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Reuse of Concrete aggregates

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Preface

This report is made as the final thesis of the master education at the Technical University of Denmark in cooperation with the department of Civil Engineering. The project accounts for 30 ECTS points and the project began 23rd of January and ended 23rd of June 2017.

The report was written using LaTeX and all data has been processed using Microsoft Excel.

Both during the experimental work, which all has been conducted at DTU BYG, and the creation of the report a number of people have contributed to the completion. The people who contributed during either the experimental work or the creation of the report and whom deserved to be thanked are as follows:

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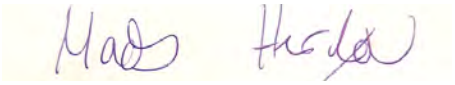
- Assisting supervisor Gunvor M. Kirkelund
- Laboratory coordinator Ebba C. Schnell
- Laboratory technician Marlene Grønvold
- Concrete technician Per Leth

Furthermore fellow students Kristian N. Jensen and Louise G. Pedersen both assisted in the creation of the report and took part in most of the experimental work performed during the project period.

Kongens Lyngby, June 23



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Abstract

This report contains the study of the effects recycled concrete aggregates (RCA) have on the fresh and hardened properties of new concrete. Important properties of the RCA was also investigated to get a better understand of their effects on recycled aggregate concrete (RAC). RCA was collected at a local construction site and tested for its various properties.

The porosity for RCA was found to be in the range of 19-25%, which was approximately twice as high as what other studies has reported. Attached mortar adhered to the RCA was found to be in the range of 16-27% which is significantly lower than what has been reported previously. Regardless of the amount of mortar still adhered to the aggregates, the density was found to be lower than the norm at approximately 2300 $\frac{kg}{m^3}$. The grading of the RCA was found to slightly deviate from the ideal grading curve, which affected the workability of the fresh RAC.

Following the investigation of RCA properties, the RCA was used to cast new concrete specimens, substituting 0-100% of the natural fine (4-8 mm) and/or coarse aggregates (8-16 mm) by weight (NA). The slump was determined to see how the use of RCA influenced the workability of the concrete. In addition to this the air content of the fresh concrete and the compressive strength of the hardened specimens was tested. The workability experienced when casting new concrete using RCA was not very good, due to the combination of high porosity, poor grading and the general angular shape of RCA. The slumps measured were therefore in the range of 0-60 mm. The air content measured when casting using RCA had no deviation to casting with NA.

The compressive strengths found when casting with RCA did not deviate significantly compared to casting with NA. On the other hand it was discovered that 50% RCA content performed the best, and increasing the amount RCA only lead to further decreases in strength. Furthermore it was discovered that casting with dry RCA or saturated RCA had no influence on the final compressive strength achieved.

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CHAPTER 1

Introduction

The huge usage of concrete worldwide has created a higher demand in the supply of natural aggregates (NA), this demand has increased the extraction of natural resources and has therefore created an ecological imbalance. It has therefore been necessary to find an alternative to the huge usage of NA. One way to achieve this is by replacing the NA with recycled concrete aggregates (RCA). Increasing the usage of RCA will automatically lead to a decrease in demand and usage of NA, which in return will reduce the environmental impact the extraction of virgin aggregates has (M. Safiuddin et al. 2013).
Let alone in Denmark 4.2 million tons of industrial waste was produced in the year of 2015, this is more than 1/3 of the general waste generated for that year. If soil is taken into account this amount of waste is more than doubled at 9 million tons of waste in 2015. The generation of industrial waste from the construction sector is highly dependable on the economic situation, in years of low economy the generation is generally lower than when the economy is high. In the period from 2014 to 2015 the generation increased by 100.000 tons, whereas the economic activity increased by 4%. A large fraction of this increase in waste came from concrete, masonry and ceramics, due to many renovation projects and demolition and rebuilding of old buildings (Miljøstyrelsen 2017).
Concrete and asphalt each stand for more than 20% of the waste generated and it is therefore ideal to find new ways to reuse some of this waste. Traditionally Denmark has a high reuse of industrial waste, which peaked at 95% in the years after 2000. Since then the reuse of waste has decreased due to increased focus on removing pollutants from the industrial waste. Even though the reuse of industrial waste has decreased, the amounts of waste reused are still high at 3.626 tons in the year of 2015 (87%)(Miljøstyrelsen 2017). In order to further increase the amounts of waste recycled each year, new and innovative thinking is required and since concrete and asphalt is the most common industrial waste in Denmark, even slight improvements can have a huge impact.

