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Optimal sand-clay mixture for sand sculptures

An experimental investigation

T̃U Delft

16 June 2016

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By

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in partial fulfilment of the requirements for the degree of

Bachelor of Science

in Civil Engineering

at the Delft University of Technology.

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TUDelft

Preface

This report was written as part of a bachelor thesis for Civil Engineering. During 10 weeks a literature study and experiments were carried out. Gratitude goes out to ir. P. Lubking for interviewing him and for the useful information that was provided by him. Gratitude goes out to dr. ir. L. van Paassen, who spent time and effort as supervisor and to A. Mulder who supported me in the lab. Ultimately, I gratitude goes out to Y. Kulshreshtha for reviewing this report.

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Delft, June 2016

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Abstract

Sand sculptures are an inspiration source for an environmentally friendly building material, consisting only of sand, clay and water. The art of sand sculpting is generally dealt with low technical consideration. There is a need of comprehensive technical look on this topic in order to make standards for sand-sculpting. This study involves literature and experimental investigation to find out the optimal sand-clay mixture for sand sculpting with focus on the best preparation method, optimal water content, highest strength and the development of strength over time.

Four sand clay mixes were prepared, 100% sand, 95% sand – 5% clay, 90% sand – 10% clay and 85% sand – 15% clay. Standard Proctor compaction tests were carried out to find the water content, at which the soil achieved the highest dry density for standard compaction energy. It was expected that the highest dry density corresponds with the maximum strength. On this water content, cubes of 3,5 cm on all sides were constructed. These cubes were tested on ultimate unconfined compressive strength (UCS), after oven drying (at 0% water content). Also the strength development over the drying time at room temperature was tested using the UCS.

The optimal preparation method was found to be to soak the clay in the water for 24 hours in small cubes to get the clay as liquid as possible. Then the sand can be mixed through without the presence of clay lumps. With the proctor tests it was found that the dry density increases with increasing clay content. The optimum water content decreases with increasing clay content and values ranged between 11% and 17%. Additionally, UCS values were found to be increasing with increasing clay content. The highest value of 1,2 MPa was recorded for 85% sand. 1,0 MPa was recorded for 90% sand and a significantly lower value of 0,4 MPa for 95% sand. The strength after a drying time of 3 days was found to be the same as for oven drying 1,2 MPa for 85% sand, 1,0 MPa for 90% sand and 0,5 MPa for 95% sand. However, these values are lower for a drying time of 8 days. This suggests there might be an optimum water content, that is higher than the equilibrium moisture content.

The results of this report indicate that a properly prepared mixture consisting of 15% clay and 85% sand at an optimum water content is suitable for an artist to make a strong sand sculpture on the beach.

1 Introduction

Nowadays, almost any building is constructed using steel or concrete. These building materials are transported everywhere. Often, good building materials can be found in the direct surroundings. Sand, clay and water are all abundant materials. Thousands of years ago, people were already building successfully with these (local) materials. The quality of the material that can be made from these local materials can vary a great deal. Which means that a lot of local research will be required to investigate the best building material. Whereas, concrete and steel are highly standardized materials and its research can be applied everywhere. Steel and concrete are known as highly environmentally unfriendly materials, local materials would help a great deal towards a more sustainable society. Some of the people who always have been building with sand, clay and water are sand sculpture artists. We can create a better view on these materials by looking at what has been done in the sand sculpture world and by investigating how to make a better sand sculpture.

This report answers the questions to how a sculpture sand with clay can be best prepared. In particular the following **research questions** will be answered:

- What is the best preparation method for a sand-clay mixture?
- At what water content can the highest dry density be reached for different sand-clay ratios?
- For what clay-sand ratio can the highest dried strength be reached?
- How does the strength of the mixtures develop over time for different sand-clay ratios?

This study includes a literature review and an experimental part. The literature review comprises the current state of knowledge in sand sculpting, sand clay mixtures and rammed earth. The experimental part involves an investigation to the best preparation method, compaction tests and unconfined compressive strength tests.

2 Literature study

2.1 Sand sculpting

Sand sculpture artists need a fine grained sand, because in their experience this holds the water the best, and they can create their sculpture in more detail (Archisand Professional Sand Sculptors, 2012). Sand artists preferably use a fluvial sand and not a beach sand. The fluvial sand is younger and more angular because it has been through less erosion. In fluvial sand there is also a higher fraction of clay and silt, according to the sand sculpture artists this helps to bond the sand better (World Sand Sculpting Academy, 2016) (Sand In Your Eye, 2016). The building process that demonstration companies use to build their largest, strongest and longest standing sculptures seems roughly the same. This process involves a (wooden) mold, filled up with a sand and water mixture and this is compacted. The strength of the mold seems bounding for the amount of compaction. For many layers sand is compacted. Then sculpting commences from top down and over the course of hours to months the lower parts of the mold are taken off (Sandstorm Events Pty Ltd, 2016). This technique is known as "hard packing". As opposed to the more flexible "soft packing", where compressing is done with hand or shovel without the use of a formwork. Maintenance consists of spritzing fresh water or keeping the sculpture in a climate controlled environment with high humidity (Archisand Professional Sand Sculptors, 2012). Sometimes a bio-degradable glue is used to help the cohesion on the surface of the sculpture, which is most susceptible to drying out soon (Farmer, 2006) (Sand In Your Eye, 2016). Adding ingredients to the natural sand is considered cheating by some artists (World Sand Sculpting Academy, 2016), but there is already some clay in the river sand that most artists prefer. The addition of clay can then hardly be called cheating. Shells and other sand specific material can be disastrous for the cohesion of the sand. Therefore, the sand is sometimes sieved before usage to remove these large particles (Bocconi, 2010).

