205	8.9794	0.00742	8.9849
8:15:00	15.7	66	31.2	80	13.375	8.8275	0.00729	8.8270
8:30:00	15.1	65	30.9	78	12.870	8.3655	0.00691	8.3823
8:45:00	16.7	66	31.1	77	14.256	9.4090	0.00778	9.3761
9:00:00	16.8	65	30.7	79	14.347	9.3256	0.00771	9.2896
9:15:00	16.8	65	30.8	76	14.347	9.3256	0.00771	9.2896
9:30:00	16.7	66	30.9	77	14.256	9.4090	0.00778	9.3761
9:45:00	16.7	65	31.0	79	14.256	9.2664	0.00766	9.2340
10:00:00	16.6	65	31.4	80	14.166	9.2079	0.00761	9.1786
10:15:00	16.8	67	31.3	79	14.347	9.6125	0.00795	9.5755
10:30:00	17.5	69	30.9	77	14.997	10.3479	0.00857	10.2835
10:45:00	18.1	70	31.3	76	15.575	10.9025	0.00903	10.8122
11:00:00	18.6	70	30.9	77	16.771	11.7397	0.00974	11.1377
11:15:00	19.3	69	30.5	78	16.789	11.5844	0.00961	11.4419
11:30:00	21.0	73	30.1	78	18.650	13.6145	0.01132	13.3707
11:45:00	21.5	73	30.3	79	19.231	14.0386	0.01168	13.7640
12:00:00	22.1	73	30.2	78	19.948	14.5620	0.01213	14.2492
12:15:00	22.9	74	30.5	80	20.941	15.4963	0.01292	15.1235
12:30:00	23.6	73	29.9	78	21.845	15.9469	0.01330	15.5275
12:45:00	24.0	75	29.8	79	22.377	16.7828	0.01402	16.3198
13:00:00	24.4	75	29.8	77	22.922	17.1915	0.01437	16.6940
13:15:00	25.1	75	30.1	77	23.897	17.9228	0.01499	17.3667
13:30:00	25.5	74	30.1	79	24.471	18.1085	0.01515	17.5247
13:45:00	25.7	75	30.4	79	24.764	18.5730	0.01555	17.9618
14:00:00	26.2	75	30.2	80	25.509	19.1318	0.01603	18.4711
14:15:00	27.0	76	30.1	78	26.739	20.3216	0.01705	19.5694
14:30:00	27.6	76	30.0	78	27.696	21.0490	0.01768	20.2301
14:45:00	28.1	75	29.9	79	28.514	21.3855	0.01797	20.5218
15:00:00	28.7	76	29.7	78	29.525	22.4390	0.01888	21.4916
15:15:00	29.4	77	30.1	79	30.745	23.6737	0.01996	22.6229
15:27:15	30.3	79	30.3	79	32.376	25.5770	0.02162	24.3726

HYBRID PYKRETE

Time	Temperature inside the box (°C)	Relative humidity inside the box (%)	Temperature outside the box (°C)	Relative humidity outside the box (%)	Saturation pressure of water vapor (mmHg)	Partial pressure of water vapor (mmHg)	Specific humidity (g of water/ 1g of air)	Absolute humidity (g of water/ 1 m3 of air)
0:00:00	29.9	74	29.9	75	31.642	23.4151	0.01973	22.3406
0:15:00	16.1	63	29.9	74	13.721	8.6442	0.00714	8.6321
0:30:00	11.5	57	29.8	75	10.176	5.8003	0.00477	5.8853
0:45:00	8.9	55	30.2	76	8.551	4.7031	0.00386	4.8168
1:00:00	8.6	54	30.3	75	8.380	4.5252	0.00372	4.6391
1:15:00	8.3	53	30.2	77	8.211	4.3518	0.00357	4.4663
1:30:00	8.3	53	30.4	77	8.211	4.3518	0.00357	4.4663
1:45:00	8.4	52	30.4	77	8.267	4.2988	0.00353	4.4103
2:00:00	9.4	52	30.4	79	8.845	4.5994	0.00378	4.7018
2:15:00	9.9	51	30.6	78	9.147	4.6650	0.00383	4.7604
2:30:00	10.1	51	30.5	80	9.271	4.7282	0.00389	4.8211
2:45:00	10.5	52	30.8	79	9.521	4.9509	0.00407	5.0417
3:00:00	11.8	52	30.9	79	10.380	5.3976	0.00444	5.4708
3:15:00	11.3	55	30.8	79	10.042	5.5231	0.00454	5.6080
3:30:00	12.5	60	31.1	77	10.870	6.5220	0.00537	6.5940
3:45:00	12.9	63	30.0	78	11.158	7.0295	0.00579	7.0976
4:00:00	12.6	64	31.3	79	10.941	7.0022	0.00577	7.0774
4:15:00	12.6	65	30.0	79	10.941	7.1117	0.00586	7.1880
4:30:00	12.3	65	31.5	78	10.728	6.9732	0.00575	7.0551
4:45:00	12.0	64	31.6	78	10.518	6.7315	0.00555	6.8179
5:00:00	13.7	67	31.7	79	11.756	7.8765	0.00650	7.9306
5:15:00	13.2	63	31.7	80	11.379	7.1688	0.00591	7.2306
5:30:00	13.1	64	31.9	79	11.305	7.2352	0.00597	7.3001
5:45:00	14.3	62	31.5	81	12.223	7.5783	0.00625	7.6142
6:00:00	14.6	62	31.6	80	12.462	7.7264	0.00637	7.7552
6:15:00	14.3	63	31.2	81	12.223	7.7005	0.00635	7.7370
6:30:00	14.3	64	32.0	79	12.223	7.8227	0.00646	7.8598
6:45:00	13.7	64	31.2	78	11.756	7.5238	0.00621	7.5755
7:00:00	14.5	65	31.0	79	12.382	8.0483	0.00664	8.0809
7:15:00	15.8	67	31.1	79	13.461	9.0189	0.00745	9.0152
7:30:00	15.8	69	31.3	78	13.461	9.2881	0.00768	9.2843
7:45:00	16.0	68	31.2	77	13.634	9.2711	0.00767	9.2611
8:00:00	16.0	69	31.2	81	13.634	9.4075	0.00778	9.3973
8:15:00	16.4	68	31.2	80	13.987	9.5112	0.00787	9.4874
8:30:00	16.3	68	30.9	79	13.898	9.4506	0.00782	9.4304
8:45:00	16.1	68	31.1	78	13.721	9.3303	0.00771	9.3172
9:00:00	15.3	66	30.7	78	13.037	8.6044	0.00711	8.6154
9:15:00	15.5	67	30.8	78	13.205	8.8474	0.00731	8.8528
9:30:00	15.5	67	30.9	78	13.205	8.8474	0.00731	8.8528
9:45:00	15.7	67	31.0	77	13.375	8.9613	0.00741	8.9608
10:00:00	16.1	68	31.4	78	13.721	9.3303	0.00771	9.3172
10:15:00	16.2	68	31.3	79	13.809	9.3901	0.00776	9.3736
10:30:00	16.1	69	30.9	79	13.721	9.4675	0.00783	9.4542
10:45:00	16.3	69	31.3	78	13.898	9.5896	0.00793	9.5690
11:00:00	15.9	70	30.9	77	13.547	9.4829	0.00784	9.4760
11:15:00	15.8	70	30.5	79	13.461	9.4227	0.00779	9.4189
11:30:00	15.7	70	30.1	77	13.375	9.3625	0.00774	9.3620
11:45:00	15.6	70	30.3	79	13.290	9.3030	0.00769	9.3054
12:00:00	16.7	70	30.2	78	14.256	9.9792	0.00826	9.9443
12:15:00	17.3	70	30.5	77	14.809	10.3663	0.00858	10.3086
12:30:00	17.9	69	29.9	79	15.380	10.6122	0.00879	10.5317
12:45:00	18.4	70	29.8	78	15.871	11.1097	0.00921	11.0065
13:00:00	20.1	69	29.8	77	17.644	12.1744	0.01010	11.9919
13:15:00	22.1	70	30.1	79	19.948	13.9636	0.01162	13.6636
13:30:00	23.7	72	30.1	78	21.977	15.8234	0.01320	15.4022
13:45:00	25.7	71	30.4	78	24.764	17.5824	0.01470	17.0039
14:00:00	26.4	72	30.2	79	25.812	18.5846	0.01556	17.9312
14:15:00	27.4	73	30.1	78	27.374	19.9830	0.01676	19.2180
14:30:00	28.7	73	30.0	77	29.525	21.5533	0.01812	20.6432
14:42:14	30.0	75	30.0	75	31.824	23.8680	0.02012	22.7656

