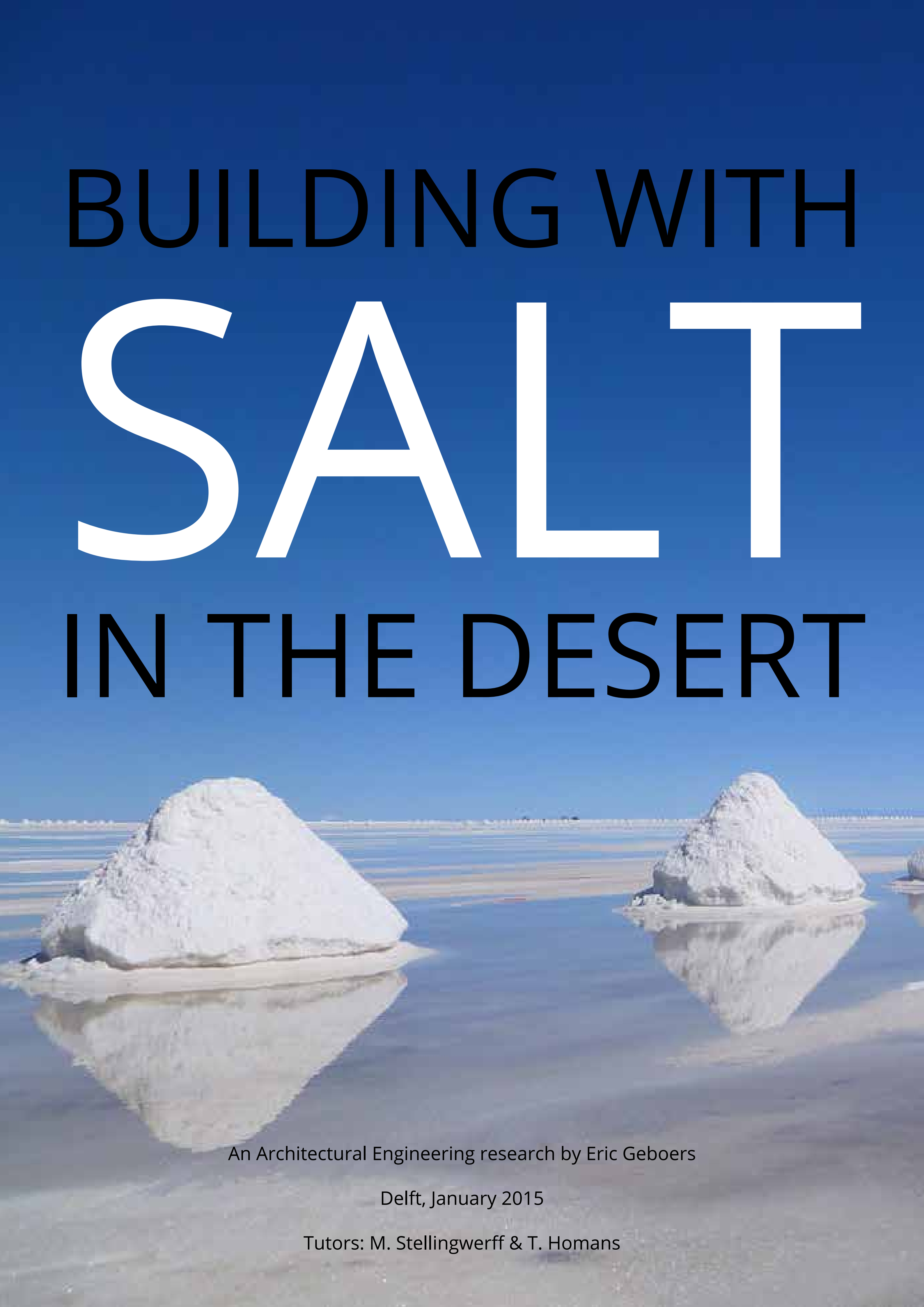

BUILDING WITH SALT IN THE DESERT

An Architectural Engineering research by Eric Geboers

Delft, January 2015

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Abstract

In our time of overpopulation and desertification it is essential we look for new ways of living and building. This study is an exploratory research on how to use salt as a building material in desert climates. The desert climate is briefly reviewed, followed by an overview of the use of 3D printing in the process, the exact composition of the material and the building process. This leads to tests of the tensile and compressive strength of the material along with its density and a comparison to other construction materials and an assessment of rules of thumb for dimensioning structures. Finally a guideline is given for designing with salt in which different building components are proposed. The final conclusion is a case study of a longstay living unit built out of salt.

Key words: *salt, biomaterial, desert, 3D printing, biomimicry, compression based structures*

Introduction

The massive growth of human population combined with the technological advancements of the last 200 years have lead to serious pollution, climate change and a series of other problems. It is now clear that we have been using resources in an unsustainable way and created huge amounts of waste which we don't know how to deal with. The hunt for resources has caused large areas of forest to be logged or burned down to be used for agriculture, mining or housing leading to habitat loss, loss of biodiversity and desertification. Many underground water supplies are currently being emptied and used for irrigating crops. When they run out the land is left deserted. We as humanity can not sustain growth at our current rate.

The fascination at the start of this project came from the ideas on biomimicry of Janine Benyus and Michael Pawlyn who both wrote fantastic books on the subject. The idea of biomimicry is that for many of the problems we currently face, nature has already found a solution – we just need to find it. Nature has been evolving, adapting and optimizing for 3,7 billion years and thus we can learn from it on several levels (Pawlyn, 2011).

Michael Pawlyn explains to us that we can look at three levels of biomimicry. The first is structure: nature has evolved to use the minimum amount of materials. This costs the least amount of energy and thus means a better chance of survival. An example are the honeycombs made from beeswax with its structurally efficient hexagonal system. The second level is about looking at processes in nature. A process we can learn from for example is the way termite hills are constructed. The temperature differences between day and night in the Zimbabwean savannah can be up to 40 degrees Celsius, yet the eggs are kept at the exact same temperature year-round. The principles of this system have been implemented in Mick Pearce's Eastgate Center in Harare, leading to a significant decrease in need for mechanical cooling and heating. (Pawlyn, 2011).

The final level is the level of the organism and the ecosystem which is about the complex integration of an organism in its habitat. Janine Benyus defines 10 rules for how organisms behave in a mature ecosystem:

1. Use waste as a resource
2. Diversify and cooperate to fully use the habitat
3. Gather and use energy efficiently
4. Optimize rather than maximize
5. Use materials sparingly
6. Don't foul their nests
7. Don't draw down resources
8. Remain in balance with the biosphere
9. Run on information
10. Shop locally (Benyus, 1997)

We are currently at the point in our technological advancement that we can actually design our buildings the same way nature does it. This means using local materials, looking at the whole cycle of those materials, optimizing structures to minimize the use of those materials and using parametric tools to optimize orientation, climate systems and construction. Meanwhile we should map and utilize the waste streams in the built environment, minimize the impact on the existing ecosystem (or fully integrate it in in this ecosystem) and move towards a 100% solar

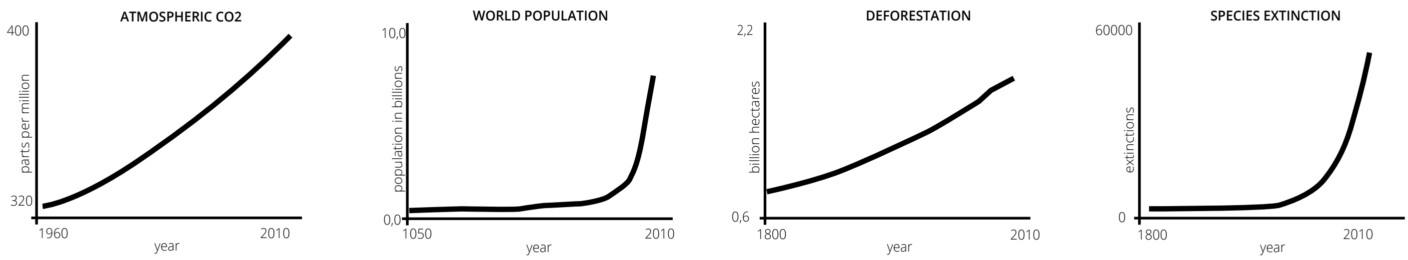


Image 1. Graphs showing world-wide changes (IPCC, 2013)

based system. On a larger scale we should move towards a circular economy, where waste is simply another resource to be utilized. Another important factor is managing growth by mass customization: nature is not the same everywhere, it is specialized and optimized to its location, allowing growth in a sustainable matter.

This research is an attempt to take a step in the right direction. This material research is strongly related to the design aim of using seawater as the resource for a construction project. 98% Of all water on earth is seawater, an endless supply. The goal is to separate the fresh water from the salt using the sun's energy. The fresh water can then be used to grow crops while the salt is the main component of a new building material. By doing this a 'waste' material is created of which we can never have enough: fresh water. The separation of seawater in salt and freshwater will happen through a designed 'seawater infrastructure'. The design itself will not be within the scope of this article but an explanation can be found in the appendix.

Salt is also a waste product in many desert environments. Much of the drinking water in Israel and Middle Eastern countries is won from seawater using a process called reverse osmosis. This separates seawater in fresh water and a brine with a high salt content and chemicals used for treating the water. This brine is then deposited back in the sea with devastating ecological results. (Dawoud & Al Mulla, 2012) Using this brine to create value would be a fantastic proposal.

This brings us to the main research question:

How can we use salt as a building material in a desert environment?

And the following sub questions:

- *What climate conditions do we need to deal with?*
- *What building method can we use?*
- *How does the material cycle look?*
- *What extra material do we need to build with salt?*
- *What are the material properties?*
- *To what kind of structures do the material properties lead?*
- *How thick must these structures be?*

Methods

The desert offers interesting conditions for building. Its name already implies it is deserted. It is also growing – an interesting contradiction with our current exponential population growth as it means valuable farm land availability is decreasing twofold. Housing a part of the population in this so readily available (and cheap!) desert thus seems like an attractive option. But what are the climate conditions we need to deal with in a typical desert environment? This will be researched via literature.

The inspiration for embarking on this design and research journey comes from a little company based in Berkeley, California called Emerging Objects. It is lead by two associate professors from Berkeley University. They are researching new techniques and materials for 3D powder printing with Zcorp 3D-printers. They have succeeded in printing with wood, a polymer concrete and salt. As said, this research will be towards salt with a focus on 3D-printing.

Several aspects of the material and the technique will be explored before conducting the experiments needed to establish the material properties of the final salt-based material. The first thing explored is the technique needed for 3D-printing with a powder printer and its scalability. For this literature research will be conducted over the internet and via interviews.
After the technique's capabilities have been established it is possible to assess extra materials needed and their ratios to each other. A small chapter will be dedicated to exploring the material cycle of these different materials. This will be done via literature research.

Experiments are then conducted with the material. There will be several experiments: first several exploratory experiments to determine how to create a high quality salt-base material. This is because of the lack of access to a powder printer due to high costs. There is also a lack of industrial equipment hence why the material is created in a standard kitchen oven.

After creating the material it is tested on its structural properties by measuring the maximum tensile stress on several standardized salt beams. A UTM (Universal Testing Method) machine puts a point force on the middle of a beam placed on two supports. The computer measures the force put on the beam and the stretching of the beam. This information can be used to calculate the maximum bending stress with the formula $\sigma = M/W$. The strain ε is also measured. This then allows one to draw a stress-strain curve from which the material's Young's Modulus is deducted by measuring the tangent of the curve. To get a statistically relevant number a minimum of 6 beams is required.
Along with the tensile stress test a compression stress test is done. A machine measures pressure in kN put on a salt cube and the formula $\sigma = F/A$ gives us the maximum compression stress. This is repeated 10 times to acquire a statistically significant number.

The density of the material is also measured. Several testing sticks are weighed and then submerged in water. The weight is divided by the volume to determine the density.

With this data the material is compared to existing building materials and structures made of these materials and rules of thumb are deduced.