It can be concluded that most of the knowledge in sand sculpting is based on experience. Trial-and-error defined the best sand and methods for every artist.

2.2 Rammed earth

Dried sand clay mixtures are also referred to as rammed earth. Rammed earth buildings were very common in prior times, in particular in arid climates, where some still exist. Examples are the Potala Palace in Tibet and the Alhambra in Spain (Jaquin P. A., Augarde, Gallipoli, & Toll, 2009). But in modern times, rammed earth is not used anymore as steel, concrete and bricks took the stage. Bricks are essentially a form of rammed earth, but the drying is replaced by oven heating, in which some of the minerals melt and solidify to each other.

Most rammed earth has a grain size distribution of 45-80% of sand and gravel, 10-30% of silt and 5-20% of clay (Jaquin, Augarde, & Legrand, 2008). Jaquin explains how the forces in rammed earth work. Suction plays a large role in the strength of rammed earth. Suction is the water in pores that create an attractive force. This force exists because of the surface tension in the water (Jaquin, Augarde, & Legrand, 2008). Suction is increasing with decreasing water content as the rammed earth is drying. However, there is a peak in the strength of a rammed earth soil as water content decreases (Jaquin P. A., Augarde, Gallipoli, & Toll, 2009). This suction is also called matric suction. The relative humidity is very important for the total suction that the soil is subjected to. Jaquin shows that a drop in relative humidity from 100% to 95% causes an increase of suction of about 1 MPa. While the range of suction from 95% to 0% relative humidity leads to much smaller increases in suction. The suction from 95% to 0% humidity is generally very high. This explains why al lot of long standing rammed earth buildings are in arid climates (Jaquin P. A., Augarde, Gallipoli, & Toll, 2009). Once the relative humidity gets really close to 100%, the suction will get marginal and rammed earth buildings will be less strong.

The cohesion of rammed earth is largely dependent on the method of preparation. The sand water clay mixture needs enough mixing to get the required cohesion, but interestingly, there also seems to be a maximum mixing time. As Minke found out, mixing a silty mud for 10 minutes resulted in a 57% higher binding force than the same mixture that was only mixed for only one minute. But mixing for 20 minutes resulted in an 11% lower binding force than mixing for 10 minutes. This means that there is an optimal mixing time (Minke, 2006). Mixing can be combined with (dynamic) compaction to increase the strength. However, as Minke shows, mixing is counterintuitively more important than compaction. He reached some higher strengths in a silty clay with 15 minutes of mixing and no compaction, opposed to 2 minutes of mixing and compacting for 30% to 40%. The samples that were not compacted had a 28% to 38% higher compressive strength. This underlines the strength of the bindings that the clay particles can get when they are optimal (parallel) positioned. The movement and the water help the particles most to get into this orientation.

Jaquin did an experiment to uncover the relation between suction and the strength of rammed earth (Jaquin P. A., Augarde, Gallipoli, & Toll, 2009). The material that was used was from locally dug material near Durham, UK, this consisted for 25% of aggregate, 60% of sand and 15% of clay. The water content for which the highest dry density was reached, was determined with a vibrating hammer test instead of a standard proctor test, because Jaquin believed this resembled the compaction used in rammed earth walls better (a description of the proctor test can be found in chapter 4). He found a clear relation between the water content and suction as well as strength. However, this state will only be intermediary in a sculpture, because eventually, the material will go to the equilibrium moisture content dependent on the relative humidity. This would, on the other hand, be useful to know when the soil is hard enough to begin sculpting on. When the water content will be to low (RH is very low), the strength due to suction is starting to fall back, but this low RH will probably never be reached in most of earth's climates (Jaquin P. A., Augarde, Gallipoli, & Toll, 2009).

2.3 Physical behaviour

As opposed to sand and silt, in clay binding forces (ion-binding) play a large role in the inter particle forces (Minke, 2006). Sand alone basically is not influenced by these electrical forces and is much more affected by the force of gravity. The crystalline structure of clay is such that layers with a negative charge are on the outside of the clay particles. For instance, aluminium is surrounded by hydroxyl groups (OH-) or silicon is surrounded by oxygenations (O--). These inter particle forces are mobilized by water, because in the water are positively charged ions (cations), which form a bonding between the particles. Water, being polar, is also attracted to these cations, and in this manner a film of water between the particles is formed also known as osmotic suction (Tang, Zhou, Ren, & Yang, 2014). Minke confirms this hypothesis. Dry clay swells when water is added to it, because the water creeps in between the plates that are the clay particles (Minke, 2006). When this water later (partly) evaporates, the plates get the chance to arrange themselves in a parallel pattern due to the forces of electrical attraction and repulsion. And the plates are packed tighter. The optimum water content for a clay is when the particles are as parallel as possible. Too little water means that the clay particles do not get the chance to position themselves parallel, and too much water means that a large part of the soil is water, so the dry density will be low (Chen, 2010). The same study by Chen shows that especially on the dry side of the optimum, the parallel positioning of the particles may not be achieved. Barden and Sides (1970) confirm this, they did a study with compacting clay and made observations with a microscope (as stated by (Fang, 2013)).