SALTED REGULAR ICE

Time	Temperature inside the box (°C)	Relative humidity inside the box (%)	Temperature outside the box (°C)	Relative humidity outside the box (%)	Saturation pressure of water vapor (mmHg)	Partial pressure of water vapor (mmHg)	Specific humidity (g of water/ 1g of air)	Absolute humidity (g of water/ 1 m3 of air)
0:00:00	29.9	75	29.9	75	31.642	23.7315	0.02001	22.6425
0:15:00	21.5	40	29.9	76	19.231	7.6924	0.00635	7.5419
0:30:00	7.2	49	29.7	74	7.617	3.7323	0.00306	3.8460
0:45:00	5.9	57	30.6	76	6.965	3.9701	0.00326	4.1101
1:00:00	7.0	59	30.3	75	7.513	4.4327	0.00364	4.5712
1:15:00	9.5	59	30.3	77	8.905	5.2540	0.00432	5.3688
1:30:00	9.0	61	30.4	78	8.609	5.2515	0.00432	5.3765
1:45:00	9.0	59	30.4	77	8.609	5.0793	0.00418	5.2002
2:00:00	8.8	61	30.5	78	8.494	5.1813	0.00426	5.3081
2:15:00	9.6	60	30.6	79	8.965	5.3790	0.00442	5.4947
2:30:00	9.2	60	30.6	80	8.727	5.2362	0.00431	5.3564
2:45:00	8.5	61	30.8	80	8.323	5.0770	0.00417	5.2070
3:00:00	9.4	60	30.9	79	8.845	5.3070	0.00436	5.4251
3:15:00	9.0	59	31.1	78	8.609	5.0793	0.00418	5.2002
3:30:00	9.4	62	31.1	79	8.845	5.4839	0.00451	5.6060
3:45:00	10.6	58	31.1	79	9.585	5.5593	0.00457	5.6590
4:00:00	10.4	58	31.3	77	9.458	5.4856	0.00451	5.5880
4:15:00	10.7	59	31.4	79	9.649	5.6929	0.00468	5.7930
4:30:00	9.8	59	31.5	77	9.086	5.3607	0.00441	5.4722
4:45:00	10.2	60	31.6	76	9.333	5.5998	0.00461	5.7080
5:00:00	10.0	59	31.7	75	9.209	5.4333	0.00447	5.5422
5:15:00	10.0	58	31.7	75	9.209	5.3412	0.00439	5.4482
5:30:00	11.0	60	31.9	75	9.844	5.9064	0.00486	6.0036
5:45:00	10.9	61	31.9	76	9.779	5.9652	0.00491	6.0654
6:00:00	10.7	60	31.9	77	9.649	5.7894	0.00476	5.8912
6:15:00	10.5	59	32.0	75	9.521	5.6174	0.00462	5.7204
6:30:00	10.6	58	32.1	75	9.585	5.5593	0.00457	5.6590
6:45:00	11.6	62	32.3	76	10.244	6.3513	0.00523	6.4418
7:00:00	11.4	60	32.2	75	10.109	6.0654	0.00499	6.1563
7:15:00	11.6	62	32.2	74	10.244	6.3513	0.00523	6.4418
7:30:00	12.3	61	32.0	75	10.728	6.5441	0.00539	6.6210
7:45:00	12.5	62	32.3	77	10.870	6.7394	0.00555	6.8137
8:00:00	12.0	62	32.2	76	10.518	6.5212	0.00537	6.6048
8:15:00	12.1	61	32.2	75	10.588	6.4587	0.00532	6.5390
8:30:00	11.4	60	32.3	75	10.109	6.0654	0.00499	6.1563
8:45:00	10.9	59	32.3	74	9.779	5.7696	0.00475	5.8665
9:00:00	11.8	60	32.1	73	10.380	6.2280	0.00513	6.3124
9:15:00	11.6	60	31.9	75	10.244	6.1464	0.00506	6.2340
9:30:00	11.9	61	31.9	77	10.449	6.3739	0.00525	6.4579
9:45:00	11.0	59	30.8	78	9.844	5.8080	0.00478	5.9035
10:00:00	11.8	60	30.7	73	10.380	6.2280	0.00513	6.3124
10:15:00	11.1	59	30.6	73	9.910	5.8469	0.00481	5.9408
10:30:00	11.0	59	30.7	72	9.844	5.8080	0.00478	5.9035
10:45:00	11.5	59	30.6	73	10.176	6.0038	0.00494	6.0918
11:00:00	11.4	59	30.5	73	10.109	5.9643	0.00491	6.0537
11:15:00	11.6	61	31.0	72	10.244	6.2488	0.00515	6.3379
11:30:00	12.1	61	30.3	73	10.588	6.4587	0.00532	6.5390
11:45:00	11.9	60	30.1	73	10.449	6.2694	0.00516	6.3520
12:00:00	11.6	60	30.8	72	10.244	6.1464	0.00506	6.2340
12:15:00	11.8	61	30.2	72	10.380	6.3318	0.00521	6.4177
12:30:00	12.4	61	30.6	73	10.799	6.5874	0.00543	6.6623
12:45:00	12.4	61	30.7	72	10.799	6.5874	0.00543	6.6623
13:00:00	13.0	60	31.4	73	11.231	6.7386	0.00555	6.8017
13:15:00	13.6	59	31.2	73	11.680	6.8912	0.00568	6.9408
13:30:00	14.2	59	31.2	73	12.144	7.1650	0.00591	7.2015
13:45:00	14.9	59	30.6	72	12.706	7.4965	0.00618	7.5164
14:00:00	15.7	59	30.5	72	13.375	7.8913	0.00651	7.8908
14:15:00	16.3	58	31.0	73	13.898	8.0608	0.00665	8.0435
14:30:00	17.0	59	30.3	72	14.530	8.5727	0.00708	8.5339
14:45:00	18.2	62	30.1	73	15.673	9.7173	0.00804	9.6336
15:00:00	19.3	62	30.8	73	16.789	10.4092	0.00862	10.2811
15:15:00	20.0	63	30.2	73	17.535	11.0471	0.00916	10.8853
15:30:00	21.6	65	30.6	73	19.349	12.5769	0.01044	12.3267
15:45:00	22.2	66	30.7	72	20.070	13.2462	0.01101	12.9572
16:00:00	23.4	67	31.4	72	21.583	14.4606	0.01204	14.0897
16:15:00	24.4	69	31.2	73	22.922	15.8162	0.01319	15.3585
16:30:00	25.6	71	31.2	73	24.617	17.4781	0.01461	16.9088
16:45:00	26.8	71	30.6	73	26.426	18.7625	0.01571	18.0801
17:00:00	28.7	73	30.5	72	29.525	21.5533	0.01812	20.6432
17:05:57	30.0	75	29.9	75	31.824	23.8680	0.02012	22.7656