Image 2. Saltygloo. (Emerging Objects, 2014)

Lastly the material's response to several climate conditions is tested. It is tested on handling of cold, heat, moisture and UV light. Several test beams are put in hot, cold, moist and sunny environments and then compared with the standard unexposed beams.

The material data retrieved from these experiments leads to conclusion and the formulation of a strategy on how to design with salt. What will a typical salt construction look like? What typologies are very suitable for this material? What building parts can we make out of salt? Can salt work as a structural element? How thick must this structure be? This strategy or 'design guide' will culminate in a case study of a small building that is made out of salt in order to showcase the possibilities and properties of the material. This is very much a research by design exercise.

Results

Part 1 - A desert climate

There are several types of desert in the world. Normally, a desert is defined as an arid region where little precipitation occurs and with very sparse or no vegetation. Then a distinction is made between cold deserts such as Antarctica and hot deserts such as the Sahara. In this article the focus is on the latter

Hot deserts share several similarities when it comes to challenges for building. The main difficulties for desert building and living are temperature differences, UV-radiation and erosion. (Ashrafian, Tabatabaei et al, 2011)

Temperature differences

The low latitudes of most hot deserts mean that the sun is very powerful. Their extremely low humidity means that most of the time there is no cloud cover. Add to this their lack of vegetation to protect the bare soil and it creates conditions where the bare rock and sand heat up very quickly. At night the clear skies allow all the heat to radiate back into space, cooling down the soil. This means the temperature differences between day and night are very high (up to 30 degrees). When building this must be taken into account. It would be beneficial to make thick structures with a high thermal mass to keep a comfortable interior climate.

Image 3. The Negev desert in Israel (Wikimedia, 2013)

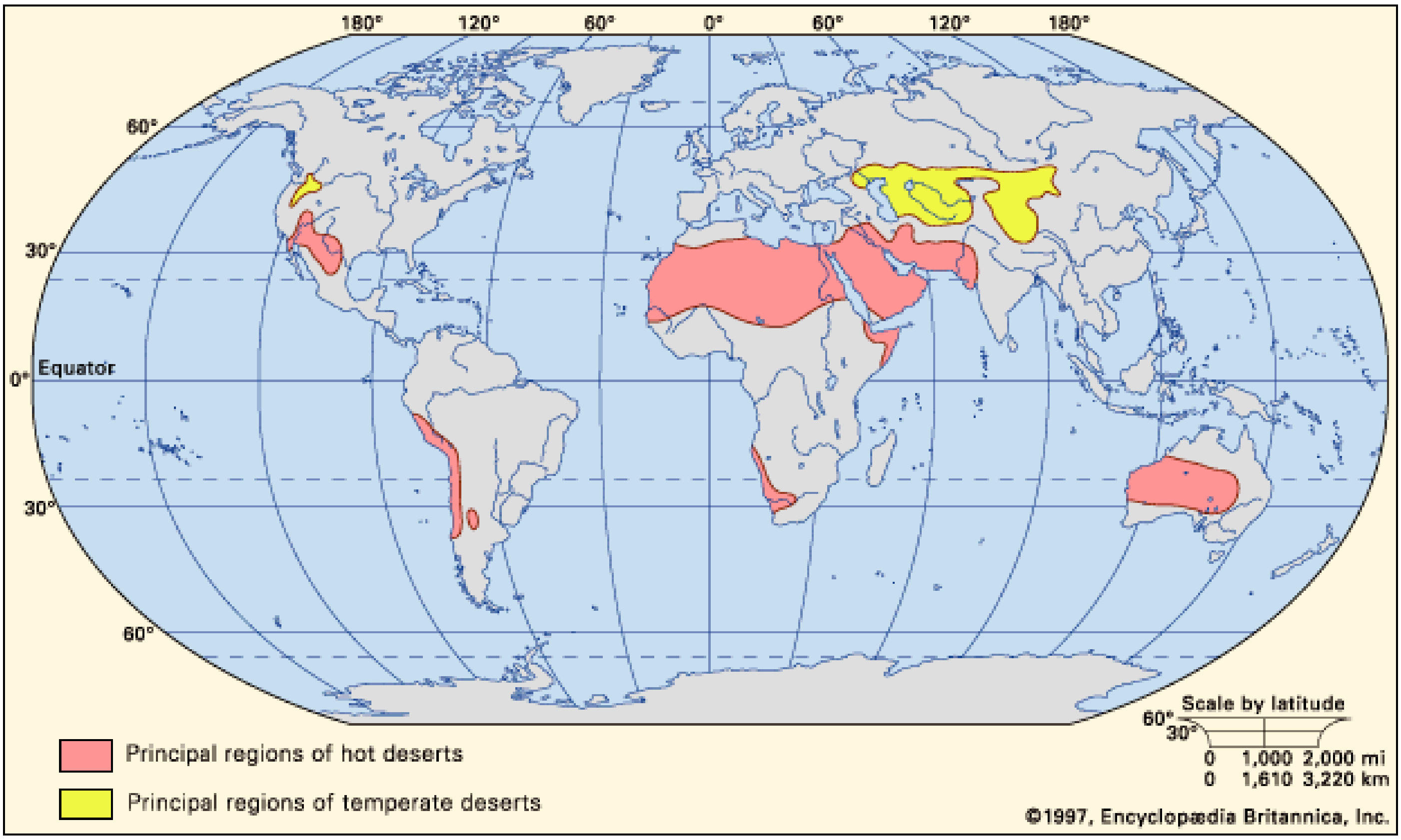


Image 4. Deserts world-wide (Smith, J., 2014)

UV-radiation

The sun is very powerful in a hot desert. A part of the sunlight is UV-radiation which can degrade polymers, leading to cracking, fading or loss of strength. This must be taken into account when testing the material. The salt itself will not be affected as it is a mineral. Added materials might be affected.

Erosion

The heat from the sun and the lack of vegetative cover makes the exposed rock crack and erode, forming sand. Then the wind carries the sand and dust over great distances, forming sand and dust storms. When building in a desert one must keep these harsh conditions in mind. The material must be either strong enough to resist erosion over a long period of time or it must be possible to add material to heavily eroded parts of the construction.

Part 2 – 3D printing technology

The inspiration for this research came partly from the 3D-printed Saltygloo by Emerging Objects. This is why a link with 3D-printing salt is made There are a few ways of 3D-printing. The most common and cheap way is Fused Deposition Modeling (FDM), where a fine thread of plastic (ABS, PLA, nylon) is heated to the point of melting and laid on layer after layer with a printing head. (3Dprinting.com, 2014). This technique is not relevant as salt is a powder material.

Another way of printing is Selective Laser Sintering, or SLS. It uses a high-power laser to melt a powder substance following a profile defined by a 3D-model. The powder is laid on layer after layer and melted together by the laser. At the end of the process the unused powder is removed, leaving the product sintered. (3Dprinting.com, 2014). It can be done with very simple technology as proven by Markus Kayser. He took a simple lense to the desert and was able to sinter sand together. (Kayser, 2011) The problem when it comes to sintering salt is that it requires high temperatures (salt has a melting point of 800 ºC) and that when melted together salt forms a very brittle polycrystalline structure.

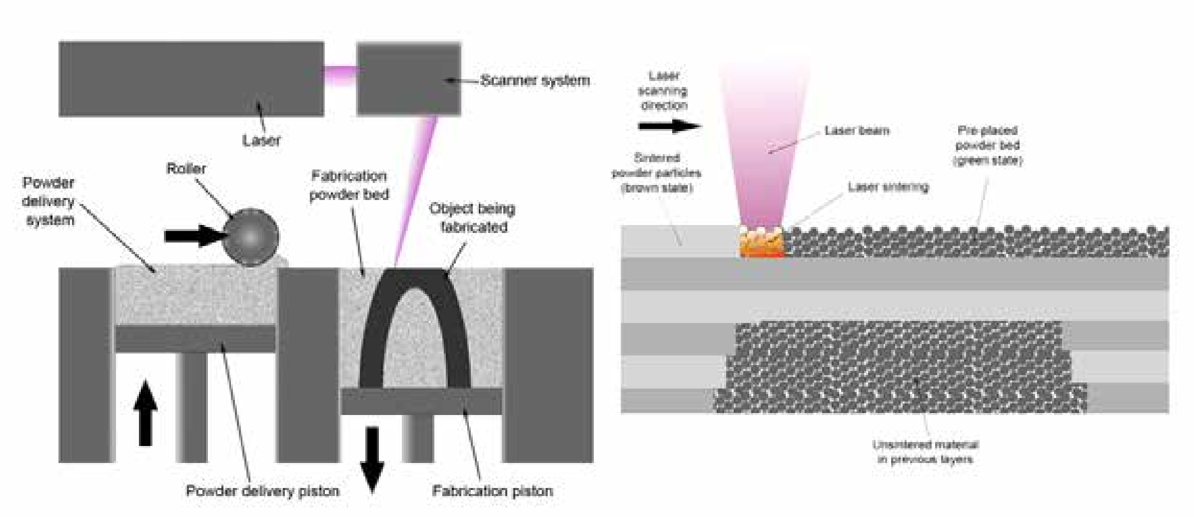


Image 5. Workings of a SLS printer (Materialgeeza, 2014)

The method used for this research is patented by Zcorp and simply called Powder printing. It involves the use of a powder mixture and a binder. It works similarly to SLS, except instead of a laser a binder is applied which significantly reduces energy need. The 3D-model is similarly cut up in layers (its thickness dependent on the printer's accuracy) and every layer is laid out with powder and the model's profile is sprayed with the binder. This way the model is built up from the bottom. The powder that is not used supports the model itself which means no support structure is needed to print projections or protrusions. This means any shape imaginable can be printed, the only restriction is the size and accuracy of the printer. (3Dprinting.com, 2014)

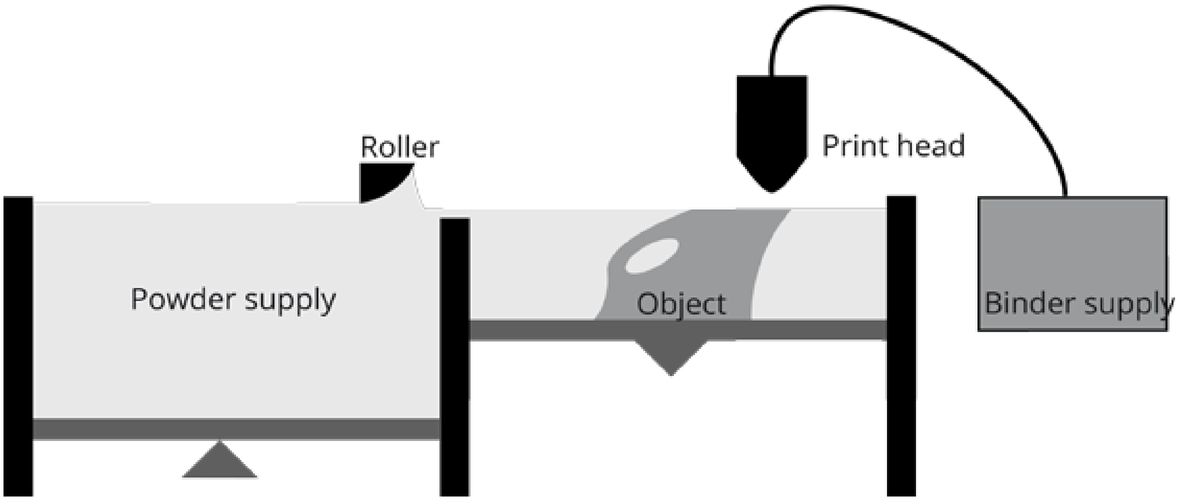


Image 6. Workings of a powder printer (Geboers, 2014)

Currently ZCorp's largest printer has a maximum net print volume of 508x281x229 mm (Zcorp, 2014). Italian inventor Enrico Dini has created a printer using the very same principle with a print volume of 6x6x6 meters. With this printer he scales up the entire process. While Zcorp printers build a model up with layers of 0,1 mm thick, Dini's printer creates layers of 5-10 mm, significantly speeding up the printing process but also reducing accuracy. When making buildings, a reduced accuracy of 5 mm is acceptable. Dini uses sand as a powder and a chemical binder to 'glue' the sand together, creating a material which he describes as similar to marble, with the same strength. (Dini, 2014).