To ensure that the right amount of water is used in the mixture, and the soil is as compact as possible, the proctor test is often used. Especially in road construction, this maximum density is linked with the highest achievable strength.

The shrinkage and swelling that the clay is subjective to is dependent on the clay mineral that is used. The cracks that can occur after drying out are very harmful especially to a sand sculpture. It is disastrous to the overall strength and it is aesthetically very unappealing for a sculpture. However, not all water will evaporate, after a while, an equilibrium with the humidity in the air will form (Minke, 2006). On the surface of a sand sculpture, the equilibrium of the soil will be lower because of extra evaporation due to wind and sun.

This may have a negative impact on the binding forces. In conventional sand sculptures (only sand and water) it surely has, this is way artists use a water spray, or glue to keep the binding forces on the surface strong enough. Shrinkage is also dependent on the ratio of sand to clay. In general, the more sand is used the less shrinkage occurs (Minke, 2006). The grain size distribution can be an important property for a sand-clay sculpture. Designing shrinkage joints can reduce the effect of unwanted shrinkage cracks, but it might be very hard to implement in a sculpture and it is also not beneficial to the artwork's aesthetics. According to Minke, slow drying is another way to prevent cracks, this might practically mean to shelter the sculpture from the sun and the wind.

2.4 Other studies

Vanapalli found in an experimental study that the variation of suction (so also strength) in a clay till is a function of the initial water content. He subjected 3 mixtures around the optimum water content to shear strength tests (Vanapalli, Pufahl, & Fredlund, 1998).

Emiroglu did a study on sand clay ratios (Emiroglu, Yalama, & Erdogdu, 2015). The mixture was made by mixing dry clay and sand in different ratios. Water content was put on 35% of the weight of the clay, near the liquid limit to achieve ease of application. No compaction effort was made. And these mixes were dried for 24 hours in an oven on both 60°C and 105°C. It was found that the optimum clay sand ratios were between 0,43 and 0,66 (clay to sand).

Khan did experiments with sand clay mixtures (Khan, Azam, Raghunandan, & Clark, 2014) in which they used a coarser sand/gravel. Three mixtures were made, of which optimum water contents were retrieved through proctor tests, only clay (w_{opt} 27%, NC), sand 80%-clay 20% (w_{opt} 22%, CS-1) and sand 60% clay 40% (w_{opt} 20% CS-2). The samples were not dried and subjected to unconfined compressive strength tests. The highest compressive strength corresponded to the samples with the lowest water content, and showed a brittle behaviour. The clay showed higher strength than the 2 sand mixes. Khan explains this due to the higher heterogeneity of the 2 sand mixes and the loss of sand grains from the side of the samples during compressive testing. Resulting in more strain at the same stress level.

3 Soil preparation method

3.1 Sand properties

The sand that was used is a silica sand (Sibelco S60, 99,5% SiO_2), see Figure 1. Brief sieving was done to compare the sand to other sands available in the lab, a sieve of 0,25 mm and 0,125 mm were used. The result can be seen in Table 1. According to the producer, the sand is industrially processed; sieved, washed and classified. "A silica sand that is excellent raw material for the glass-, crystal- and ceramic industry, for foundries, for tile glues, plasters, mortars, coatings etc…"

TABLE 1 – SAND PROPERTIES

Producer information		Measured	
D_{50} / AGS	230		μm
AFS	60		
> 500 μm			%
> 355 μm	1		%
> 250 μm	28	23,5	%
> 180 μm	86		%
> 125 μm	99,4	96,6	%
> 90 μm	99,9		%
< 63 μm	traces		%
density	2,65		kg/dm3
Bulk density	1,5		kg/dm3

FIGURE 1 – THE SAND

3.2 Clay properties

The clay that was used is also produced by Sibelco, normally used in ceramics. Orange/red baking, Dutch river clay sold as K122, without addition of chamotte, Vingerling clay. The clay as it is stored in the climate room at 100% humidity, was found to be at a moisture content of 33%. The moisture content was determined by taking a sample and drying for 24 hours in an oven at 105°C. See Table 2. The plastic limit (PL) of the clay is at 23% water content and the liquid limit (LL) was determined at 57% water content. This means the plasticity index is (PI = LL - PL) 34, which indicates that it is a highly plastic clay.

TABLE 2 – WATER CONTENT CLAY

	Mass (g)	Without dish (g)
Dish	107,52	
Wet soil	197,71	90,19
Dry soil	175,14	67,62
Water		22,57
w (m_{water}/m_{dry})		33,38%

3.3 Mixtures

The clay at the moisture content at which it is stored cannot be mixed with the sand, because the clay is not liquid enough. The clay barely falls apart when applying a force to it and lumps stay in the sand no matter how long it is mixed. Mixing by hand as well as by machine (Hobart Legacy Floor Mixer, see Figure 3) does not work. Practice showed that the moisture content of the clay has to be increased above the liquid limit before it can be mixed with the sand. This is why attempts were made to first make a slurry. However, the clay does not mix with water either. But the clay does dissolve for a bit. The clay was cut into cubes of about 3 centimeter, to increase the surface area and thus speed up the water uptake. To these clay cubes, some amount of water was added to reach 66,7% water content. This mixture was left for 24 hours in the climate room. After this the clay cubes had swollen and taken up a lot of the water. Now the clay lumps could be mixed and in 10 minutes (low speed; agitator 94 RPM, attachment 54 RPM) a uniform slurry (as shown in Figure 2) was formed that could be mixed with the different proportions of sand.