SALTED PAPER PYKRETE

Time	Temperature inside the box (°C)	Relative humidity inside the box (%)	Temperature outside the box (°C)	Relative humidity outside the box (%)	Saturation pressure of water vapor (mmHg)	Partial pressure of water vapor (mmHg)	Specific humidity (g of water/ 1g of air)	Absolute humidity (g of water/ 1 m3 of air)
0:00:00	29.9	75	29.9	75	31.642	23.7315	0.02001	22.6425
0:15:00	15.5	59	29.9	74	13.205	7.7910	0.00643	7.7957
0:30:00	9.9	56	29.7	75	9.147	5.1223	0.00421	5.2271
0:45:00	10.9	54	30.2	76	9.779	5.2807	0.00434	5.3693
1:00:00	11.5	55	30.3	75	10.176	5.5968	0.00460	5.6788
1:15:00	12.5	52	30.3	77	10.870	5.6524	0.00465	5.7148
1:30:00	12.9	51	30.4	78	11.158	5.6906	0.00468	5.7457
1:45:00	12.6	54	30.4	77	10.941	5.9081	0.00486	5.9715
2:00:00	12.7	55	30.5	79	11.031	6.0671	0.00499	6.1200
2:15:00	12.4	61	30.6	78	10.799	6.5874	0.00543	6.6623
2:30:00	11.5	67	30.6	79	10.176	6.8179	0.00562	6.9178
2:45:00	12.4	68	30.8	79	10.799	7.3433	0.00606	7.4268
3:00:00	13.0	65	30.9	79	11.231	7.3002	0.00602	7.3685
3:15:00	12.9	65	31.1	79	11.158	7.2527	0.00598	7.3230
3:30:00	11.9	66	31.1	77	10.449	6.8963	0.00568	6.9872
3:45:00	13.6	64	31.1	78	11.680	7.4752	0.00617	7.5290
4:00:00	13.5	65	31.3	79	11.604	7.5426	0.00622	7.5996
4:15:00	13.3	65	31.4	79	11.453	7.4445	0.00614	7.5064
4:30:00	13.6	66	31.5	78	11.680	7.7088	0.00636	7.7642
4:45:00	13.8	69	31.6	78	11.833	8.1648	0.00674	8.2177
5:00:00	12.8	67	31.7	79	11.085	7.4270	0.00613	7.5017
5:15:00	13.7	68	31.7	80	11.756	7.9941	0.00660	8.0489
5:30:00	13.4	67	31.9	79	11.528	7.7238	0.00637	7.7853
5:45:00	13.7	68	31.9	81	11.756	7.9941	0.00660	8.0489
6:00:00	15.2	69	31.9	80	12.953	8.9376	0.00739	8.9524
6:15:00	15.8	69	32.0	80	13.461	9.2881	0.00768	9.2843
6:30:00	16.5	70	32.0	79	14.076	9.8532	0.00815	9.8254
6:45:00	16.8	72	31.2	78	14.347	10.3298	0.00855	10.2901
7:00:00	16.5	67	31.0	79	14.076	9.4309	0.00780	9.4043
7:15:00	16.6	69	31.1	79	14.166	9.7745	0.00809	9.7435
7:30:00	17.0	69	31.3	78	14.530	10.0257	0.00830	9.9804
7:45:00	17.3	69	31.2	77	14.809	10.2182	0.00846	10.1613
8:00:00	17.8	69	31.2	80	15.284	10.5460	0.00873	10.4692
8:15:00	18.1	67	31.2	80	15.575	10.4353	0.00864	10.3488
8:30:00	18.7	68	30.9	79	16.171	10.9963	0.00911	10.8837
8:45:00	18.8	69	31.1	78	16.272	11.2277	0.00931	11.1093
9:00:00	18.6	68	30.7	78	16.771	11.4043	0.00946	10.8195
9:15:00	18.8	66	30.8	79	16.272	10.7395	0.00890	10.6263
9:30:00	18.9	67	30.9	78	16.374	10.9706	0.00909	10.8512
9:45:00	18.7	68	31.0	77	16.171	10.9963	0.00911	10.8837
10:00:00	19.0	66	31.4	78	16.477	10.8748	0.00901	10.7525
10:15:00	19.7	67	31.3	79	17.212	11.5320	0.00956	11.3746
10:30:00	19.7	68	30.9	79	17.212	11.7042	0.00971	11.5443
10:45:00	19.8	64	31.3	78	17.319	11.0842	0.00919	10.9292
11:00:00	19.8	65	30.9	77	17.319	11.2574	0.00933	11.1000
11:15:00	20.1	66	30.5	79	17.644	11.6450	0.00966	11.4705
11:30:00	20.3	67	30.1	77	17.863	11.9682	0.00993	11.7813
11:45:00	20.4	68	30.3	79	17.974	12.2223	0.01015	12.0272
12:00:00	20.6	68	30.2	78	18.197	12.3740	0.01027	12.1683
12:15:00	20.9	68	30.5	77	18.536	12.6045	0.01047	12.3827
12:30:00	21.3	66	29.9	79	18.996	12.5374	0.01041	12.3009
12:45:00	21.5	64	29.8	78	19.231	12.3078	0.01022	12.0671
13:00:00	22.0	66	29.8	77	19.827	13.0858	0.01087	12.8088
13:15:00	22.4	65	30.1	79	20.316	13.2054	0.01098	12.9086
13:30:00	23.0	67	30.1	78	21.068	14.1156	0.01175	13.7715
13:45:00	23.7	66	30.4	78	21.977	14.5048	0.01208	14.1187
14:00:00	24.1	68	30.2	79	22.512	15.3082	0.01276	14.8808
14:15:00	24.9	68	30.1	78	23.616	16.0589	0.01340	15.5694
14:30:00	25.4	69	30.0	77	24.326	16.7849	0.01402	16.2491
14:45:00	25.6	70	29.9	75	24.617	17.2319	0.01440	16.6707
15:00:00	26.6	71	29.7	77	26.117	18.5431	0.01552	17.8801
15:15:00	26.9	70	30.1	78	26.582	18.6074	0.01558	17.9247
15:30:00	27.2	69	30.3	77	27.055	18.6680	0.01563	17.9650
15:45:00	27.5	70	29.9	76	27.535	19.2745	0.01615	18.5304
16:00:00	27.6	72	30.2	77	27.696	19.9411	0.01672	19.1654
16:15:00	28.1	74	29.9	75	28.514	21.1004	0.01772	20.2481
16:30:00	28.3	73	29.9	75	28.847	21.0583	0.01769	20.1953
16:45:00	28.7	74	29.8	75	29.525	21.8485	0.01837	20.9260
17:00:00	29.3	74	29.7	74	30.568	22.6203	0.01904	21.6233
17:02:11	29.9	75	29.9	75	31.642	23.7315	0.02001	22.6425