1.1 Objective

The objective with this report has therefore been, to shed some further light onto the research of recycling concrete aggregates for new concrete, in order to decrease the amounts of waste and the environmental impact extraction of virgin aggregates has. This was done by testing the compressive strength and workability of concrete specimens cast with varying amounts of RCA and treatments.

Parallel to this, the varying properties of the RCA was investigated, such as the particle size distribution, attached mortar, density and porosity. This was done to get a better understanding of the influence each of these parameters has on the final compressive strength and workability of RCA concrete.

CHAPTER 2

Theory

2.1 Concrete in general

Concrete is the most used construction material in the world, this is due to its price, usability, durability and properties in its hardened state. This combined with steel reinforcement makes it highly suitable to almost any kind of construction, such as houses, bridges and roads (K. K. Hansen 2012).
Concrete consists of various components, where the largest part consists of rocks and sand and the rest of the concrete consists of cement (or other hydraulic binders such as flyash), admixtures and water. As mentioned, admixtures can be added to the concrete recipe to control the properties of either the fresh or hardening concrete or even both. Figure 2.1 shows the different components of concrete and which result you get by mixing them, for instance mixing cement, additives and water results in cement paste and so forth.

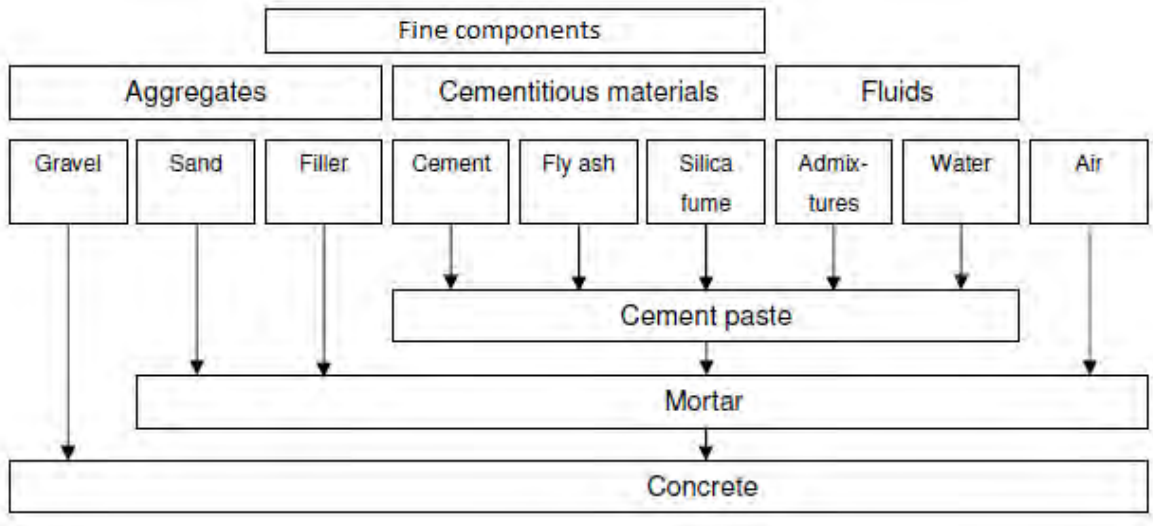


Figure 2.1: Components and phases in concrete. See Table D5.2 found in (K. K. Hansen 2012).

2.2 Natural and recycled concrete aggregates

As previously mentioned the largest part of concrete is aggregates, about 70-75% (K. K. Hansen 2012, M. Safiuddin et al. 2013), of the concrete consists of a mix of sand and rocks. The amount of coarse aggregates and sand is usually desired as high as possible, because this results in a stronger and cheaper end product all together. This is due to the cheap price of the aggregates compared to cement. When choosing which aggregates to use there are things you need to consider depending on the purpose of the concrete, this could be; the density of the aggregates, the mechanical properties such as compressive strength and module of elasticity, properties regarding temperature, durability and possibly any parts of the aggregates that could degrade the concrete which could be organic material and clay. The maximum aggregate size also has to be chosen on behalf of the reinforcement, so the aggregates can pass in between the reinforcement bars (K. K. Hansen 2012).
In Denmark 3 types of aggregates are usually used, gravel material extracted from gravel pits, sea material from the sea bed of the ocean and chippings from crushed mountain rocks. The 3 types of aggregates used for concrete are classified in terms of particle size grading, maximum grain size, density and porosity, particle shape and surface roughness. The classification for NA and RCA can be seen in Figure 2.2.