FIGURE 2 – SLURRY ON MINIMUM WATER CONTENT

FIGURE 3 – HOBART MIXER

Mixtures with different clay – sand ratios were made. 100% sand, 95%, 90%, 85% and 80%, so sand really is the base material. It is forming the skeleton of the material, in order to keep close to the sand sculpture application. Respectively, 0% clay, 5%, 10%, 15% and 20% clay was in these mixtures. Clay can then be seen as an adhesive or binder in the material. The mixes will be referenced by their sand content as S100, S95, S90, S85 and S80.

As an example, the procedure for one of the mixes that was needed for the proctor tests (Chapter 4) will be explained next. For the S85 mix first the total amount of soil that was needed was determined. This was guessed to be 3500 g, since the proctor mold is 1 liter and some of the soil is lost during successive testing. 15% clay of this total is 525 g and since the water content of the clay mix is known to be 66,7%, 875 g of the mixture was taken (525 [g clay] + 0,66*525 [g water]). This mixture then has in total a water content of 10% (350 g/3500g). To this 70 grams of water was added, this made up for a total of 12% water content for the whole mixture (420g/3500g). Which was about the minimum that could be reached, because otherwise the clay would not mix with the sand since it would be under or very near to the liquid limit. This was mixed for 2 minutes and a good slurry was the result. Only now the sand is added. This is mixed for 10 minutes on low speed or 5 minutes on intermediate speed (agitator 174 RPM, attachment 100 RPM).

All the mixes were prepared in this manner, details of the proportions are in   Table 3.

TABLE 3 – CLAY-SAND MIXES

Reference	S100	S95	S90	S85
Total mass (g)	3500	3500	3500	3500
Sand percentage	100%	95%	90%	85%
Sand mass (g)	3500	3325	3150	2975
Clay percentage	0%	5%	10%	15%
Clay mass (g)	0	175	350	525
Proctor start wc	7%	7%	10%	12%
Total water (g)	245	245	350	420
Water in mix (g)	0	116,67	233,33	350,00
Water to add (g)	245	128,33	116,67	70

It was found that the S80 mixture could not be made with this procedure, the (clay and water) slurry is still above the liquid limit. The clay is consequently not workable enough to be mixed through the sand and lumps of clay will stay in the mixture for relatively large mixing times (more than 30 minutes). The clay will probably have to be dried to a powder in order to mix it properly. But this would not be comparable anymore. This is why was decided to leave the S80 out of the equation.

4 Compaction testing

4.1 Testing procedure

The compaction testing was done using a Proctor compaction test. The mixtures that were used are described in the chapter 3. The Proctor test is based on the fact that the compaction that can be required for a soil is dependent on the water content, and even an optimal water content exists (see the literature study in chapter 2). The maximum dry density and the optimum water content are the measured parameters. The test that was used is known as the Standard Proctor test (BS 1377:Part 4: 1990). This procedure starts with compacting the soil in a 102 mm diameter mold with a height of 116,4 mm, this makes up for a volume of 1,00 liter (1/4 * π * 1,02^2 * 1,164). The soil is divided in three approximately equal layers, each layer receives the same compaction effort of 27 blows of a rammer of 2,5 kg falling from 305 mm height. This makes for a total compaction effort of 605 kN.m/m^3 (27 * 3 * 0,305 * 2,5 * 0,0098 / 0,001). The soil was prepared on the lowest moisture content. The mass of the empty mold was taken, then the soil was compacted in the mold. Excessive soil was taken of carefully, so exactly 1 liter of soil is in the mold. The mass of the soil and the mold together is then taken. After this, the mold was emptied and all the soil was collected in a bowl again. Out of this bowl a small sample is taken to measure the water content. The small samples mass is measured and is put in the oven for 24 hours at 105 degrees C. This is the first test. For each successive test, the moisture content was raised by approximately 1%, by adding the 1% of the total dry mass of the soil. This means 35 grams of water on a total dry mass of 3500 g. This is mixed for 2 minutes on intermediate speed and then the test starts over.
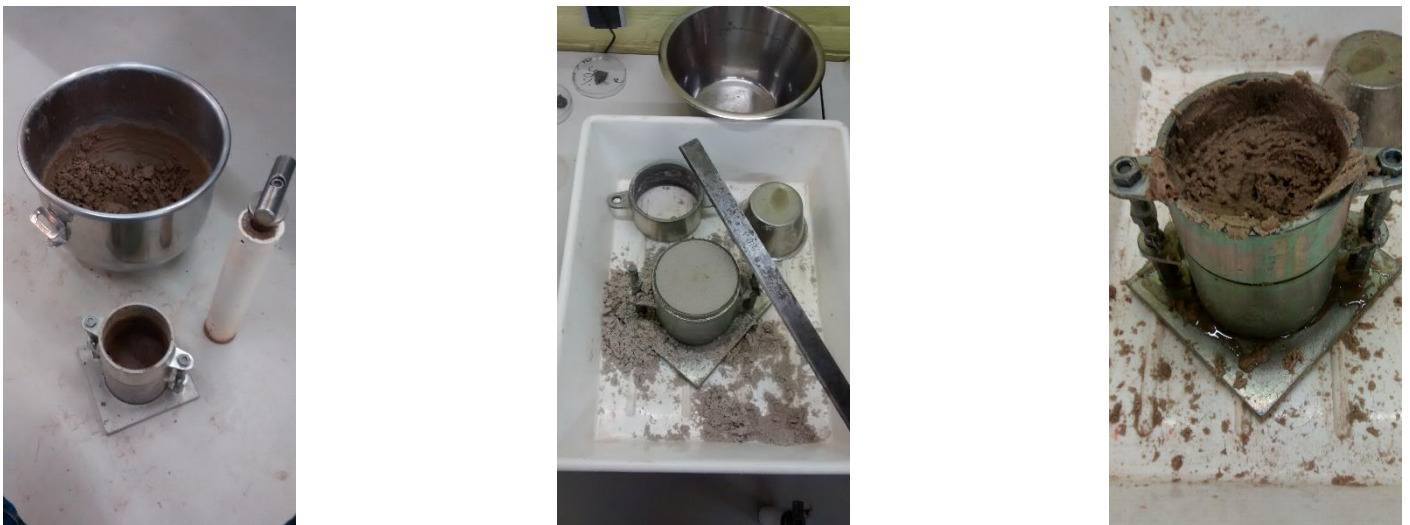