Part 3 - Powder and binder

Salt itself is unlikely to form large solid structures. Salt blocks found in nature have typically been exposed to very high pressure over long periods of time causing it to form a solid structure called halite. This process is of course very energy intensive. This is why in order to create solid salt blocks a production process is needed to bind the salt together. There have been two researches to 3D-printing with salt. One is done by the aforementioned Emerging Objects who are understandably secretive about their technology. The other research has been done by students of the University of Washington in Seattle at the Solheim lab led by Mark Ganter and Duane Storti. They publish their results online (http://open3dp.me.washington.edu/) and have succeeded in printing with salt and their findings form the basis of this research.
The powder they use is a mixture of 8 parts salt and 1 part maltodextrin (by weight). The salt is grinded to a very fine powder whichs spreads “extremely well” and produces the “best surface finish we’ve ever seen”. (Klee & Chan, 2011)

The binder used is a custom alcohol based binder which they call XF1. The exact contents are shown below. Its active component is water which reacts with the maltodextrin to make it hard. How this process works exactly is described in the Results section, part 10. The alcohol is needed to adjust the viscosity of the binder so it does not plug the print head. It can be replaced with glycerol if needed.

The ratio of powder to binder is 40 to 1, meaning for 40 cm^3 of powder, 1 cm^3 of binder is needed. (Ganter, 2009)

For extra strength and water resistancy the printed model can be coated with injection based epoxy. (Ganter, 2012)

Image 7. Material ratios (Geboers, 2014)

Part 4 - Material cycles

In this chapter the material cycles are reviewed. The material cycles form a key element in the Salt Infrastructure described in appendix A.

Salt. Salt is the main ingredient of the building material. It can be mined or retrieved from evaporating seawater. In small quantities it can be returned to the sea, in very large quantities this is not desirable as it will impact the ecosystem. It is a very common mineral used of course to add flavour in food. Most of the salt produced though is used for chemical processes. Another use is de-icing of roads in Northern countries. Total worldwide production of salt is around 200 million tonnes. When large amounts of salt enter the soil, degrading the soil hampering plant growth.

Maltodextrin. Maltodextrin is retrieved from starch. Starch has very similar properties as maltodextrin and can be used as a replacement in 3D-printing. Starch is a carbohydrate, a complex polymer which can be retrieved from starch-rich crops such as potatoes, corn, rice and cassava and like salt it is cheap. It is fully biodegradable. Another possibility is to retrieve starch from algae. Certain species have a starch content of up to 40%, from which 90% is harvestable. (Barbosa, 2014)

Water. There is not much water available in desert climates but the amount needed is very small making the process feasible.

Alcohol. Obtained from fermenting sugar-rich crops and fully biodegradable.

Epoxy. Polymers derived mostly from petrochemical processes. Some epoxies can be made from glycerol, a byproduct from the production of biodiesel (supply is expected to exceed demand by a factor six in the year 2020) (Christoph, Schmidt et al, 2006). Epoxies are organic compounds (like plastic) and will deteriorate under UV-light and will need to be replaced after 5-7 years of use. (Wikipedia, 2014). Commercial epoxies are not fully biodegradable yet. Currently research is being done at the UvA to create fully biodegradable epoxies. (UvA, 2011).
The only coating used in this experiment is epoxy. Other suitable coatings may exist but are not included in this research. It is up to other researchers to find out what the best coating is for the material.

Part 5 - production process

Due to the lack of access to a powder printer the production process followed for creating testing sticks was different.
First, the salt was grinded in a coffee grinder. Then the starch was added creating a fine powder mixture of 8 parts salt and 1 part starch. Then water is added. Alcohol is not necessary with this production method since there is no print head.
Adding the water turns the mixture into a non-newtonian fluid which feels hard to the touch but soft in the hands. In order to harden the substance heat is added in either the microwave or the oven.

The amount of water added in this experiment is more than described by Mark Ganter. This is to make sure the mixture spread well and to create a homogenous material. The result is though that more heat needs to be added in order to evaporate the extra water. This extra water can cause little bubbles in the mix leading to weakened structural strength.

Image 8. Several salt bricks (Geboers, 2014)

The bricks shown on the previous page are retrieved from the microwave and ordered by thickness, starting from the top right going counter-clockwise. There is a clear difference in surface finish. The difference in surface finish indicates the presence of bubbles in the material. The bubbles are a result from the extra water added and increased thickness of the layer.

One material property can be identified from the bricks. The salt brick is slightly translucent meaning silhouettes can be identified when a light is shined on it. The amount of translucency is dependent on the thickness and the clearness of the material, it appears that bubbles in the salt negatively impact the translucency.

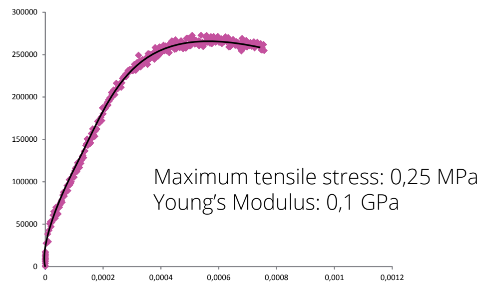
After retrieving the salt from the moulds it feels hard and brittle to the touch. The material can be sawn using either a hacksaw or a belt saw. It can also be sanded using rough 80 grit sandpaper.

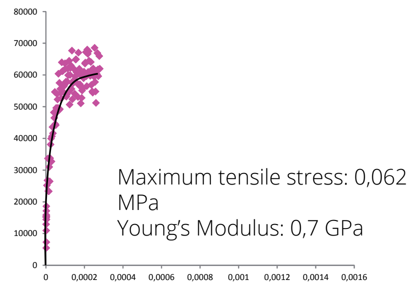
Several testing sticks were retrieved from the salt bricks in order to test their structural properties as shown in the image below. In order to waterproof the sticks a coating of injection epoxy is applied. This coating makes it impossible to fingersand the sticks and changes the hue from clear white to white with a slight yellowish tint.

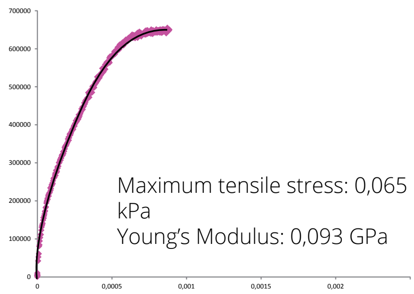
Image 9. Salt testing sticks (Geboers, 2014)

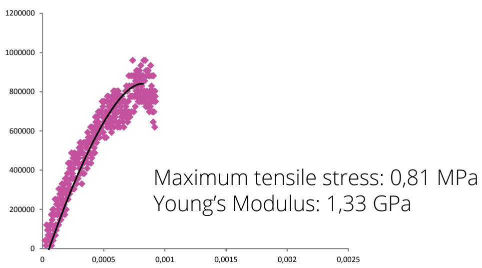
Part 6 - Tensile strength and Young's Modulus

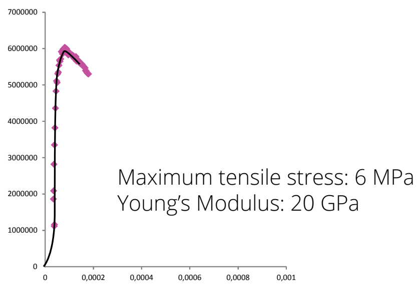
The beams were tested on tensile strength with a UTM. The aim is to retrieve the tensile strength and the material's Young's Modulus. The result per beam however has a large amount of variation. This means the composition of the beams was not homogenous and there were still bubbles of air left, making the material crack on unexpected moments or with little pressure applied. Therefore the test results shown in the graphs below are not suitable for retrieving solid data.
It must be noted that the testing was done with epoxy coated sticks, making the material slightly stronger.











Graph 1 to 5. Stress-strain curves and the difference in test results (Geboers, 2014)

To get an accurate measurement the production process of the beams needs to be standardised to acquire similar density throughout the material. Due to time constrains this is not included in this research and it is for a next researcher to measure.

It can however be deduced that the tensile strength of the salt-based material is fairly low. The material cracks easily with fairly low amounts fo pressure. The hypothesis is that its compressive strength will be comparatively high. This can be found in the next chapter.

Part 7 - Compressive strength

The compressive strength is calculated by putting pressure on a salt cube. The force is measured by the machine and divided by the surface area of the cube on which the pressure is placed. This lead to the following results.

	l in m	b in m	A in m2	Fmax in N	Tension in Pa	
1	0,017	0,017	0,000289	1730	5986159	
2	0,018	0,016	0,000288	1660	5763889	
3	0,018	0,018	0,000324	1380	4259259	
4	0,016	0,016	0,000256	1170	4570313	
5	0,017	0,018	0,000306	1300	4248366	
6	0,017	0,016	0,000272	1870	6875000	
7	0,018	0,015	0,00027	1250	4629630	
8	0,018	0,018	0,000324	970	2993827	
9	0,016	0,017	0,000272	2060	7573529	
10	0,017	0,017	0,000289	1720	5951557	
					5285153	N/m2

Average max compression strength:	5,285153	MPa
Standard deviation:	1,313287	Mpa

The standard deviation is large. This is again because of the non-homogenous material by fault of the lacking production process. Improving and standardising the production process will decrease the standard deviation.
To put this number in perspective we can compare it to the strength of concrete. In The Netherlands, concrete is divided in strength classes based on the 'karakteristieke druksterkte', or charactaristic compression strength. The demand is that at least 95% of the concrete in this class is of the right quality. The formula to calculate this compression strength is:

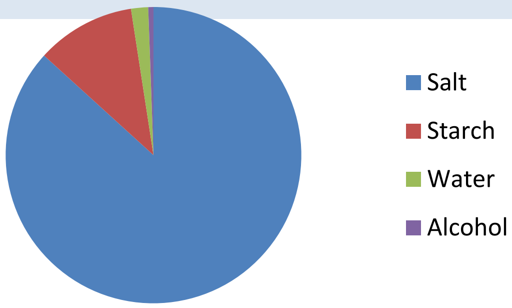
$f_K = f_M - 1{,}64 * s$

f_M Here is the average value of 5,28 MPa in the case of salt. This leads to an f_K of 3,43 MPa.

The concrete classes start with class C8/10. This means an fk of 8 MPa for a cilinder-shaped test piece or 10 MPa for a cubic test piece. The salt is currently around three times weaker than low strength concrete. In the following chapters this comparison is explored further.

Part 8 - Density & material comparison

The measuring of compressive strength is useless without a measurement of the density. The following table shows the expected density based on the material ratios that are already deduced.



Material	Ratio in kg	Density	Volume
Salt	1	2,17 kg/l	0,46 l
Starch	0,125	1,50 kg/l	0,08 l
Water	0,028125	1,00 kg/l	0,03 l
Alcohol	0,009375	0,79 kg/l	0,01 l

Total weight:	1,16 kg
Total volume:	0,58 l
Total density:	1,99 kg/l

Keeping this information in mind the density of the salt bricks is measured. The goal was mainly to determine if there was air in the bricks and if so, how much air is in the bricks.
The table below shows the average density of the measured salt blocks.

No.	Weight in g	Volume in ml	Density in g/ml
1	109	90	1,211111
2	33	30	1,1
3	53	45	1,177778
4	67	65	1,030769
5	34	30	1,133333
6	32	25	1,28
7	24	20	1,2
8	37	25	1,48
9	29	20	1,45
10	32	25	1,28
		Average:	1,234299
		Standard Deviation:	0,136248

The comparatively large standard deviation and low density mean that there is a significant amount of air left in the material. .
The difference between the expected density and the final density is 0,73 kg/l. This means that in every kilo of salt brick material there is now 0,31 liters of air. With a standardised industrial process this amount will be much lower.