Physical property	NCA	RCA
Shape and texture	Well rounded, smooth (gravels) to angular and rough (crushed rock)	Angular with rough surface
Specific gravity (saturated surface-dry based)	2.4–2.9	2.1–2.5
Bulk density (compacted) (kg/m^3)	1450–1750	1200–1425
Absorption (wt. %)	0.5–4	3–12
Pore volume (vol. %)	0.5–2	5.0–16.5

Figure 2.2: Physical properties of NA and RCA. Found in (M. Safiuddin et al. 2013).

2.2.1 Shape and texture

As seen in Figure 2.2 the properties of RCA are all different from the properties of NA. First off the shape and texture of the the RCA is more angular with a rough surface. This is because of the crushing procedure and due to the presence of old mortar still being attached to the aggregates. The amounts of old mortar still being attached to the aggregates is typically 30-60% but vary depending on the aggregate size, smaller aggregate fractions tend to adhere more than larger fractions. Due to this some researchers don't recommend the use of small RCA, though many contractors still

successfully substitute 10-20% of the small aggregates and some even 100% (ECCO 1999).

2.2.2 Density and porosity

The density of RCA is usually lower than NA which is also shown in Figure 2.2. The density of RCA will normally be 5% to 10% lower than the virgin aggregates originally used in the concrete. This is also due to the amount of old attached mortar (ECCO 1999). As seen in Figure 2.2 the density of NA ranges from 2.4-2.9 and RCA ranges from 2.1-2.5.
The porosity of the aggregates also have a huge influence on the strength of concrete. The higher the pore volume, the more water the aggregates can contain, and also absorb. The porosity of the aggregates is therefore important to know in order to get the desired workability, durability and compressive strength. The pore volume of RCA is significantly higher than NA due to the attached mortar, and it is seen in Figure 2.2 that the pore volume can be up to 10 times higher for RCA than NA. This increased pore volume also has an influence on the water absorption, which is seen to be up to 6 times higher for RCA than NA.

2.2.3 Contaminants

Demolition contractors are not always able to supply clean RCA and it can therefore contain various contaminants. These contaminants could be admixtures, asphalt, glass, rubber, gypsum, steel reinforcement, wood, clay and soil among others. Clay and soil are the biggest problem of the previously mentioned contaminants, because excessive clay in the mixture can increase the water demand and therefore decrease the strength and should therefore be avoided completely if possible. Other contaminants have a maximum allowable limit, either by volume or weight percentage. For instance asphalt is tolerated up to 1% by volume, gypsum by 0.5% by weight of SO3 and organic substances by 0.15% by weight (ECCO 1999).

2.3 Cement

Cement is another crucial component in concrete, and the most commonly used is Portland Cement. Cement is usually the priciest component in concrete, and a portion of the cement is therefore often replaced with other hydraulic binders with similar properties such as flyash or micro silica. Portland cement is defined as a product containing 2/3 calcium silicates (C_3S, C_2S) and the rest is A (aluminium), F (iron) and other oxides.
Portland cement is produced from the raw materials calcium, clay and gypsum. This is done in an oven at 1400-1500°C where the materials are sintered into particles, also called cement clinkers, which consists of the minerals (C_3S, C_2S etc.). The portland

cement is then mixed with gypsum in order to control the early reaction process with water. The most important of these minerals can be seen in Table 2.1.

Table 2.1: The most important cement clinker minerals, their chemical notations and composition.

Chemical formula Full notation	Chemical formula Short notation	Clinker name
$3CaO \cdot SiO_2$	C_3S	Alite
$2CaO \cdot SiO_2$	C_2S	Belite
$3CaO \cdot AI_2O_3$	C_3A	Aluminate
$4CaO \cdot AI_2O_3 \cdot Fe_2O_3$	C_4AF	Ferrite

The clinker minerals displayed in Table 2.1 all have different reaction times. The minerals important to the strength development are C_3S and C_2S, where C_3S has a great influence on the early strength development and C_2S has influence on the long term strength development. On the other hand C_3A and C_4AF both have a very low impact on the strength development (K. K. Hansen 2012).