FIGURE 5 – PROCTOR TEST EQUIPMENT, FILLED AND SMOOTHENED PROCTOR MOLD, SATURATED COMPACTED SOIL (LEFT TO RIGHT)

FIGURE 4 – EMPTYING OF MOLD, WEIGHING THE FILLED MOLD, WEIGHING A SAMPLE FOR WATER CONTENT (LEFT TO RIGHT)

4.2 Results

The results are shown in the graph in Figure 6, we can see clearly that there is an optimum for the three sands with clay added (S85, S90 and S95). For S100, the optimum is much less distinctive. The optimum density and water content are shown in Figure 6 – Proctor test results

Table 4. In the graph we can see that the S85 test was started on a water content that was too high, the starting water content is near the optimum or already past. A slightly lower starting water content can be reached but not by much, since the clay has to stay above the liquid limit to be mixed well (see also chapter 3 on the soil preparation method). We can also see that with increasing clay content, the dry density increases. This was expected as the (small) clay particles fill the pores of the sand skeleton. The optimum water content decreases with increasing clay content. This can be explained because the pores that are filled with water on low clay content, get replaced by clay particles on higher clay content. The complete data of the proctor tests can be found in the appendix. In this data we see the moisture content steps were smaller than the calculated 1%. An explanation for this is the moisture that evaporates during the tests. An interesting point is the first S95 point (8,3%). This point is an outlier because the test for this point was executed by another person. The person executing the test has influenced the test result, this reduces the reliability of the test, as it is less repeatable. Personal errors can affect the result of the proctor test significantly.