SALTED WOOD PYKRETE

Time	Temperature inside the box (°C)	Relative humidity inside the box (%)	Temperature outside the box (°C)	Relative humidity outside the box (%)	Saturation pressure of water vapor (mmHg)	Partial pressure of water vapor (mmHg)	Specific humidity (g of water/ 1g of air)	Absolute humidity (g of water/ 1 m3 of air)
0:00:00	29.9	75	29.9	75	31.642	23.7315	0.02001	22.6425
0:15:00	13.9	53	29.9	74	11.910	6.3123	0.00520	6.3511
0:30:00	13.0	59	29.7	75	11.231	6.6263	0.00546	6.6883
0:45:00	13.6	62	30.2	76	11.680	7.2416	0.00597	7.2937
1:00:00	13.8	62	30.3	75	11.833	7.3365	0.00605	7.3840
1:15:00	14.1	62	30.3	77	12.065	7.4803	0.00617	7.5214
1:30:00	15.3	63	30.4	78	13.037	8.2133	0.00678	8.2238
1:45:00	14.5	62	30.4	77	12.382	7.6768	0.00633	7.7080
2:00:00	14.0	63	30.5	79	11.987	7.5518	0.00623	7.5959
2:15:00	14.5	63	30.6	78	12.382	7.8007	0.00644	7.8323
2:30:00	14.4	64	30.6	79	12.302	7.8733	0.00650	7.9081
2:45:00	13.5	65	30.8	79	11.604	7.5426	0.00622	7.5996
3:00:00	13.3	65	30.9	79	11.453	7.4445	0.00614	7.5064
3:15:00	13.1	64	31.1	79	11.305	7.2352	0.00597	7.3001
3:30:00	13.2	63	31.1	77	11.379	7.1688	0.00591	7.2306
3:45:00	14.6	64	31.1	78	12.462	7.9757	0.00658	8.0054
4:00:00	14.4	64	31.3	79	12.302	7.8733	0.00650	7.9081
4:15:00	14.3	64	31.4	79	12.223	7.8227	0.00646	7.8598
4:30:00	14.3	63	31.5	78	12.223	7.7005	0.00635	7.7370
4:45:00	15.2	65	31.6	78	12.953	8.4195	0.00695	8.4334
5:00:00	15.6	66	31.7	79	13.290	8.7714	0.00725	8.7737
5:15:00	16.6	65	31.7	80	14.166	9.2079	0.00761	9.1786
5:30:00	16.3	65	31.9	79	13.808	8.9752	0.00742	9.0143
5:45:00	15.2	63	31.9	81	12.953	8.1604	0.00674	8.1739
6:00:00	15.4	64	31.9	80	13.121	8.3974	0.00693	8.4052
6:15:00	15.1	64	32.0	80	12.870	8.2368	0.00680	8.2533
6:30:00	15.3	64	32.0	79	13.037	8.3437	0.00689	8.3543
6:45:00	15.2	66	31.2	78	12.953	8.5490	0.00706	8.5632
7:00:00	15.1	63	31.0	79	12.870	8.1081	0.00669	8.1243
7:15:00	15.3	64	31.1	79	13.037	8.3437	0.00689	8.3543
7:30:00	15.1	63	31.3	78	12.870	8.1081	0.00669	8.1243
7:45:00	14.8	63	31.2	77	12.624	7.9531	0.00656	7.9771
8:00:00	14.9	65	31.2	80	12.706	8.2589	0.00682	8.2807
8:15:00	14.8	66	31.2	80	12.624	8.3318	0.00688	8.3570
8:30:00	15.1	64	30.9	78	12.870	8.2368	0.00680	8.2533
8:45:00	15.0	64	31.1	77	12.788	8.1843	0.00676	8.2032
9:00:00	15.2	67	30.7	79	12.953	8.6785	0.00717	8.6929
9:15:00	15.3	66	30.8	76	13.037	8.6044	0.00711	8.6154
9:30:00	15.8	66	30.9	77	13.461	8.8843	0.00734	8.8806
9:45:00	15.8	65	31.0	79	13.461	8.7497	0.00723	8.7461
10:00:00	15.6	66	31.4	80	13.290	8.7714	0.00725	8.7737
10:15:00	16.3	66	31.3	79	13.898	9.1727	0.00758	9.1530
10:30:00	17.0	67	30.9	77	14.530	9.7351	0.00805	9.6911
10:45:00	17.9	67	31.3	76	15.380	10.3046	0.00853	10.2264
11:00:00	18.5	68	30.9	77	15.971	10.8603	0.00900	10.7556
11:15:00	19.4	68	30.5	78	16.894	11.4879	0.00953	11.3426
11:30:00	20.1	67	30.1	78	17.644	11.8215	0.00981	11.6443
11:45:00	20.7	68	30.3	79	18.309	12.4501	0.01034	12.2394
12:00:00	21.3	68	30.2	78	18.996	12.9173	0.01073	12.6736
12:15:00	22.0	68	30.5	80	19.827	13.4824	0.01121	13.1970
12:30:00	22.8	69	29.9	78	20.815	14.3624	0.01196	14.0211
12:45:00	23.5	70	29.8	79	21.714	15.1998	0.01267	14.8048
13:00:00	24.4	70	29.8	77	22.922	16.0454	0.01339	15.5811
13:15:00	25.2	71	30.1	77	24.039	17.0677	0.01426	16.5333
13:30:00	25.9	72	30.1	79	25.060	18.0432	0.01509	17.4375
13:45:00	26.5	74	30.4	79	25.964	19.2134	0.01610	18.5322
14:00:00	27.1	73	30.2	80	26.897	19.6348	0.01646	18.9014
14:15:00	27.8	73	30.1	78	28.021	20.4553	0.01717	19.6472
14:30:00	28.4	74	30.0	78	29.015	21.4711	0.01805	20.5847
14:45:00	29.0	74	29.9	79	30.043	22.2318	0.01870	21.2722
15:00:00	29.6	74	29.7	78	31.102	23.0155	0.01938	21.9794
15:06:42	30.1	75	30.1	79	32.007	24.0053	0.02024	22.8893