The salt mix is compared to other materials in the following graph, based on compressive strength and density. As seen in the previous chapter, salt has a compressive strength of at least 5,3 MPa. This number is not final and is likely to be higher. The researcher's speculation is that with standardised industrial production (under which 3D-printing can be counted), it should be able to reach 10 MPa. It should be repeated this is a personal suspicion and not yet confirmed.

Compressive strength and density comparison

	Compressive strength in MPa		Density in kg/l	
Soil brick	1,5	up to 4,5	2,65	
Rammed earth	4,3		1,54	
Ice	5	up to 25	0,93	
Salt brick	5,3	up to ?	1,23	to 1,99
Masonry wall	7	up to 15	1,8	to 2,1
Concrete (low performance)	14	up to 42	1,68	to 3,00
Common house brick	20	up to 40	1,4	to 2,4
Cedar	27		0,38	to 0,58
Oak	46		0,6	to 0,9
Marble	50	up to 65	2,6	to 2,8
Pinewood (yellow)	58		0,42	
Concrete (high performance)	70		1,68	to 3,00
Clay brick	100		1,8	to 2,6
Granite	100	up to 250	2,7	
Glass	1000		2,4	to 2,8

The table shows salt is a fairly weak material compared to 'modern' construction materials such as concrete and masonry. Itt also shows that it's strong compared to ancient materials with which constructions were built such as ice (iglo's) and rammed earth (countless desert communities).

On the next page this information is more clearly displayed in a graph showing the range of density and compressive strength of different materials.

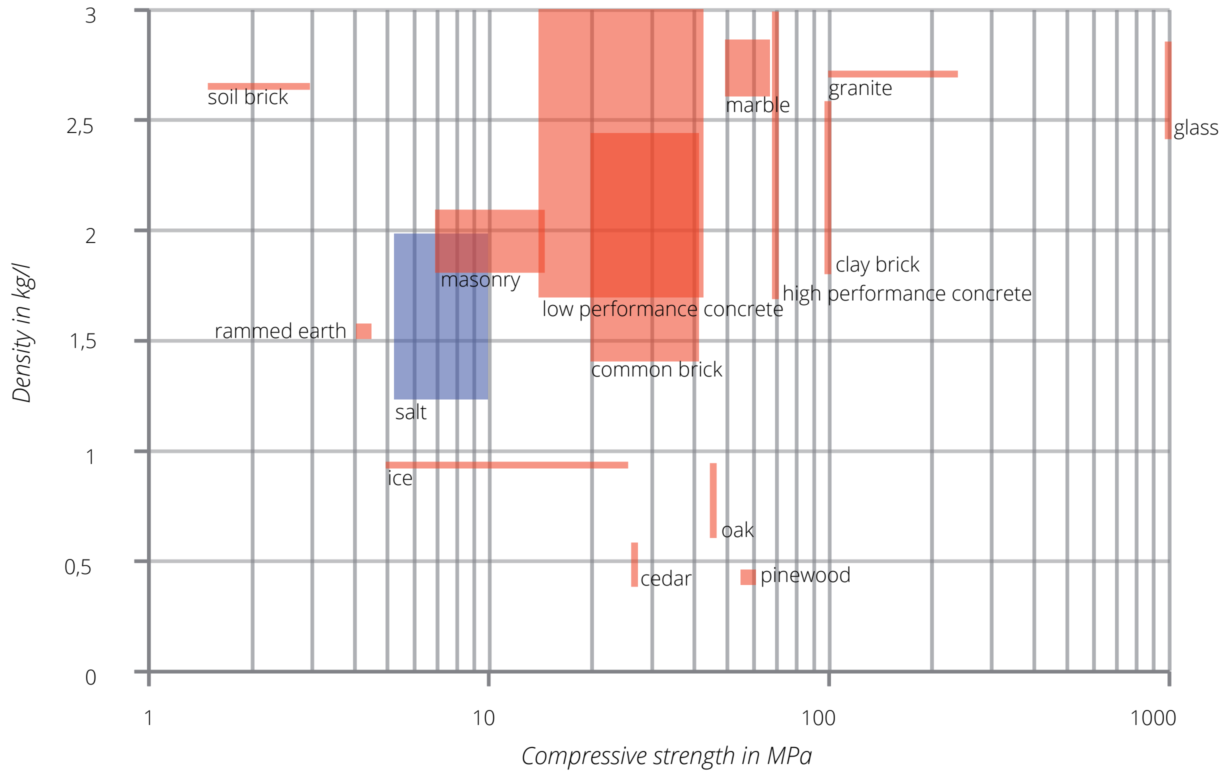


Image 10. Comparison of density and compressive strength of salt and other materials (Geboers, 2014)

This graph shows the range of densities and compressive strengths of different materials in red compared to salt in blue. When picking a material it is somewhere in the range shown in the graph. Beware that the graph has a logarithmic scale on its x-component.

In the graph it becomes very clear with what materials we must compare salt when we think of making buildings. The salt is stronger than rammed earth with a similar density. It is in strength similar to ice yet slightly heavier and on the upper end of the spectrum it has some overlap with masonry constructions.

Knowing that there is still progress to be made in the refining of the production process and recipe, the conclusion is that the salt brick has significant potential as a building material. The Conclusions section shows to what kind of structures the material will lead to when used as load-bearing elements.

Part 9 - Young's Modulus

After determining the material's compressive strength and density it is necessary to determine the Young's Modulus of the material. This is because knowing the Modulus is key when calculating the thickness of all construction types. Part 6 of this chapter shows inability to deduce the modulus from the tension/stress diagrams due to the non-homogenous composition of the material, a result of the DIY production process. Therefore the salt is compared to existing materials based on composition and density to give an estimation. The density of the material is between 1,23 and 1,99 kg/l and the material consists of a mineral (NaCl) and a complex polymer (starch).

Using the Cambridge Mechanical Engineering department's material sheet the salt is compared with existing materials. The estimation is that salt will have a Young's Modulus between 3 GPa and 11 GPa: somewhere between MDF and low grade brick/ceramics. This needs to be accurately determined by a next researcher.

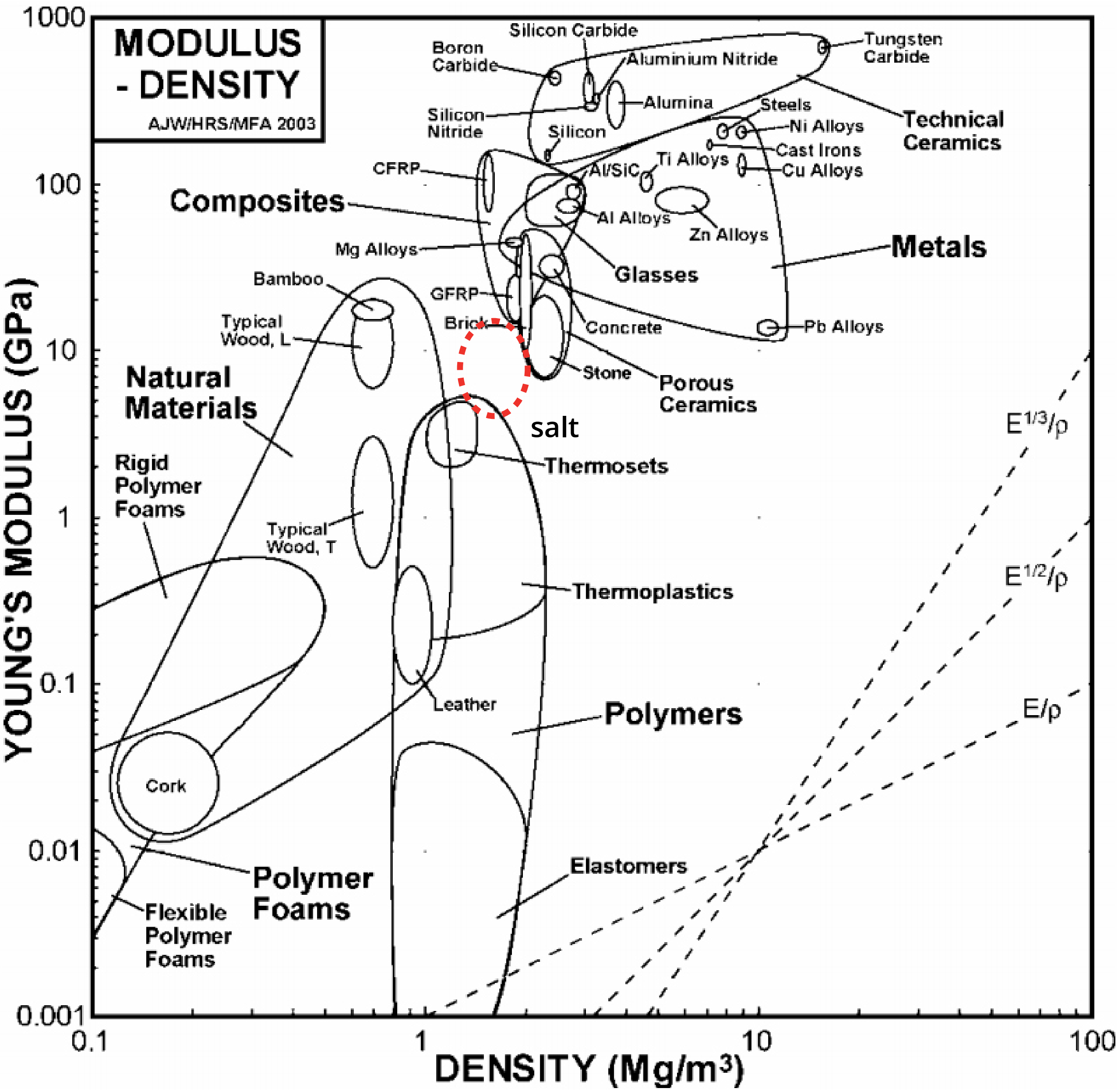
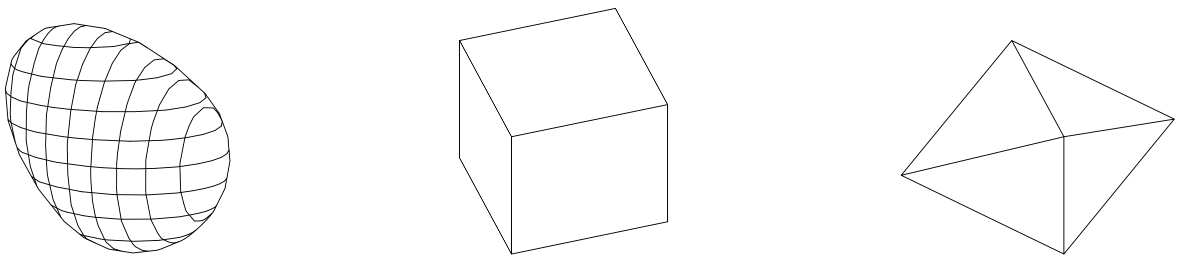


Image 11. Comparison of density and Young's Modulus of salt and other materials (Cambridge, 2003)

Part 10 - A Microscopic scale

To determine the material's potential for improvement the microscopic scale is explored. This means looking at the starch grains, the salt crystals and the influence of water and heat.

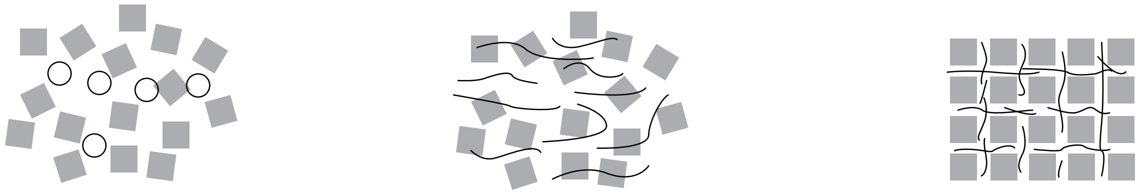
A starch grain is a polycrystalline structure. It is an organic molecule that is ordened along a clear pattern, as seen in the simplified image below.
Salt is also a crystalline structure. NaCl crystals are little cubes. Different salts form different shapes of crystals, but NaCl is the most common kind. $NaSO_4$ is different for example, it's structure looks more like two pyramids with their bottoms attached.