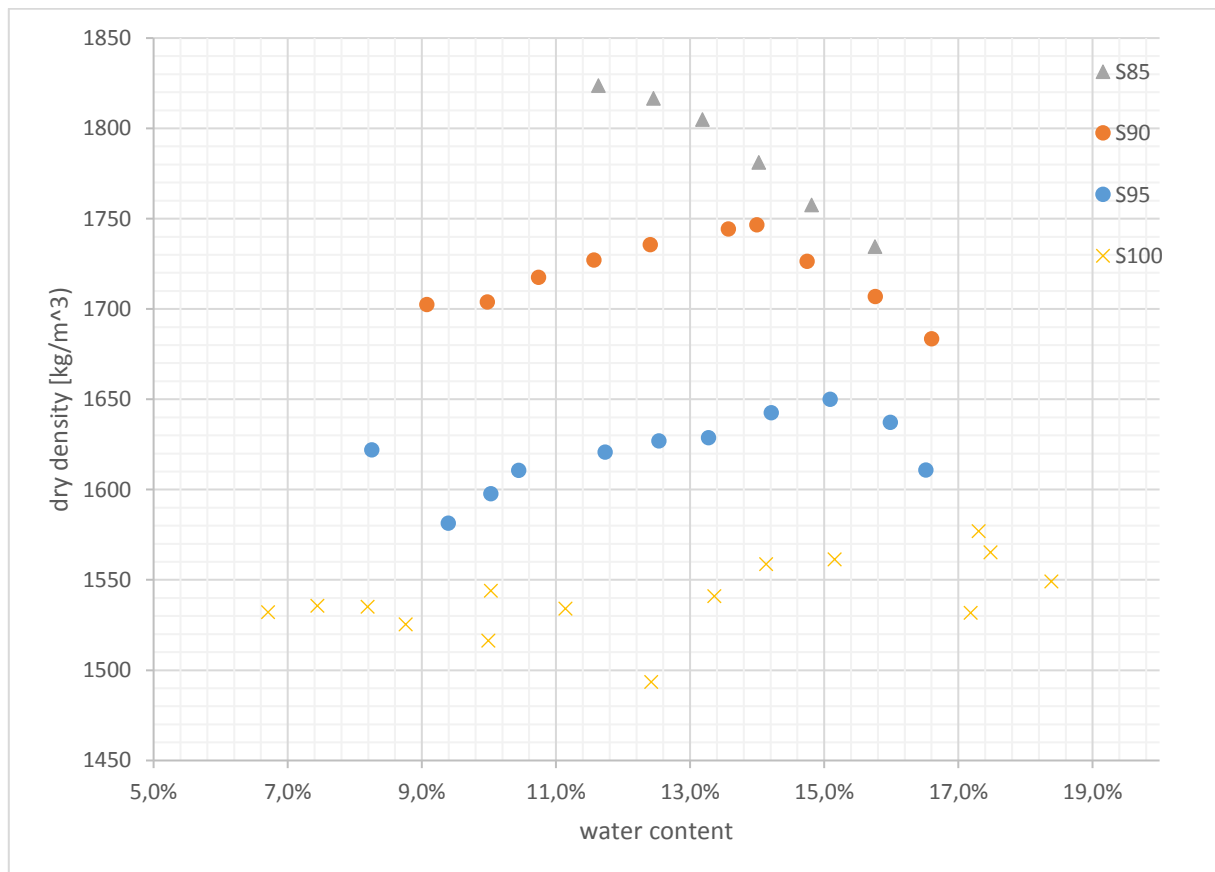**FIGURE 6 – PROCTOR TEST RESULTS**

TABLE 4 – OPTIMUM WATER CONTENTS AND DRY DENSITIES

	S100	S95	S90	S85
Opt. water cont.	17%	15%	14%	11%
Max. dry density (kg/m^3)	1577	1650	1746	1824

5 Compressive testing

5.1 Testing procedure

The results of the compression tests were used to prepare samples for an unconfined compressive strength (UCS) test. The machine used for this test is "Matest E161N cement compression machine 250 kN, servo-plus evolution". New mixtures were made of S100, S95, S90 and S85, the moisture content used was the optimum moisture content that was determined. The samples were cubes of 3,5 cm. These cubes were made in a mold. The mold was made of cement that was casted over a silicone mold, intended for making ice cubes. The cement casting was necessary to keep the silicon mold from deforming when the soil is compacted. In this mold the rammer of the Proctor tests could not be used. The mold would be damaged, and the diameter of the rammer is too large. This is why the compaction effort was exerted by hand. The exact same compaction effort cannot be reached for all the samples, but it was tried to put around the same effort on each sample. To reduce the uncertainty that is introduced this way, three samples of each mix were made. These samples were dried in an oven at 105°C. After 24 hours the samples were taken out of the oven and they were released from the mold. None of the samples did shrink at all, which is a good result, because this means there is a low risk on the development of cracks. However, this also meant that the samples were hard to remove from the mold. The S100 mix had no cohesion as was expected, but all the other mixes were changed in cohesive cubes. The cubes were damaged when they were released. These blocks were tested on unconfined compressive strength.

5.2 Results

The results are presented in Table 5 and Figure 7. The results are probably not very accurate, especially for the S85 mix. S85-1 was damaged and S85-2 was slightly damaged. The S85 blocks were damaged most badly when they were removed from the mold, because they were the strongest and most cohesive, thus stuck to the mold the most. S85-3 is the most reliable cube of the 3, the value for cube 3 is also the highest. This is why the real value for S85 will be higher than in the test. The test also shows a bigger difference in UCS from S95 to S90, than from S90 to S85. This might suggest that there is an optimal clay-sand ratio (for a certain ratio there is a maximum UCS), it might also be another effect of the damaged samples.

TABLE 5 – UCS (MPA)

	S95	S90	S85
Cube 1	0,400	0,901	0,795
Cube 2	0,258	1,017	0,866
Cube 3	0,375	1,038	1,220
Average	0,344	0,985	0,960
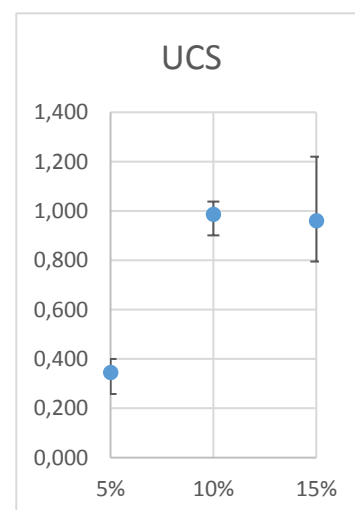
FIGURE 7 – UCS AVERAGE, MAXIMUM, MINIMUM

FIGURE 8 – MIXES FILLED IN MOLD, DAMAGED DRIED CUBES, CUBE IN UCS TEST MACHINE (LEFT TO RIGHT)

The masses of the dry cubes were measured, the mold is known to have an volume of 42,875 cm^3 (3,5 x 3,5 x 3,5 cm). The densities that can be calculated are shown in Table 6. The last column shows the optimum dry density reached in the Proctor test. The dry densities of the cubes are lower than the dry densities reached in the Proctor test. This means the compaction effort on the cubes was lower than the compaction effort on the Proctor tests. This will likely also lead to lower strengths for the cubes than possible.

As an interesting side note the colors of the mixes should be mentioned, as can be seen in on the left. As sand sculptures are artworks, different colors of sand can bring it to the next level.