When water is added to the clinker minerals they react, and the chemical reaction for the 4 clinker minerals shown in Table 2.1 are as follows:

Alite reaction:

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH$$

Belite reaction:

$$2C_2S + 4H \rightarrow C_3S_2H_3 + CH$$

Aluminate reaction:

$$C_3A + 6H \rightarrow C_3AH_6$$

Ferrite reaction:

$$C_4AF + 2CH + 10H \rightarrow C_3AH_6 + C_3FH_6$$

When this reaction happens the concrete starts to harden, and the schematic of this process can be seen in Figure 2.3.
The 3 stages seen in Figure 2.3 all last for different amounts of time. The 1st stage (the rest period) happens within the first hour of the concrete getting cast. The 2nd stage (the reaction) then happens from 1 hour after casting up to 1 week afterwards, and the final stage (the hardening) is from 1 day up to 28 days. It is clearly seen that throughout the reaction, as the cement reacts with water, a structural skeleton in created in the concrete.

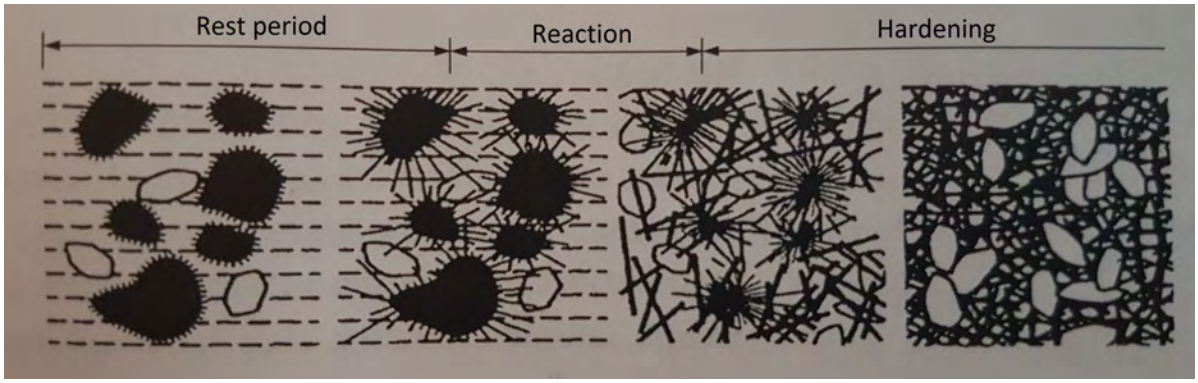


Figure 2.3: Structural development of the cement reaction. Found in (K. K. Hansen 2012).

2.4 Mechanical properties

One of the most important properties of concrete is the compressive strength. The compressive strength is limited to the weakest component of the concrete which is either the cement paste or the aggregates and how strong the phase between paste and aggregates is. When casting concrete using NA, the NA usually have a higher strength than the cement paste, and the paste and phase will therefore be the deciding factor. The strength of the cement paste depends on the water to cement ratio and how long it has been allowed to cure (Portland 2007). The raw tensile strength of concrete will usually be approximately 10% of the compressive strength.
The theoretical compressive strength of concrete can be described using *Bolomey's equation*. For concrete with a water to cement ratio of $0.45 < \text{w/c} < 1.25$ and air content of 1.5% to 2% Bolomey's equation is as follows (K. K. Hansen 2012, Portland 2007):

$$f_c = K\left(\frac{1}{w/c} - \alpha\right) \tag{2.1}$$

Where:

- f_c is the compressive strength of the concrete
- K is a constant which depends on the type of cement and curing time
- w/c is the water to cement ratio
- α is a constant which depends on the type of cement and curing time

It is seen in Equation 2.1 that increasing w/c will lead to a decrease in the strength. Guiding values for the constants K and α can be seen in Table D.1, see Appendix D. The cement used during this project was a Basis Portland Cement and the constants are therefore:

- 7 days
  - K = 24
  - $\alpha = 0.7$
- 28 days
  - K = 29
  - $\alpha = 0.6$

2.5 Recycled aggregate concrete

2.5.1 Workability

The increased angularity of RCA combined with the surface roughness makes the workability harder and therefore harder to finish. The degree increases with increased substitution of RCA, and it is necessary to add more water to recycled aggregate concrete (RAC) to obtain the same workability as natural aggregate concrete (NAC). Usually the initial slump is fulfilled when casting RAC, but the workability is lost shortly after mixing and this limits the time you have to place the concrete and finish (M. Safiuddin et al. 2013). Values for the fresh properties can be seen in Table 2.2.

Table 2.2: Fresh properties of NA and RCA concretes. Values from M. Safiuddin et al. 2013.