Starch grain NaCl $NaSO_4$

Image 12. Structure of starch, NaCl and $NaSO_4$ (Geboers, 2014)

When exposed to water the starch molecule starts to dissolve and forms long strains, making a gel-like structure where the strains are semi-ordened. A part of the NaCl will dissolve in the water as well, depending on the amount of water added. Most of the salts will remain in their cubic crystalline form. The mixture turns into a non-Newtonian fluid (as described in Part 5).
When adding heat to the solution the water will evaporate, leaving the long strains of starch to form an amorphous structure (similar to how cotton candy is an amorphous structure of sugar). The strains will stiffen and form a strong bond, keeping the salt crystals together. This means that the 'strongness' of the material is dependent on several factors involved in this process. (Meesters, 2014)



Powder Powder + water Powder + water + heat

Image 13. Formation of the solid material(Geboers, 2014)

The formation and structureof the material can be compared to concrete, where starch works as the cement and the salt is the aggregate. This means that like with concrete, the material strength is dependent on several factors described below.

The first factor is the ratio between water, salt and starch. This is covered by the research of Mark Ganter to which is referred in part 3 of this Results section.

Other important factors are particle size and particle distribution. Currently the particle size is random and retrieved from the grinder unsifted. With an optimized particle mix the material will end up being stronger. What this particle mix is exactly is up to the next researcher.

Then the different salts and their crystal types come into play as well. This needs to be kept in mind when using sea salt, which is a mixture of different salts and minerals.

One could go further and try out mixes with small amounts of sand as a second aggregate. It might well be that adding a small amount of silicate (sand) to the mix will result in a stronger material. Again, this depends on the particle size and particle distribution. To figure out what the best mix is is up to the next researcher.

Conclusions

This conclusion is a guideline for designers who wish to design with the salt-based material. The material is fit for several purposes, both load-bearing and non load-bearing. There are also several ways of connecting the material. The guideline starts with an overview of building with salt as a load-bearing structure and it gives several rules of thumb for dimensioning structures. Then several possible building elements and connections in salt will be shown. After that an overview of the material's other properties is given. Lastly the article concluded with a case study of a living unit in a long-stay apartment completely made out of salt.

Salt as a supporting, load-bearing material

When using salt as a load-bearing structure one should design structures based on compression. When doing that there are three options: designing an arch, designing a dome or designing a (computer generated) composite. The image series below show several structural typologies for doing so.

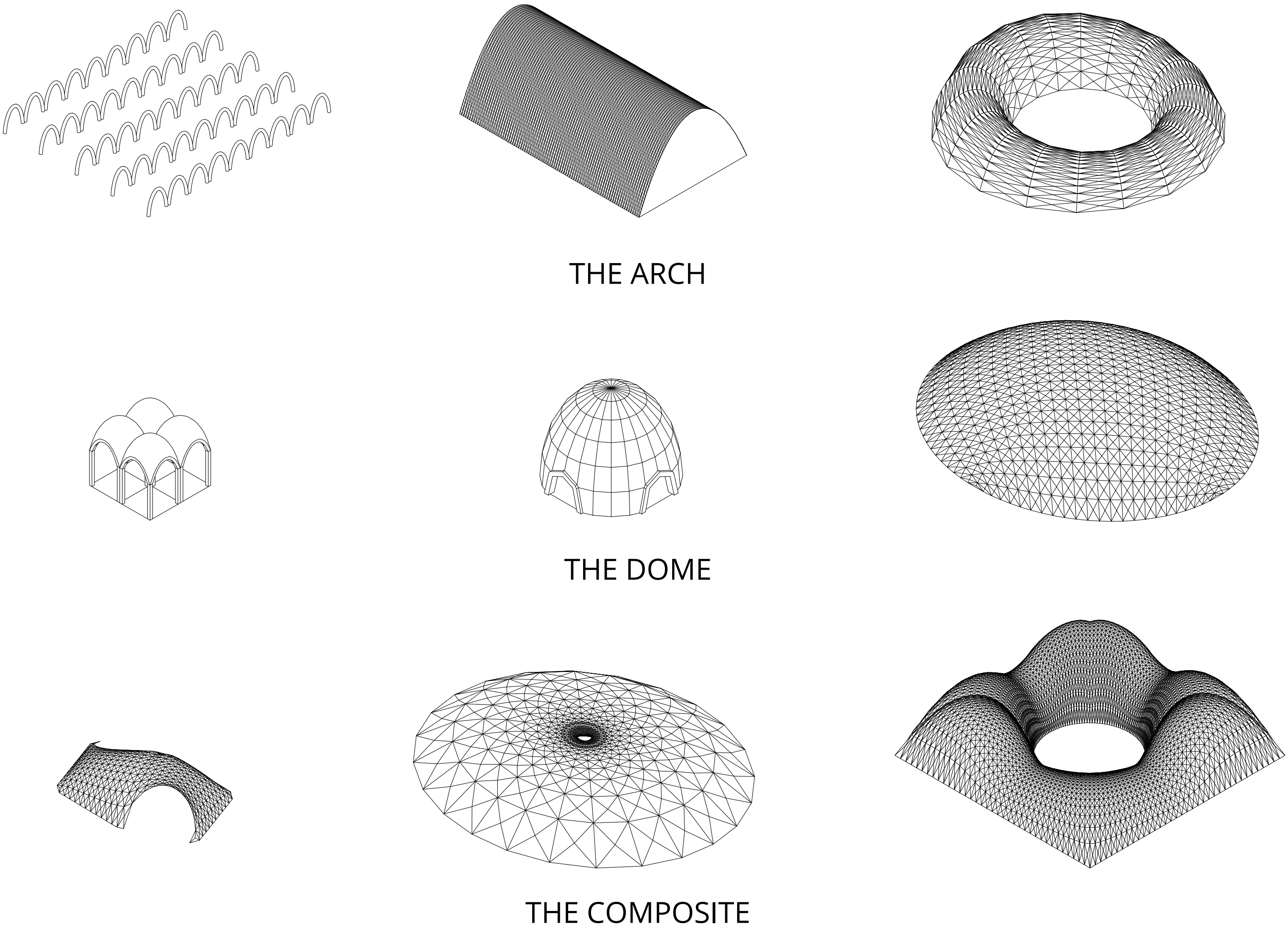


Image 14. Different structural options based on compression (Geboers, 2014)

There are three types of constructions: construction based on an arch (a barrel vault is a series of arches), construction based on a dome (which is a series of arcs pivoted around a point) and a composite which is usually computer generated.

The structures can be printed as one or printed as a series of elements that need to be connected to each other on site. The elements are then all differently sized and must be carefully organised. It is up to the specifics of the site, the architect and the builder how to organise this process. Printing a building in one makes it difficult to transport but easy to put together, printing a building in elements makes it easily transportable but can lead to complicated scaffolding and a puzzle on site.

The material's compressive strength and density will lead to fairly thick structures compared to concrete. But, when 3D-printing one can determine exactly how much material is needed at every place, allowing the designer to vary thickness along the arch which can thus make for sleeker structures.

Rules of thumb for designing with salt

The strength and density of the salt are between that of rammed earth, ice and masonry, so by looking at structures from those materials we can get an idea on construction dimensions. Three buildings are shown: one made out of ice, one out of brick and one out of rammed earth.

This ice hotel in Sweden shows the structural possibilities of ice. It consists of several barrel vaults made from a mixture of snow and ice. The span is around 5,5 meters and the height of the vault around 4 meters. The material is likely to be stronger than the salt described in this article. (ThesDIP, 2014). Because of the weight of the snow it likely has a very high live load, meaning a significant increase in dimensions


Image 15 & 16. Ice Hotel in Sweden, arches made from snow and ice (ThesDIP, 2014)

Image 17 & 18. Bricktopia pavilion designed with Rhinovault (Block13, 2014)

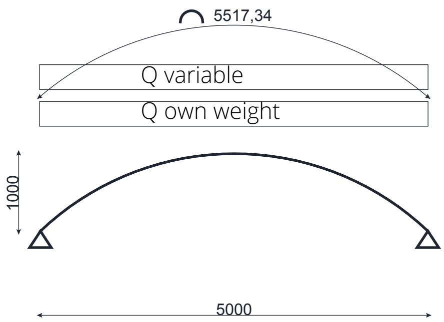
This pavilion called ‘bricktopia’ was designed to showcase the possibilities of Rhino plug-in rhinovault with which structures based on compression can be generated. (Block13, 2014) It is built from bricks and mortar, a material stronger than salt but also heavier. The use of computer-generated geometry leads to very sleek structures.

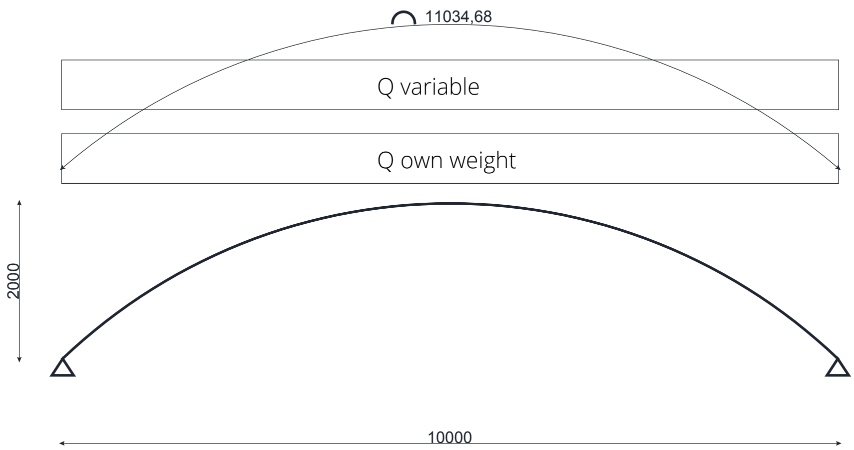

Image 19 & 20. Tamera eco-village in Portugal, built with rammed earth (Open Source Ecology, 2014)

This structure is based on the ‘nubian vault’, vaults originating in Africa using rammed earth as a construction material. This very structure consists of 3 catenary vaults made from rammed earth with on the front a stone surface finish. (OSE, 2009).

Building arches is very material efficient. In the desert the live load is low since there will be virtually no rain or snow load. For climate and production reasons it makes sense to build efficient barrel vaults in which construction and skin works as one. On the next page two barrel vaults are dimensioned to give an impression of the size of the structures we are dealing with.

Árch thickness is dependent on several factors. First of all the arch needs to have a certain height otherwise it works as a beam: it still takes on tensile stress. From a height of 1/5th of the width of the arch the structure will work as an arch taking on only compressive stress. An arch with a width of 5 m thus needs to be at least 1 m high. When the arch is higher than that it will become more material efficient (Nijsse, 2012).





Two examples of an arch construction are shown.
In this example both arches work as a barrel vault where the beam has a width of 1 m. Both arches were calculated on usability limit ("BGT"), ultimate limit ("UGT") and buckling using Euler's formula as both a roof and a storey. For calculating buckling and the usability limit a range of Young's Moduli between 0,5 and 10 were used to minimise risk. Safety class 2 and fitting capacity factors were used, meaning a residential function. (Van Boom, Maessen et al, 2008)
This information lead to the following arch heights and ratios between span and height.

	Span	Arch width	Arch heigth	Ratio span/height
Floor	5	1	0,17	29,4
Roof	5	1	0,13	38,5
Floor	10	1	0,45	22,2
Roof	10	1	0,43	23,3

Following the square-cube law the arch heights increase faster than the span. As a general guideline the following can be used:

- Storey floors up to 5m: *h = 1/30*l*
- Roofs up to 5 m: *h = 1/35*l*
- Storey floors up to 10 m: *h = 1/20*l*
- Roofs up to 10 m: *h = 1/23*l*

This is a very general guideline for arches with a height of 1/5 of the width and with a maximum span of 10 meters. In other situations (large and small spans, large wind load) the advice is to calculate the arches using the standard method of checking the arch for usability limit ("BGT"), ultimate limit ("UGT") and buckling using Euler's formula.