TABLE 6 – DRY DENSITIES CUBES

Reference	Dry mass (g)	Volume	Dry density (g/L)	Dry dens. Proctor (g/L)
S100 (3x)	169,74	128,625	1320	1577
S95	59,07	42,875	1378	1650
S90	64,57	42,875	1506	1746
S85	66,7	42,875	1556	1824

6 UCS development over drying

6.1 Test procedure

The last test that was executed is the UCS strength after different times of drying. The mixtures S85, S90 and S95 were prepared and the cubes were compacted by hand. The same procedure as with the UCS testing in the previous chapter was adopted. The difference is that the cubes were not dried this time before they were removed from the mold. Carefully, the cubes were taken out of the mold. When one cube was made at a time, the damage was negligible, but once a batch of 15 pieces was made, the cubes were all slightly damaged during the removing. These cubes were dried for different times on room temperature. First the cubes were tested in wet state (within an hour).

6.2 Results

The UCS for the blocks direct after production was too low to be measured by the UCS machine (all cubes with no measurement are indicated with 0 MPa strength). Also the UCS of the blocks that were dried for 24 hours were still too weak to be measured by the machine. After 3 days the strength was high enough to be measured. After 3 days the strength reached is similar to the strength after oven drying, for S95 and S90 the strengths are even higher. The UCS values after 8 days of drying are, surprisingly, lower. This means that higher moisture content has a positive effect on the strength. There might be an optimum moisture content for the dried blocks, if we assume the blocks did not dry to equilibrium moisture content (see chapter 2 literature study) with the air humidity after 3 days. The batch produced blocks had lower strength, as was expected.

TABLE 7 – SINGLE PRODUCED CUBES STRENGTH AFTER DRYING TIME

Single produced			
	S95 (MPa)	S90 (MPa)	S85 (MPa)
Direct	0	0	0
24 hours	0	0	0
3 days	0,492	0,992	1,184
8 days	0,319	0,785	0,729

TABLE 8 – BATCH PRODUCED CUBES STRENGTH AFTER DRYING TIME

Batch produced			
	S95 (MPa)	S90 (MPa)	S85 (MPa)
Direct	0	0	0
24 hours	0	0	0
3 days	0,283	0,496	0,845
8 days	0	0,486	0,815

7 Conclusions and recommendations

7.1 Conclusions

The three main questions this report tries to answer are, as we recall from chapter 1:

- What is the best preparation method for a sand-clay mixture?
- At what water content can the highest dry density be reached for different sand-clay ratios?
- For what clay-sand ratio can the highest dried strength be reached?
- How does the strength of the mixture develop over time for different sand-clay ratios?

The best preparation method is explained in chapter 3. It can be concluded that the clay must be above the liquid limit before it is mixed through the sand. This can be achieved by soaking the clay in small blocks for 24 hours in the water. Only if this slurry is mixed and no lumps are in it. The sand can be added and mixed with the clay and water.

The optimal water content for the different mixes is investigated in chapter 4. Optima are close together, ranging from 11% to 17%. The optimum water content is increasing with decreasing clay content. The dry density that is linked to the optimum water content is increasing with increasing clay content.

The UCS tests in chapter 5, provided information on the best clay-sand ratio. Although, the results are thought to be inaccurate. We can conclude that a higher clay to sand ratio is better for the strength. Of the tested mixtures the S85 mixture (15% clay) was the strongest at 1,22 MPa. The compaction effort varies to each test and also varies to the Proctor tests.

In chapter 6, it was found that the UCS after 3 days of drying is surprisingly high (1,184 MPa), similar to the values found after oven drying. However, after 8 days, the strength is lower.

7.2 Recommendations

The strongest recommendation for future research is concerning the mold for the cubes. The mold could be adjusted to ensure the blocks can be removed easier. Possible adjustments are lubrication, holes to push the cubes out, or a different material such as steel or aluminum. Another option would be a detachable mold. Especially for the S85 cubes, this can improve the result a lot. Also the compaction effort can be standardized more, this can be incorporated in the design for a new mold.

Mixtures of different sand clay-ratios can be tested to get a more complete view of the UCS to clay content relation.

Other ways of preparation can be compared to the way used in this report. Especially a preparation method involving dried clay powder might be interesting to compare. Although this takes more energy, so it is less environmentally friendly.

The results will also vary if other clays and sands are used, also other factors can influence the result. For instance the mixing time, in the literature study in chapter 2 was found this can have an effect. The temperature of the cubes can influence the strength. The time between taking the samples out of the oven and the UCS testing. There can also be an effect on the strength if the mixture is left to rest for a few days.

The UCS development over time can be done more extensively and in triplets, to investigate whether there is an optimum water content (or drying time).

Appendix A

Proctor test 1 (95% sand - 5% clay)