SALTED HYBRID PYKRETE

Time	Temperature inside the box (°C)	Relative humidity inside the box (%)	Temperature outside the box (°C)	Relative humidity outside the box (%)	Saturation pressure of water vapor (mmHg)	Partial pressure of water vapor (mmHg)	Specific humidity (g of water/ 1g of air)	Absolute humidity (g of water/ 1 m3 of air)
0:00:00	29.9	74	29.9	75	31.642	23.4151	0.01973	22.3406
0:15:00	16.1	50	29.9	74	13.721	6.8605	0.00565	6.8509
0:30:00	11.6	59	29.8	75	10.244	6.0440	0.00498	6.1301
0:45:00	10.1	62	30.2	76	9.271	5.7480	0.00473	5.8610
1:00:00	11.0	64	30.3	75	9.844	6.3002	0.00519	6.4038
1:15:00	11.3	64	30.2	77	10.042	6.4269	0.00529	6.5257
1:30:00	12.9	66	30.4	77	11.158	7.3643	0.00607	7.4356
1:45:00	13.4	65	30.4	77	11.528	7.3779	0.00608	7.9081
2:00:00	14.4	64	30.4	79	12.302	8.3654	0.00691	8.9305
2:15:00	15.4	68	30.6	78	13.121	8.9223	0.00737	8.9305
2:30:00	16.0	67	30.5	80	13.634	9.1348	0.00755	9.1249
2:45:00	17.0	67	30.8	79	14.530	9.7351	0.00805	9.6911
3:00:00	17.3	69	30.9	79	14.809	10.2182	0.00846	10.1613
3:15:00	17.8	68	30.8	79	15.284	10.3931	0.00861	10.3174
3:30:00	17.6	67	31.1	77	15.092	10.1116	0.00837	10.0452
3:45:00	17.3	68	30.0	78	14.809	10.0701	0.00833	10.0140
4:00:00	17.9	68	31.3	79	15.380	10.4584	0.00866	10.3791
4:15:00	16.4	69	30.0	79	13.987	9.6510	0.00798	9.6269
4:30:00	16.6	70	31.5	78	14.166	9.9162	0.00821	9.8847
4:45:00	16.8	70	31.6	78	14.347	10.0429	0.00831	10.0042
5:00:00	16.9	71	31.7	79	14.438	10.2510	0.00849	10.2082
5:15:00	17.3	71	31.7	80	14.809	10.5144	0.00871	10.4558
5:30:00	17.4	72	31.9	79	14.903	10.7302	0.00889	10.6667
5:45:00	16.3	70	31.5	81	13.898	9.7286	0.00805	9.7077
6:00:00	15.4	69	31.6	80	13.121	9.0535	0.00748	9.0619
6:15:00	15.6	70	31.2	81	13.290	9.3030	0.00769	9.3054
6:30:00	16.5	71	32.0	79	14.076	9.9940	0.00827	9.9658
6:45:00	15.4	72	31.2	78	13.121	9.4471	0.00781	9.4559
7:00:00	16.7	70	31.0	79	14.256	9.9792	0.00826	9.9443
7:15:00	16.3	71	31.1	79	13.898	9.8676	0.00816	9.8464
7:30:00	16.3	72	31.3	78	13.898	10.0066	0.00828	9.9851
7:45:00	16.0	71	31.2	77	13.634	9.6801	0.00801	9.6697
8:00:00	16.2	71	31.2	81	13.809	9.8044	0.00811	9.7872
8:15:00	16.8	72	31.2	80	14.347	10.3298	0.00855	10.2901
8:30:00	16.7	72	30.9	79	14.256	10.2643	0.00850	10.2284
8:45:00	17.2	71	31.1	78	14.715	10.4477	0.00865	10.3934
9:00:00	17.8	71	30.7	78	15.284	10.8516	0.00899	10.7726
9:15:00	18.1	72	30.8	78	15.575	11.2140	0.00930	11.1211
9:30:00	18.3	70	30.9	78	15.772	11.0404	0.00915	10.9414
9:45:00	18.0	71	31.0	77	15.477	10.9887	0.00911	10.9017
10:00:00	18.2	71	31.4	78	15.673	11.1278	0.00922	11.0320
10:15:00	19.8	71	31.3	79	17.319	12.2965	0.01021	12.1246
10:30:00	20.8	71	30.9	79	18.422	13.0796	0.01087	12.8540
10:45:00	21.7	73	31.3	78	19.468	14.2116	0.01183	13.9241
11:00:00	22.4	70	30.9	77	20.316	14.2212	0.01184	13.9015
11:15:00	23.7	69	30.5	79	21.977	15.1641	0.01264	14.7604
11:30:00	24.3	69	30.1	77	22.785	15.7217	0.01311	15.2718
11:45:00	25.0	70	30.3	79	23.756	16.6292	0.01388	16.1179
12:00:00	25.8	71	30.2	78	24.912	17.6875	0.01479	17.0994
12:15:00	26.5	72	30.5	77	25.964	18.6941	0.01565	18.0313
12:30:00	27.2	71	29.9	79	27.055	19.2091	0.01609	18.4857
12:45:00	27.4	72	29.8	78	27.374	19.7093	0.01653	18.9548
13:00:00	27.6	73	29.8	77	27.696	20.2181	0.01696	19.4316
13:15:00	28.1	73	30.1	79	28.514	20.8152	0.01748	19.9745
13:30:00	28.9	73	30.1	78	29.870	21.8051	0.01833	20.8704
13:45:00	29.4	74	30.4	78	30.745	22.7513	0.01915	21.7415
13:49:31	30.2	75	30.2	79	32.191	24.1433	0.02036	23.0136

AIP Conference Proceedings

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Cite as: AIP Conference Proceedings **2296**, 020082 (2020); https://doi.org/10.1063/5.0032995
Published Online: 16 November 2020

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Study of Pykrete Viability As Protective Insulation in Cold Storage Application

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Abstract. Pykrete is an impact-resistant ice composite material developed in secret by British during World War 2, designed as a substitute material for steel for building warships due to the shortage of metals at that time. It is made by freezing water mixed with paper or wood-based reinforce material. This paper studied the cooling performance of pykrete by observing the fluctuations of air temperature and humidity affected by Pykrete's cooling and it's viability as protective insulation material for cold storage. The experiment involves placing a pykrete sample inside an open-topped box, exposed towards room temperature. Two hygrometers and thermometers recorded the change in relative humidity and temperature every 15 minutes. The data gathered was processed and plotted into a line chart which showed the fluctuations of temperature, specific humidity and absolute humidity of ambient air as the time passed from the start of the experiment until the sample completely melted. Then, the charts of pykrete samples is compared with chart result of ice, which provides a vinal verdict of pykrete's viability. Results from this experiment has found that pykrete has a much better cooling duration and temperature at the cost of cooling stability.