Elements

Walls

The translucency of the material makes the salt an interesting choice for thin room separating walls or non load-bearing walls. When 3D-printing one could vary the thickness of the material, thus playing with the translucency. Any shape is possible, which means in the design process many functions can be integrated into the material, saving time and money during construction. Below a few possibilities are outlined.

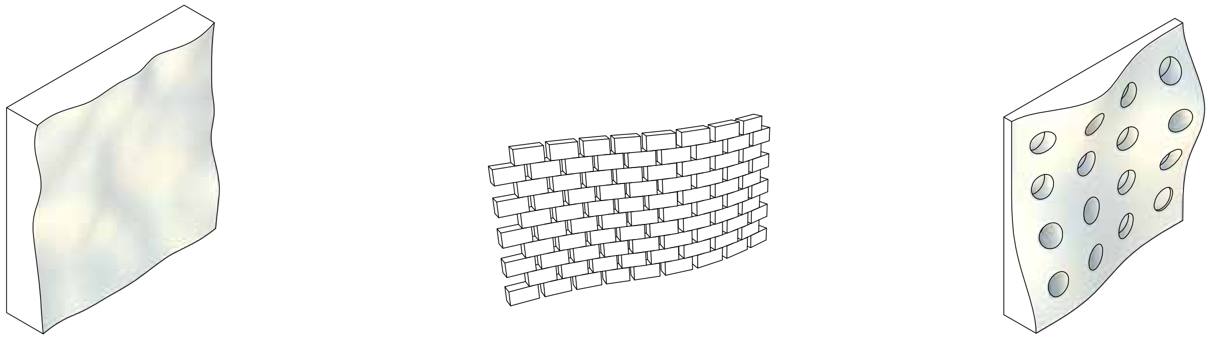


Image 26. Three different wall options (Geboers, 2014)

The first example is a standard non load-bearing wall. By playing with the thickness of it the translucency will vary, making for very exciting light and shadows. The second example is a simple semi-transparent wall. By playing with the size of the blockwork interesting shapes are generated. In the last example the furniture is directly integrated in the wall. Ducts for piping and wiring can also be integrated during printing, saving much time and money.

Floors

The hardness of the material after coating makes it very suitable for floor and wall tiles. The material will need to be given a suitable thickness and possibly an extra thick coating with epoxy. This can lead to very interesting floor patterns and even varying heights of the floor. Integrated furniture is also possible.

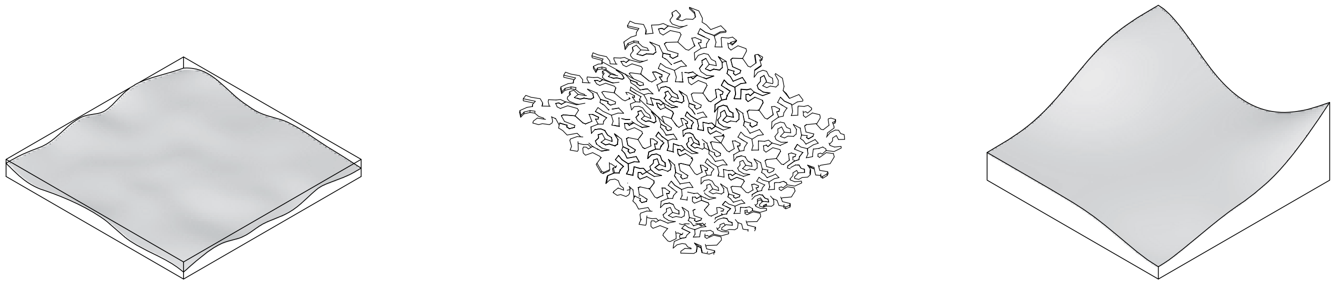


Image 27. Three different floor options (Geboers, 2014)

Again in the image series you see three different types of flooring. The first one is a fairly simple floor. The height is varying and then finished with a transparant epoxy layer making for an exciting ‘rocky river bed’ effect in the floor.
The second one is an example of what can be done with tiling. Since every tile can be different, bent and curved tiling patterns can be made for no extra cost.
Lastly an example of integrating a furniture system directly in the floor is shown. The salt can make for new interpretations of living and working by integrating a full-scale landscape system in the floor itself for only the added cost of more material.

Openings

In the 3D-printer everything can be integrated so in theory one could integrate salt window frames as well. Using a salt window frame with a glass panel though will lead to the salt breaking fairly easily as it is not very flexible. It could also scratch the glass. There are several better options, shown below.

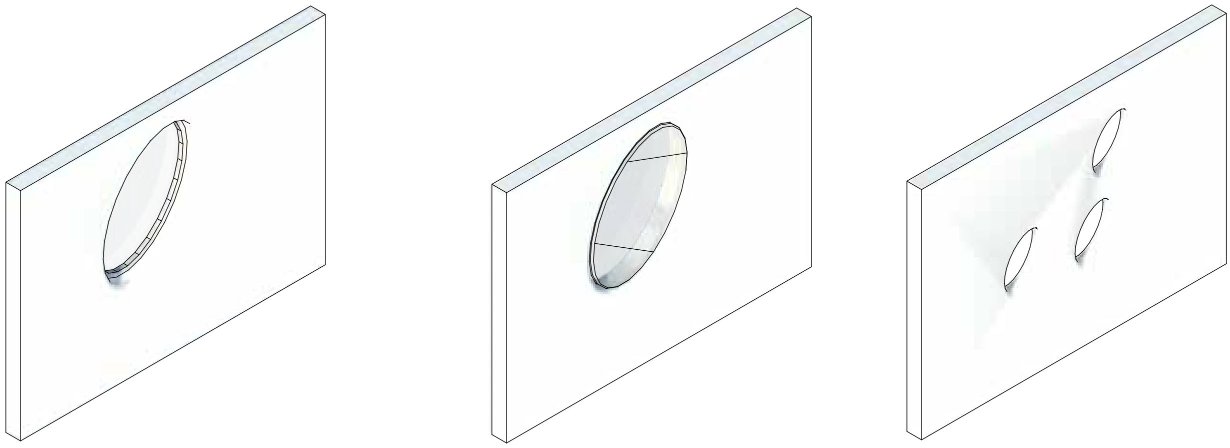


Image 28. Three different wall openings (Geboers, 2014)

The first option, if one wishes a glass panel, is to print a frame in which wooden or aluminium standard window frames can be placed. This is straightforward and will make for easy assembly on site.

The second option is to not use glass but instead use ETFE pillows. These pillows are very light and thus won't put a large strain on the salt. ETFE is UV-resistant, fully recyclable and self-cleaning. The salt can be printed in such a way that the pillows can be inflated easily.

Finally there is a last option and that is to not fill up the hole with another material. This is a suitable option for small windows on the first floor and above. It means great natural ventilation, it is non-taxing for the salt and in the desert there is hardly a reason to worry about rain coming in. Wooden boards to cover the holes during dust storms or when not at home can be imagined.

Connections

An important thing to keep in mind when 3D-printing with salt is the limit of the printer. When using Enrico Dini's D-Shape the limit is a print volume of 6x6x6 meters. If the piece one wishes to construct fits in this cube it can be printed as a whole. If the piece is larger than that it needs to be built up from elements. There are several ways of connecting those elements.

The objects can simply 'click' together as seen in the image below. Key to this is maximising the contact surface in order to make the connection as solid as possible. To make the material stick together you can use the same salt, starch and water mix used in the printer as a mortar. Just add more water to the starch and salt mix until you get a thick paste, apply it to the material and stick it together. The sun will then harden it out. A coating of epoxy or a different water repellant resin is then needed to keep the water out.

When the elements are thick enough they can simply be 'glued' together using the very same mortar.

The last option is to use a different material, for example steel, as a light-weight 'web' in which you then hang the salt panels.

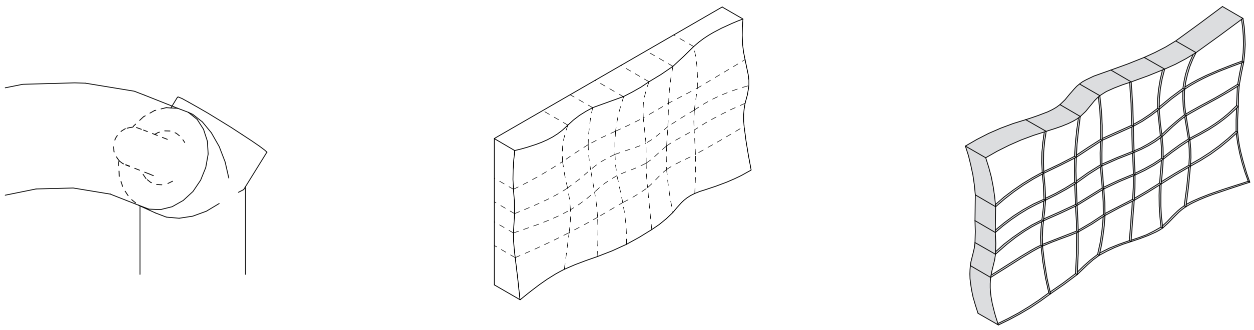


Image 29. Three different ways of connecting (Geboers, 2014)

In the image above the three ways of connecting the salt are shown. The first image is an arch attached to a support using the click system. The contact surface is maximised. In the second image you see the salt blocks glued together and lastly you see the metal support web where panels are suspended in.

Other material properties

Hardness

The salt is very hard. It is difficult to scratch the surface but possible with a metal object. When sawn in half, the opened new surfaces are not resistant to finger sanding, the moisture of your hands will allow you to take some of the material off. After epoxy coating this is no longer possible, and only a serious attempt at assault with a metal object will allow you to scratch the surface.

Reaction to UV-light

The salt and starch mix itself has no reaction to UV light, it will stay very white. The epoxy however goes from a very clear and fully transparent to a slightly more yellow-brownish colour. Depending on the type of epoxy coating chosen, a new coating might be necessary after 5-7 years.

Reaction to moisture

The base salt material before coating will dissolve in water quickly, leaving only an aerogel of the starch behind. All the salt will be washed away. Therefore it must be protected with the epoxy coating. It is essential that the epoxy coating is covering all surface area of the material. The desert environment is dry, but a small hole in the coating can lead to 'rot', moisture eating the material away. The epoxy will not hold against continuous submersion so this must be avoided. A simple household test showed to what exposure to moisture can lead to. Three salt testing sticks (coated once in epoxy) were left in a moist environment for a week. It became obvious very quickly that the coating was not done well. The sticks swelled up and lost all structural strength. In the desert we won't find these type of conditions often but it is clear the coating must be done carefully and completely.