Estimated w	7%	8%	9%	10%	11%	12%	13%	14%	15%	16%	17%
Mass total	6214	6188	6216	6237	6269	6289	6303	6334	6357	6357	6335
Mass soil	1756	1730	1758	1779	1811	1831	1845	1876	1899	1899	1877
Mass dry	1622,10	1581,39	1597,73	1610,74	1620,80	1627,06	1628,76	1642,59	1649,99	1637,25	1610,94
Mass water	133,90	148,61	160,27	168,26	190,20	203,94	216,24	233,41	249,01	261,75	266,06
Mass empty tray	107,51	109,85	106,6	46,33	106,4	45,69	42,83	43,96	41,97	45,69	43,88
Mass tray+soil	208,23	200,07	206,31	109,66	196,38	120,12	118,17	123,37	108,7	96,91	146,95
Mass soil	100,72	90,22	99,71	63,33	89,98	74,43	75,34	79,41	66,73	51,22	103,07
Mass tray+soil dry	200,55	192,32	197,22	103,67	186,93	111,83	109,34	113,49	99,95	89,85	132,34
Mass soil dry	93,04	82,47	90,62	57,34	80,53	66,14	66,51	69,53	57,98	44,16	88,46
w	8,3%	9,4%	10,0%	10,4%	11,7%	12,5%	13,3%	14,2%	15,1%	16,0%	16,5%
Error w	1,25%	1,40%	1,03%	0,45%	0,73%	0,53%	0,28%	0,21%	0,09%	0,01%	0,48%
Mass mold	4458										

Proctor test 2 (90% sand - 10% clay)

Estimated w	10%	11%	12%	13%	14%	15%	16%	17%	18%	19%	
Mass total	6315	6332	6360	6385	6409	6439	6449	6439	6434	6421	
Mass soil	1857	1874	1902	1927	1951	1981	1991	1981	1976	1963	
Mass dry	1702,48	1703,96	1717,53	1727,24	1735,67	1744,28	1746,58	1726,40	1706,96	1683,47	
Mass water	154,52	170,04	184,47	199,76	215,33	236,72	244,42	254,60	269,04	279,53	
Mass empty tray	45,68	43,96	42,78	45,68	49,35	49,56	46,31	45,59	45,9	42,72	
Mass tray+soil	125,36	117,8	120,83	123,72	139,5	124,71	143,49	149,23	132,86	135,98	
Mass soil	79,68	73,84	78,05	78,04	90,15	75,15	97,18	103,64	86,96	93,26	
Mass tray+soil dry	118,73	111,1	113,26	115,63	129,55	115,73	131,56	135,91	121,02	122,7	
Mass soil dry	73,05	67,14	70,48	69,95	80,2	66,17	85,25	90,32	75,12	79,98	
w	9,1%	10,0%	10,7%	11,6%	12,4%	13,6%	14,0%	14,7%	15,8%	16,6%	
Error w	0,92%	1,02%	1,26%	1,43%	1,59%	1,43%	2,01%	2,25%	2,24%	2,40%	
Mass mold	4458										

Proctor test 3 (85% sand - 15% clay)

Estimated w	12%	13%	14%	15%	16%	17%
Mass total	6494	6501	6501	6489	6476	6466
Mass soil	2036	2043	2043	2031	2018	2008
Mass dry	1823,82	1816,72	1805,00	1781,20	1757,61	1734,65
Mass water	212,18	226,28	238,00	249,80	260,39	273,35
Mass empty tray	42	49,23	48,77	44,18	46,33	43,31
Mass tray+soil	115,12	134,1	156,67	134,43	127,24	152,91
Mass soil	73,12	84,87	107,9	90,25	80,91	109,6
Mass tray+soil dry	107,5	124,7	144,1	123,33	116,8	137,99
Mass soil dry	65,5	75,47	95,33	79,15	70,47	94,68
w	11,6%	12,5%	13,2%	14,0%	14,8%	15,8%
Error w	0,37%	0,54%	0,81%	0,98%	1,19%	1,24%
Mass mold	4458					

Proctor test 4 (100% sand - 0% clay)

Estimated w	7%	8%	9%	10%	11%	12%	13%	14%	15%	16%	17%	18%	20%	21%	22%
Mass total	6093	6108	6119	6117	6126	6157	6163	6137	6205	6237	6256	6253	6308	6297	6292
Mass soil	1635	1650	1661	1659	1668	1699	1705	1679	1747	1779	1798	1795	1850	1839	1834
Mass dry	1532,2	1535,7	1535,2	1525,4	1516,5	1544,1	1534,1	1493,5	1541,1	1558,7	1561,3	1531,8	1577,1	1565,4	1549,1
Mass water	102,81	114,32	125,77	133,60	151,55	154,88	170,92	185,52	205,90	220,29	236,66	263,21	272,92	273,61	284,88
Mass empty tray	49,56	42,8	43,96	46,13	45,68	45,5	46,31	42,75	45,54	45,85	45,37	45,01	41,9	51,73	48
Mass tray+soil	127,33	107,46	106,69	113,93	114,8	117,46	114,64	118,23	139,21	118,37	124,84	125,96	108,94	130,57	136,97
Mass soil	77,77	64,66	62,73	67,8	69,12	71,96	68,33	75,48	93,67	72,52	79,47	80,95	67,04	78,84	88,97
Mass tray+soil dry	122,44	102,98	101,94	108,47	108,52	110,9	107,79	109,89	128,17	109,39	114,38	114,09	99,05	118,84	123,15
Mass soil dry	72,88	60,18	57,98	62,34	62,84	65,4	61,48	67,14	82,63	63,54	69,01	69,08	57,15	67,11	75,15
w	6,7%	7,4%	8,2%	8,8%	10,0%	10,0%	11,1%	12,4%	13,4%	14,1%	15,2%	17,2%	17,3%	17,5%	18,4%
Error w	0,29%	0,56%	0,81%	1,24%	1,01%	1,97%	1,86%	1,58%	1,64%	1,87%	1,84%	0,82%	2,69%	3,52%	3,61%
Mass mold	4458														

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