INTRODUCTION

The usage of vacuum-based insulation has been widely used to maintain low temperature for extended duration. It's used in a wide array of application in daily lives, from portable ice box, thermos, cold storage, to a large refrigeration unit. However, this method of insulation has a weakness: It's fragile, and it cannot be exposed towards impact shocks, since they are prone to cracking, which will severely reduce their insulative capabilities. At this point, other means of cooling must be used to preserve the low temperature inside, especially if the content inside require constant cooling to prevent it from decomposing at warmer temperature. Ice is a common cooling agent to be used due to their availability, it's cheap and readily available. However, while ice provides good cooling capacity, it does not last very long when exposed in room temperature. Aside from that, even if ice is packed inside the vacuum storage as a precaution for backup cooling in case of impact shocks, the impact itself is likely shattering the ice into smaller pieces, which, owing to it's fragility, makes it melt faster [2][3][8]. A more durable and longer-lasting cooling agent is certainly very useful in this apllication.

During World War II, Geoffrey Pyke proposed a special ice-based composite material called pykrete as a substitute material for a huge, unsinkable aircraft carrier for the British Royal Navy, which at that time having limited steel reserves to build warships [6][12]. Pykrete is an ice composite made from water mixed with cellulose-based reinforce material, and it has some interesting properties including it's high resistance towards impact shocks and relatively slow melting rate because of low thermal conductivity [1][11]. These properties make pykrete suitable for backup cooling agent in low-temperature application, since it allows an extended cooling duration while less likely to be shattered during the impact [4]. The cellulose-based reinforce material inside the pykrete usually consists of wood/ sawdust (particulate) or paper pulp (fiber). These materials are usually selected due to their availability [9]. Unlike ice, which breaks easily when exposed to impact shocks, pykrete is much more resistant due

International Conference on Science and Applied Science (ICSAS2020)
AIP Conf. Proc. 2296, 020082-1–020082-7; https://doi.org/10.1063/5.0032995
Published by AIP Publishing. 978-0-7354-4030-2/$30.00

to the reinforce material acting as a dampener towards external force while holding the ice structure together [5][6]. In addition, the reinforce material's low thermal conductivity also makes pykrete much more resistant towards natural melting at room temperature, making it perfect as a backup cooling agent to keep the temperature low in case of containment breach since it lasts longer, long enough until proper repairs and more permanent solution could be applied [1][10].

This research studied the cooling performance of pykrete with various composition ratio. A special test has been carried out to investigate the cooling effect based from the correlation between ambient air humidity and cooling effect provided by pykrete samples and plotted the results into a line chart that also showed the time it takes for the sample to melt and the fluctuations of temperature, specific humidity and absolute humidity in surrounding area. This test is also performed on regular ice for comparison.

EXPERIMENTAL METHODOLOGY

Materials

This study used one ice sample and three pykrete samples with 14% reinforce material (by volume) consisted of wood and/or paper based material. The composition of each sample is shown in Table 1.

TABLE 1. Reinforce material content of samples

Material	Material composition		
	Water (% by volume)	Wood (% by volume)	Paper (% by volume)
Regular Ice	100	0	0
Wood pykrete	86	14	0
Paper pykrete	86	0	14
Hybrid pykrete	86	7	7

Preparation of Pykrete Samples

Pykrete samples were prepared with dimensions of 20cm x 10cm x 10cm, which consists of 14% reinforce material and 86% water. Since pykrete is based from ice, expands as it freezes. The mold is open on top to provide pykrete expansion space during the freezing process (ice expansion from this space will be discarded). For wood-based pykrete, in order to obtain correct measurement of 14% reinforce material by volume, a block of teak wood measuring 2.8cm x 10cm x 10cm is shredded into fine powder while minimizing any possible loss of material. For paper-based pykrete, 1000 strips of A4 70 GSM paper measuring 2.8cm x 10cm is stacked into a single block before being shredded and turned into paper pulp. The samples are then placed inside a commercial freezer with a temperature of -15°C for 5 hours during the freezing process.

Concept of Experiment

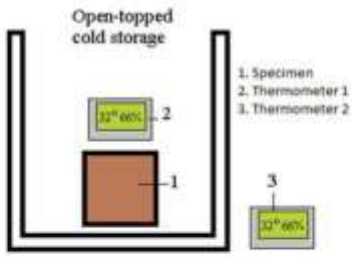

FIGURE 1. Concept for cooling performance test

The sample will be put inside an open-topped cold storage box as shown on figure 1. For tools that 's used in this experiment, a pair of digital thermometers will be used. These are TP-40 digital thermometer with integrated

hygrometer that'll measure the value of ambient air temperature and it's relative humidity. There are 2 data that'll be used in this experiment, which is the temperature of ambient air around the sample **(T)** and it's relative humidity **(Rh)**. One TP-40 is placed inside the box with the sample, while the other is placed outside the box. The timer is started, and the initial value of relative humidity and the temperature from both devices are taken. Every 15 minutes, another value is taken. These values is then inserted into the absolute humidity equation. The timer stops the moment the temperature value of digital thermometer 1 matched the value of digital thermometer 2 (Meaning the specimen no longer provides any cooling). At this point, the sample has been completely melted.

The relative humidity is the ratio of the partial pressure of water vapor to the equilibrium vapor pressure of water at a given temperature and it's represented as percentage, which is a measure of of current absolute humidity value relative to the maximum possible value for that temperature. Normally, it's around 70%-90% saturation, which fluctuates as the temperature changes. When ice cools the ambient air, it changes the relative humidity value as water vapor begin to condense at low temperature. However, using only the relative humidity does not provide any meaningful information about the cooling performance since the relative humidity changes very slightly for several degrees of change in ambient air temperature, as such it's not a very accurate indicator for cooling performance. In order to observe the cooling performance accurately, we need to look into the specific humidity (Sh) absolute humidity (Ah). The data of T and Rh obtained from the moment the test started until the specimen's complete melt over 15-minutes interval is used to calculate the value of Sh,and Ah using Magnus-Tetens equation [7], which is then plotted into a graphical curve.