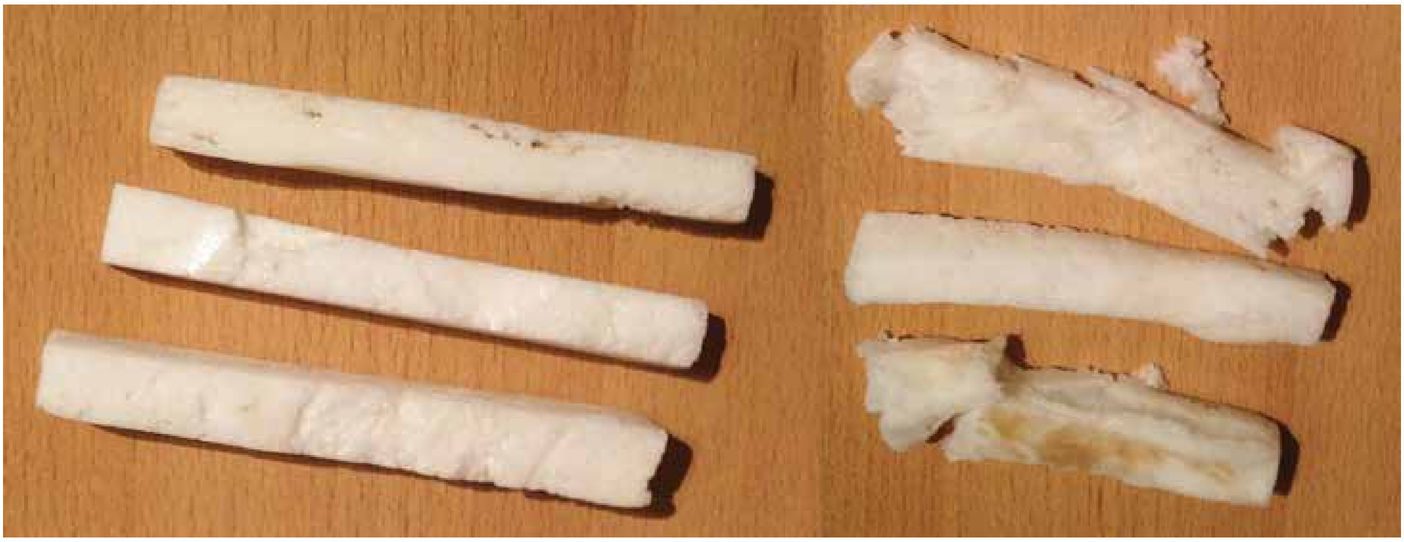


Image 30. On the left: normal salt testing sticks, on the right: testing sticks affected by moisture (Geboers, 2014)

Heat capacity

The heat capacity of a structure is its capability to store heat (or cold). This is very relevant in a desert climate since because of the large temperature differences. Having a construction that stores heat during the day and releases it in the cold nights (and vice versa) would be very beneficial.
The heat capacity of a structure is dependent on its mass m and a material specific c in J/g/K. The material specific factor of the salt is unknown (so far) and the density is similar to that of rammed earth. That the compressive strength of the salt is a bit higher than that of rammed earth, leading to sleeker structures. Rammed earth is the most common material used for creating thermal mass in desert climates. The salt constructions will not be as thick as those of rammed earth but they will still have a significant thickness. The exact heat capacity of salt is for the next researcher to find out.

Colour & translucency

After printing/baking the material has a very clear white colour. Adding the epoxy coating makes the material have a slightly more yellow/brownish glow. It is possible to add a pigment to the powder mixture to change the colour of the material.
As mentioned before, the material is slightly translucent. It gives a foggy yellow-ish white glow when a light is behind it. This gives of course fantastic architectural possibilities. Playing with the thickness of the material makes for different kind of shadows and illumination. Below you see the translucency of a 2 cm thick 'tile'.

Image 30. Translucency of the material (Geboers, 2014)

Conclusion - case study

As a final conclusion and to fully understand the possibilities of the salt material it is good to 'see it in action' by making a small design and incorporating the aforementioned techniques and possibilities. The design described below is a part of the Salt Plan as described in Appendix A of this paper.

The design is for a 2-person 'apartment' in a long-stay hotel, intented for use of up to 6 weeks at a time. The hotel room contains a little porch, a sitting area, a bathroom with shower and toilet, a double bed, a built-in closet and an integrated cupboard. Cooking and eating can take place in the shared facilities which are not designed (yet).
This unit can be copied and stacked to create an array of units. When using the 3D-printer, every unit can of course be different.

The construction is a simple barrel vault printed in 2 pieces and glued together using salt mortar. Because it is thick and heavy it will be a great heat accumulator.
The bathroom is fit in a fairly simple stretched dome large enough to fit a shower and toilet. The dome pierces through the thick outdoor vault allowing the water vapor to leave the building whilst also acting as a solar chimney. The inside of this bathroom dome needs special attention when it comes to coating.
The barrel vault is closed of with two free-form walls. The wall containing the glass door is set up with printed blocks. The thickness of the blocks is varied, allowing light to come in where it is needed and less light where it isn't necessary. The same goes for the wall closing the vault off at the very end of the hotel room.
Finally there are two means of storage. There is the integrated cupboard wall on the bathroom side for storing smaller things like books and there is a larger closet for clothes on the opposite side.

This design is not a final and 100% complete design. It does however show the virtually endless possibilities of both the material and the production method.

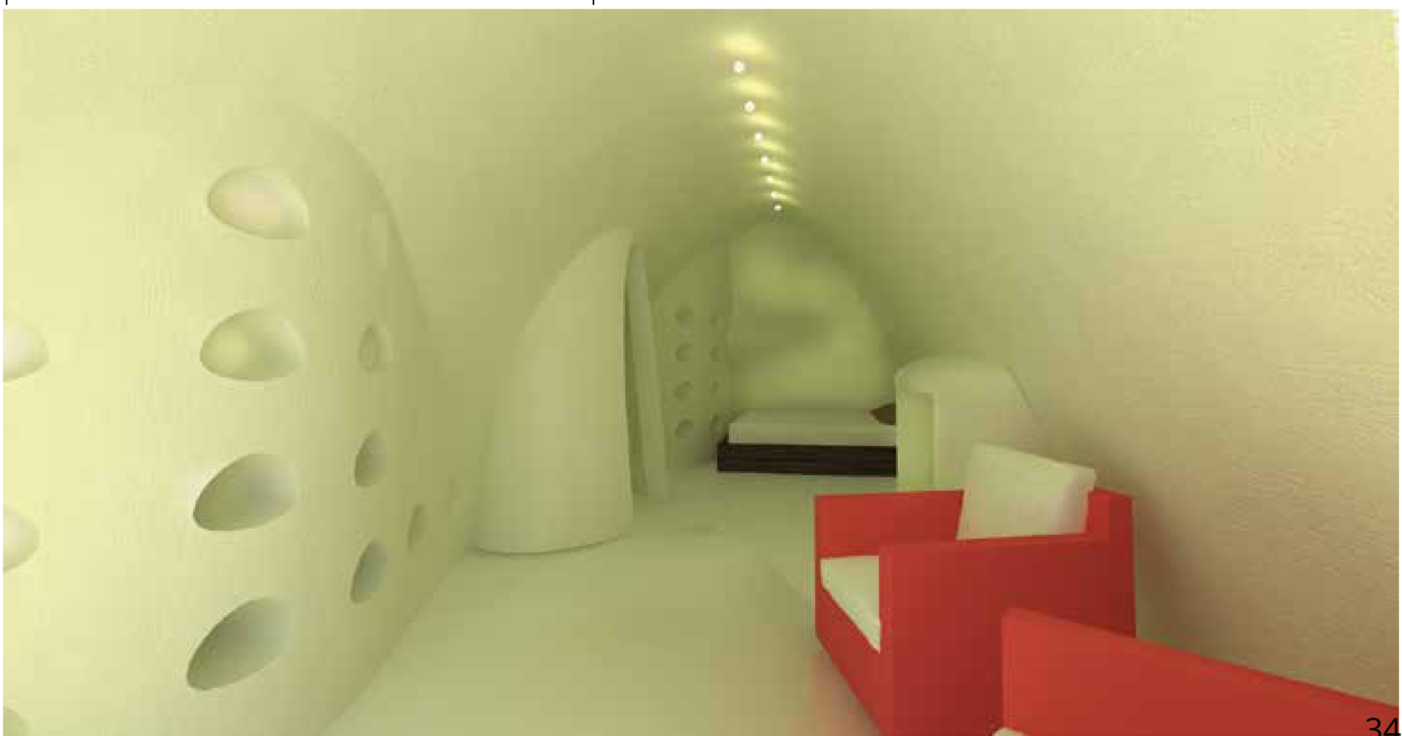


Image 31. Interior impression of the long-stay unit (Geboers, 2014)

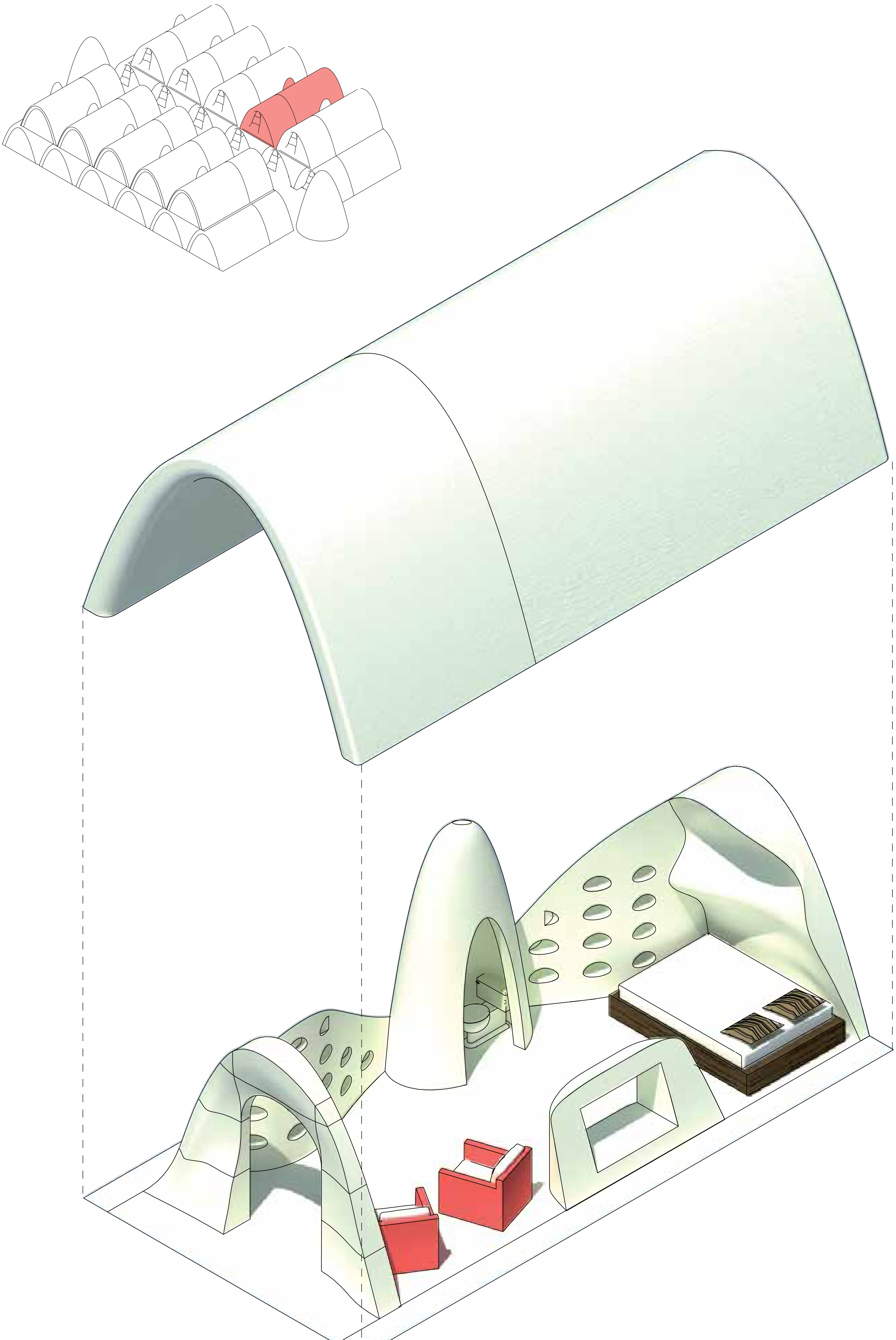


Image 32. Isometric impression of salt long-stay unit. (Geboers, 2014)

Final words & recommendations

Doing this research has been a bit of an adventure. When starting the research I had no idea where I would end up and how far I would be 'finished'. At this point I believe the research is very far from finished as this study has only been an exploration to the potential of salt as a building material.
Even though this study is far from complete I feel confident in saying that salt has a lot of potential as a building material. Early compressive and tensile strength tests give a lot of hope, especially when knowing there is a lot of room for improvement. In the article I mentioned this several times so I figured it'd be good to give a summary of what can be done by next researchers.
The next researcher can study different powder compositions, different particle sizes and distributions and various production means. The production process can be standardized and improved and the exact ratios of materials can be explored. The coatings can also be massively improved as epoxy is not yet completely degradable and bio-friendly; perhaps there are different coatings that can protect the salt better.
This will lead to better results when testing the salt, improved compressive and tensile strength and a much lower standard deviation. It will then be possible to calculate the exact Young's Modulus and give better rules of thumb and allow exact calculations for beam, arch and support size.
Several other material properties need to be determined. There is of course Poisson's ratio, the hardness of the material, the material's capability to store heat and many more.

Salt has several fantastic qualities that make it fit for building. Its strength, availability, translucency and colour make it an exciting material in desert environments that I think is very much worth further exploring. Of course salt will never be able to replace the versatility and strength of concrete or even low grade concrete but that is ok. Salt has many other advantages such as its ability to reflect the sun with its white colour, its low price and its low-energy production method.

After this research I believe salt can be a valuable building material in desert communities where the salt can simply be mined from the ground or retrieved from seawater using the heat of the sun. Its fantastic white colour and slight translucency can make for brilliant architectural solutions and its compressive strength allows for exciting compression based structures.

Acknowledgements

During this research I received a lot of great help and support. I would like to thank Ate Snijder and Jeroen de Jong for their help when it comes to 3D-printing. I would also like to thank Ger Wagenaar and prof. Erik Schlangen for their help with testing the salt. Another special thanks goes to Henk Nugteren and Gabrie Meesters of the Chemical Engineering faculty for their help in making me understand the material on the smallest scale. Lastly a special thanks goes to Tjalling Homans and Martijn Stellingwerff for their inspiring tutoring sessions.

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APPENDIX A

The Salt Plan & framework of this research.

In this appendix I would like to briefly show the context of this material research. The research started as mentioned in the introduction as a part of a grand masterplan aiming to grow crops and house people in the desert.

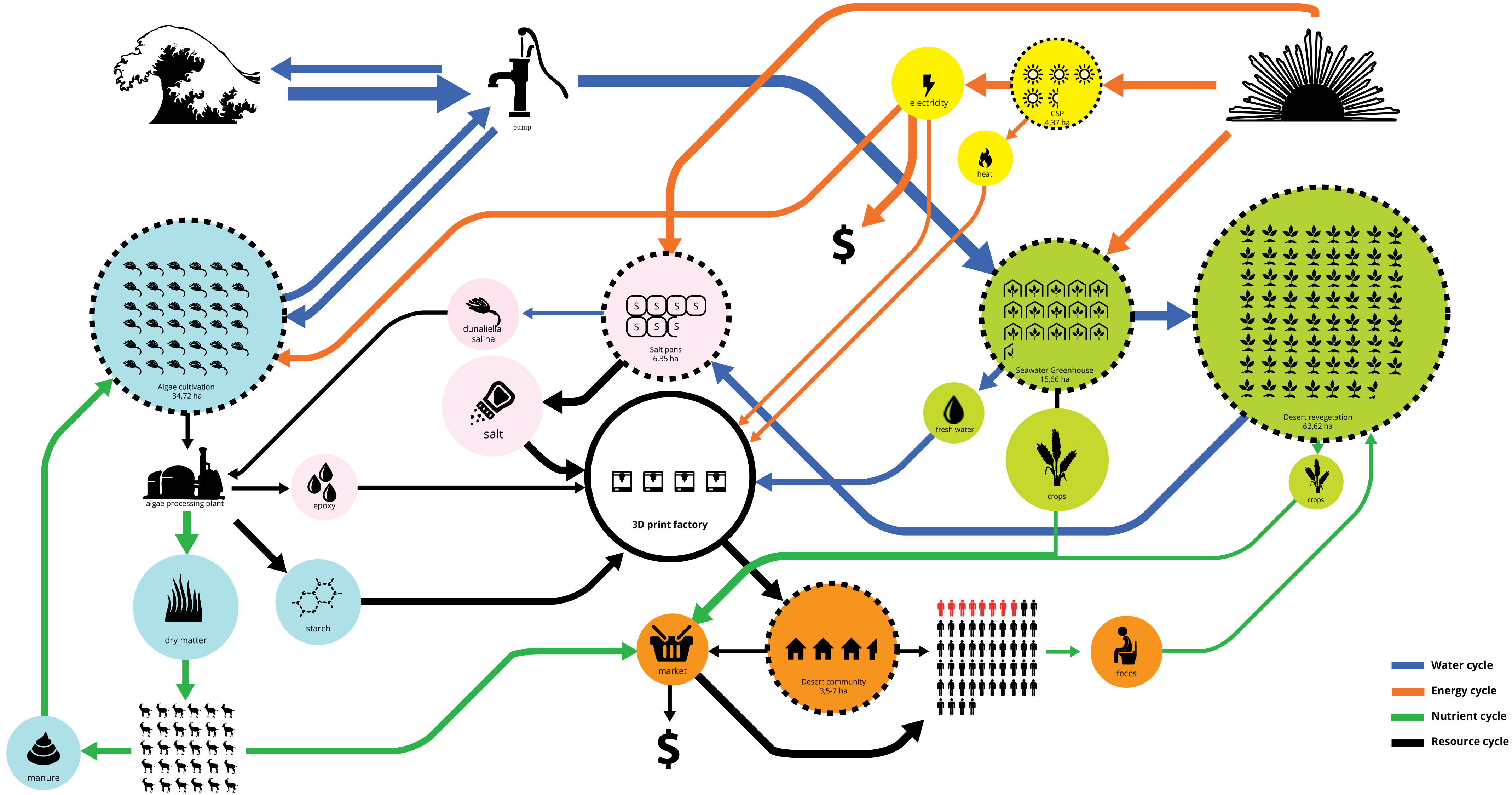
The idea is a culmination and combination of several ground-breaking ideas in different disciplines. It started with Janine Benyus's ideas on biomimicry. The important message she sends is about using local materials and building with solar energy. The next ingredients are the Sahara Forest Project and the Seawater Greenhouse. Currently they are doing very successful tests with using the plentiful sunlight in the desert to grow crops. For this they use seawater. Another important inspiration was the also already mentioned Emerging Objects research group lead by Raël San Fratello of Berkeley University in California. They have succeeded in 3D-printing with a range of different powder materials, one of them being salt.

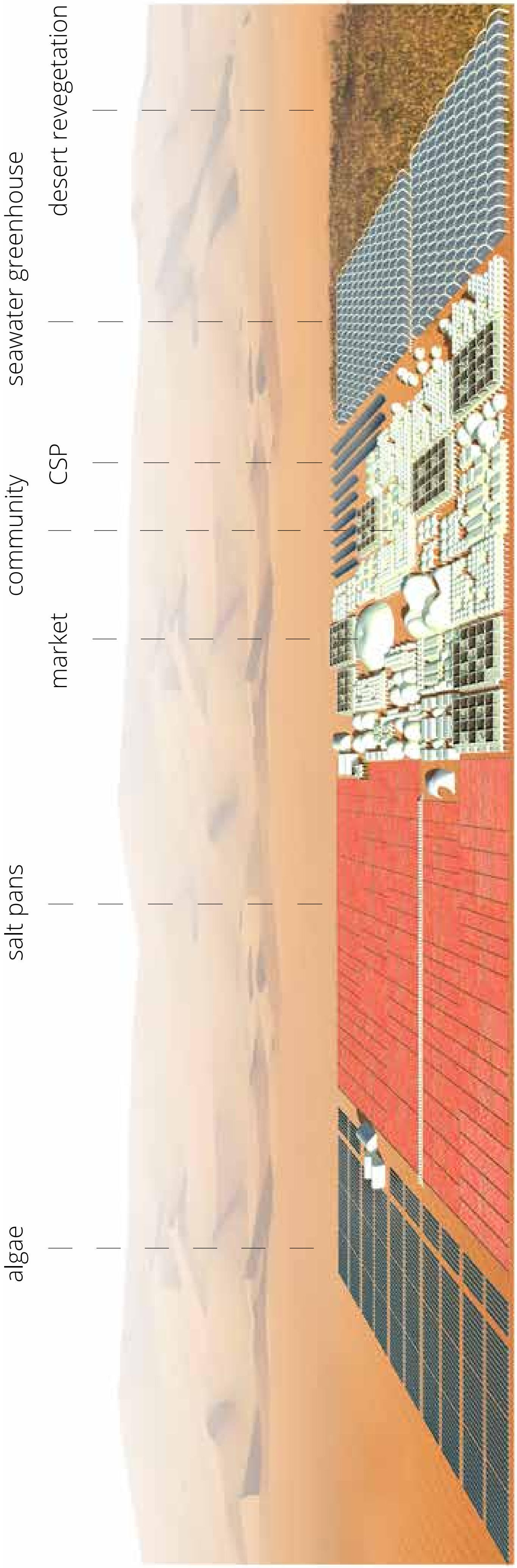
The plan is best explained with the scheme shown on the next page. Seawater is pumped to a desert location with a pump powered by solar energy. A part of the seawater is used to grow algae for starch, a key ingredient as we have learned. 40% of the algae is used for starch, the rest is dry matter used for feeding goats, whose excrement is then used to fertilize the algae. Another part of the seawater goes to seawater greenhouses. The damp they release at the back of the greenhouse creates good conditions for sturdy desert plants to grow, revegetating the desert.
Most of the water evaporates in this process, leaving a brine of now 20% salt. This brine goes to salt pans in which the remaining water can evaporate. In the brine a type of algae (dunaliella salina) can be grown. This algae contains a lot of glycerol: a key ingredient for epoxy.

Then we have all our ingredients to 3D-print with our salt. Thus a desert community town is created with housing, a market, shops, etcetera. Even the construction of the greenhouses can be printed, allowing for a scenario in which we start with just salt pans and algae and from this 'petri dish' a whole city can be grown.

The plan allows for a closed cycle of nutrients: human waste is deposited in the desert, enriching the soil and adding nutrients, allowing for more desert revegetation. This way I hope to create a positive cycle of upcycling with potential exponential growth.

The images show a city in year 20 of development, a fully functional scenario. The greenhouses feed over 4500 people and the masterplan employs around 800. This specific scenario covers around 100 ha of desert. 60 ha are desert revegetation.


pump
electricity
CSP
4,37 ha
heat
$
Seawater Greenhouse
15,66 ha
Desert revegetation
62,62 ha
fresh water
crops
crops
Algae cultivation
34,72 ha
dunaliella
salina
S S S S
S S S
Salt pans
6,35 ha
salt
algae processing plant
epoxy
3D print factory
dry matter
starch
market
Desert community
3,5-7 ha
feces
manure
$
Water cycle
Energy cycle
Nutrient cycle
Resource cycle



The Salt Plan early visuals

On this and the next page you can find some early renderings of what this salt masterplan will actually end up looking like. On the right you can find an overview with an emphasis on the community and the integration of the salt pans.
The water has a red tint because of the dunaliella salina (which are completely harmless by the way).

From left to right you see the algae organized next to the salt pans. This is because they share the algae processing facility.

The housing is organized next to the salt pans as the increased humidity will provide a slightly more liveable climate. The ommunity has a high density providing shaded streets. In the middle the market and a city hall are clearly visible and are organized around a central square.

Finally on the right you see first the CSP, the greenhouses and the revegetated desert at the back-end of the greenhouses.

It must be noted that the ratios of space for algae/community/greenhouses are not correct in this image. The ratios vary depending on the chosen scenario but typically the village will use around 6-7% of the total space in the masterplan, and the same goes for the salt pans.

On the next page you can see two preliminary renderings of the salt village when it is finished. I would like to repeat that they are (very) preliminary and they serve to give an idea of atmosphere, scale and materiality.

Eye-level perspective of the community, seen from the salt pans.

Perspective of the village seen from the roof of a long-stay unit.