Specific humidity **(Sh)** is the ratio of the mass of water vapor to the total mass of the dry air in current temperature. The specific humidity is represented as grams of water vapor per grams of dry air. This value fluctuates as the temperature changes, with low air temperature yielding lower specific humidity value as the water vapor condensates into liquid phase. In order to find the value of specific humidity, first, T (current temperature) will be used alongside with Rh. The formula for Rh is shown on equation 1 below:

$$Rh = \frac{Pw}{Psat(T)} x100 \tag{1}$$

Where:	Rh	= Relative humidity (in %)
	Pw	= Partial pressure of water vapor (mmHg)
	Psat (T)	= Saturation pressure of water vapor at T (mmHg)

We can look the value of Psat(T) value from the table of correlation between the partial water vapor pressure and ambient air temperature [7]. Thus, by using the equation (1), we can extrapolate it to get the equation 2:

$$Pw = \frac{Rh}{100} xPsat(T) \tag{2}$$

By obtaining the value of Pw in equation (2), we can now calculate the Specific humidity **(Sh)** of the ambient air by using the following equation:

$$Specific\ humidity = \frac{Mass\ of\ vapor}{Mass\ of\ dry\ air}$$

Which could be written as equation 3:

$$Sh = \frac{Pw\ x\ Mw}{(TP - Pw) x\ Md} \tag{3}$$

Where:	Sh	= Specific humidity ($g_{\ of\ water}/1g_{\ of\ air}$)
	Pw	= Partial pressure of water vapor (mmHg)
	Mw	= Molecular weight of water (18 g/mol)
	TP	= Total pressure of dry air (average 760mmHg)
	Md	= Molecular weight of dry air (29 g/mol)

As the ice cools the surrounding ambient air, the value of Sh decreases from it's initial value as water vapor condenses while temperature drops (cooler air holds less water). As the time passes, heat from ambient, non-cooled air outside the cooling range starts to affect the cooled air by raising the ambient air temperature, which raises the Sh

value of cooled air. When ice has completely melted, it no longer provides any cooling as the ambient air temperature now equalizes with room temperature and Sh returns to it's initial value.

Absolute humidity **(Ah)** is the ratio of the mass of water vapor per 1 cubic meter of the dry air in the current temperature. The value changes for even a very slight change in ambient air temperature, which is far more accurate than relative humidity for observing the cooling performance. The lower the specific and absolute humidity value, the better the cooling is (lower Ah value indicates the extent of cooling effect radius of a cooling material in a spherical area around it). In order to find the value of absolute humidity, we can use the equation 4 below:

$$Ah = \frac{6.112 \times e\hat{}[(17.67 \times T)/(T + 243.5)] \times Rh \times 18.02}{(273.15 + T)} \quad (4)$$

Where: Ah = Specific humidity ($g_{\text{of water}}/1m^3_{\text{of air}}$)
T = Air temperature (°C)
Rh = Relative humidity

If the resulting line chart of Sh and Ah of a sample is similar, then the calculation is correct, since both specific and absolute humidity is the measure of humidity in ambient air, albeit at different units of measurement (mass and volume respectively).

RESULTS AND DISCUSSION

4 samples has been created for this experiment as seen on figure 2 below, one is regular ice and the other 3 is pykrete composite with different level of reinforce material contents. Each are tested for their cooling performance by observing the fluctuations of Temperature, Relative humidity, Specific humidity and Absolute humidity before comparing the results in order to provide a verdict about pykrete's viability as a protective insulation in cold storage application.

(a) (b) (c) (d)

FIGURE 2. The 4 samples used for this experiment. From left to right: Regular ice (a), Paper pykrete (b), Wood pykrete (c) and Hybrid pykrete (d)

Temperature

The temperature fluctuations of all 4 samples has been plotted into the following figure 3:

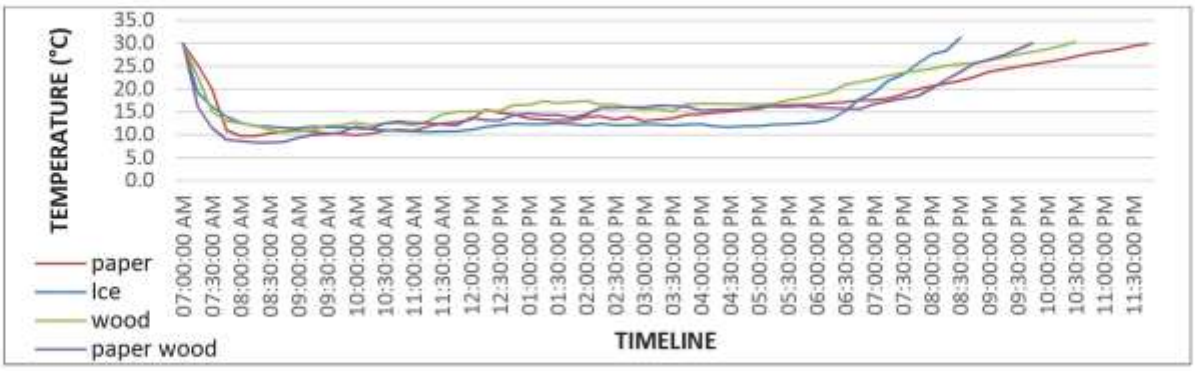

FIGURE 3. Chart of temperature fluctuations of the 4 samples over time

From the chart, we can see that all pykrete samples possess a much longer cooling duration than regular ice, at the cost of cooling stability (regular ice has a far less fluctuations when compared with all 3 pykrete samples, indicating a relatively stable temperature) The temperature chart can be summarized in Table 2 below.

TABLE 2. Temperature and cooling duration

Material	Lowest temperature attained (°C)	Total cooling duration
Ice	10.6	13:17:54
Paper pykrete	9.7	16:42:35
Wood pykrete	10.5	15:27:15
Hybrid pykrete	8.3	14:42:14

All pykrete sample are much better than regular ice in terms of cooling duration and lowest attainable temperature (although this last one only lasts briefly). From the initial room temperature of 30°C, ice managed to attain the lowest air temperature of 10.6°C, while all pykrete samples managed to attain even lower, with hybrid pykrete managed to reach 8.3°C. Although it should be noted that such low temperature lasts for a short duration.

Specific humidity

The specific humidity fluctuations of all 4 samples has been plotted into the following figure 4.

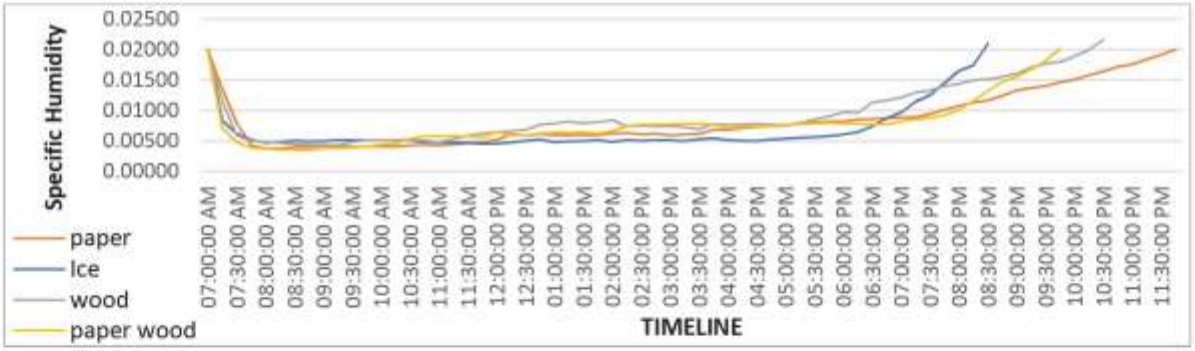

FIGURE 4. Chart of specific humidity fluctuations of the 4 samples over time

All pykrete samples have shown to have a lower specific humidity value compared to regular ice. Since specific humidity value is ratio between grams of water per grams of air, this indicates that pykrete have better cooling capability than regular ice. The specific humidity of 4 samples can be summarized in a following table 3

TABLE 3. Specific humidity

Material	Ice	Paper	Wood	Hybrid
Lowest Specific humidity	0.00452	0.00378	0.00429	0.00353

Hybrid pykrete possess the lowest specific humidity value compared to regular ice and other pykrete samples. Specific humidity of hybrid pykrete is 0.00353g of water/ g of air, compared to regular ice, which is 0.00452 g of water/ g of air. This means that hybrid pykrete could reduce the temperature of ambient air much better than regular ice, although when we correlate this with plotted lines on figure 3, we can see that hybrid pykrete cannot maintain this cooling performance for a long time.

Absolute humidity

The specific humidity fluctuations of all 4 samples has been plotted into the following figure 5.

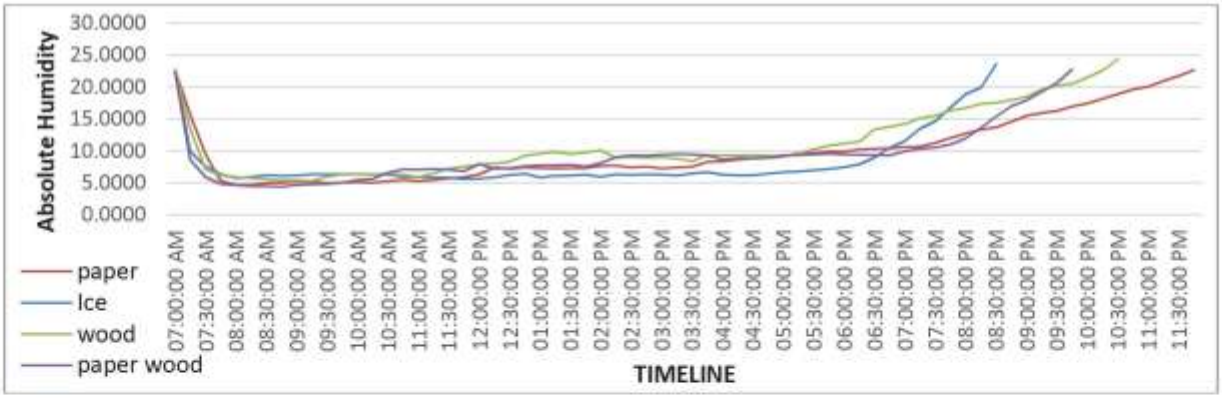

FIGURE 5. Chart of absolute humidity fluctuations of the 4 samples over time

Absolute humidity is a ratio between grams of water per a cubic meter of air. It mesures the cooling performance based on the area of cooling (lower number means better cooling). All pykrete samples have been observed to have better absolute humidity value compared to regular ice. The absolute humidity of 4 samples can be summarized in the table 4 below.

TABLE 4. Absolute humidity

Material	Ice	Paper	Wood	Hybrid
Lowest Absolute humidity	5.5966	4.7003	5.3032	4.4103

Due to inherently unstable cooling of pykrete, these state of low-value absolute humidity only lasts for a while when compared with regular ice, as shown in the chart. Hybrid pykrete posses the lowest absolute humidity value at 4.4103 g of water/ 1 m^3 of air, compared to regular ice at 5.5966 g of water/ 1 m^3 of air.

All of the data from figure 3,4 and 5 shows that pykrete's peak cooling performance is only at the beginning of the test, essentially giving them a much better cooling performance than ice for a brief period of time before it starts to drop over time, longer than total cooling duration of ice. It's assumed that this is due to how pykrete melts. Unlike ice, which steadily melts into water, when pykrete melts, the icy portion of outer layer turns liquid, but leaves the reinforce material in place, inhibiting the heat propagation from the outside from reaching the deeper layer of pykrete before it crumbles in chunks, exposing the deeper layer with room temperature, starting the process all over again (this also explains the frequency of fluctuations on all pykrete samples).

CONCLUSION

Based from the results of 3 line charts, it can be concluded that, compared to regular ice, all pykrete samples sacrifices cooling stability for much longer cooling duration. While pykrete managed to attain lower temperature

than ice, it lasts very briefly (the same could be said to pykrete's specific and absolute humidity values). In comparison, ice tend to give consistent cooling as it melts, while pykrete gives an "initial burst" of better cooling than pykrete for a brief period of time as it melts. However, when being applied in cold storage application for protective insulation purpose, the longer cooling duration is generally more preferable than cooling stability, since the intent is not to cool the already-cooled content, but significantly slow down the temperature change of ambient air that could affect the content in the event of containment breach.

ACKNOWLEDGEMENTS

The authors wish to thank for the support from the Laboratory of Computational and Simulation of Materials and Metallurgical Engineering, ITS who provided insight and service for material development and testing

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This thesis has been put on presentation on scientific conference by International Conference on Science and Apllied Science (ICSAS) 2020 by Universitas Sebelas Maret. The conference is performed online on 7 July 2020 from Surakarta, Indonesia by using Zoom service. The paper version of this thesis has been sent to AIP Conference Proceedings for publication.

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AUTHOR PROFILE

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Putra Ridhan Firdaus, born on 31st July, 1993 on Probolinggo, East Java, Indonesia as the first of three siblings. Since early age, he is interested in science, particularly in the field of military and aviation technlology. His hobby includes of drawing concept art of mechanical stuff, dismantling computers and tinkering with computer software, while his English language education largely being self-taught.

He finished his elementary school education from SD Al-Furqan Jember on 2006, followed with his intermediate school on SMP Negeri 3 Jember on 2010, and his high school education on SMA Negeri 2 Jember on 2013. He continued his undergraduate education (D4, comparable to S1) on Surabaya Shipbuilding State Polytechnic (PPNS Surabaya) from 2013 to 2017, majoring in design and manufacturing class with specialization in design aspect. During this time he's also having an internship program on Indonesian Aerospace (PT Dirgantara Indonesia), Bandung as apprentice drafter for modeling the ergonomic of aircraft maintenance. He finished his S1 undergraduate education with his conceptual design of portable railgun system as the subject of his final project. In 2018, he continued his undergraduate education (S2) on ITS Material and Metallurgical Engineering Department.

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