Fresh property	NCA Concrete	RCA Concrete
Workability		
Slump (mm)	90-275	70-255
Slump loss normal concrete (after 45min) (%)	50	75
Slump loss self-consolidating concrete (after 1h) (%)	2.4-2.6	7.4-10.4
Stability		
Wet density (kg/m3)	2325-2455	2250-2370
Air content (%)	1.3-6.3	1.5-6.9

2.5.2 Density

The density of RAC is usually lower than NAC, due to old mortar still being attached to the aggregates when casting. The amount of attached mortar can vary and it ranges from 30% to 60% by volume depending on the aggregate size. Smaller aggregates tend to have more mortar attached due to the higher surface area, and since the mortar has a

lower density than the aggregates this leads to a decrease in the density (ECCO 1999). The dry density of RAC is therefore usually 5-15% lower than NAC (T. C. Hansen 1986). Table 2.2 also shows that the wet density of RAC is lower than NAC as well, approximately 1%.

2.5.3 Compressive strength

The compressive strength of RAC is usually lower than NAC, this can be seen in Figure 2.4.

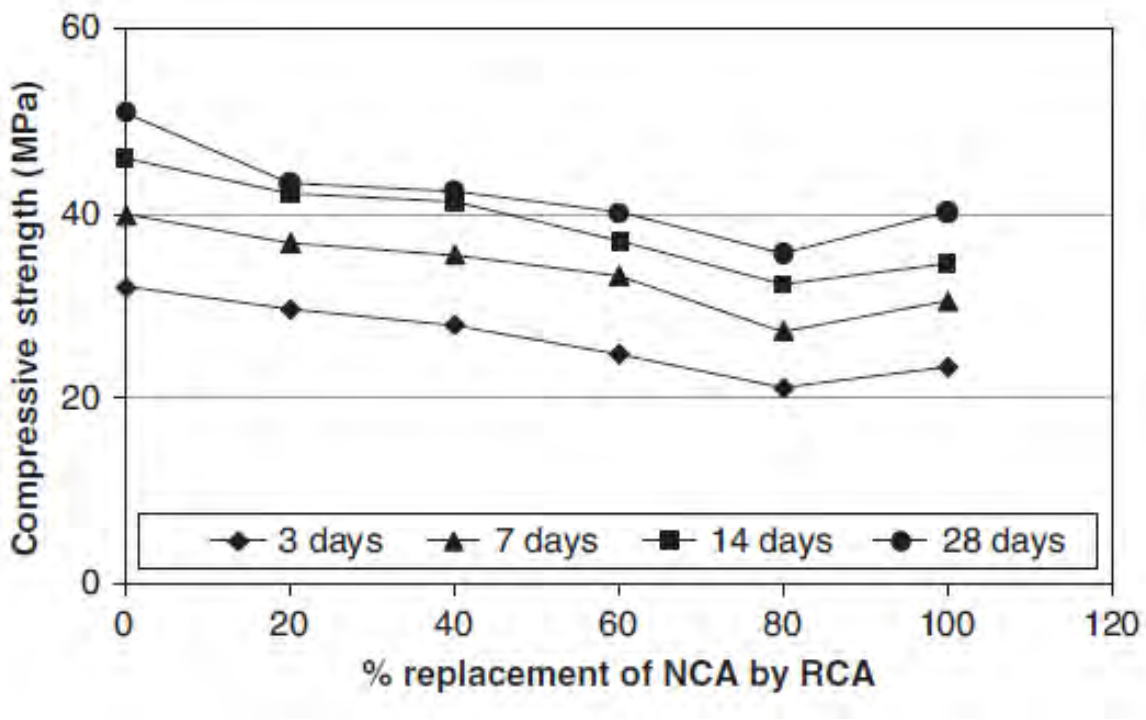


Figure 2.4: The effects of RCA substitution on concrete compressive strength. Found in (Nelson 2004).

Figure 2.4 shows that increased substitution of RCA decreases the final compressive strength. Generally the compressive strength of RAC is 5-10% lower than concretes cast with conventional aggregates, but can go as far as up to 20% decrease in compressive strength (M. Safiuddin et al. 2013, T. C. Hansen 1986). The decreased density of the RAC is one of the reasons for this, and also the increased air content in RAC. The compressive strength of concrete is decreased by 4-5% for each % increase in air content. However the RAC can actually achieve the same or even higher compressive strength than that of the original concrete, if the RAC is cast with the same or lower water to cement ratio (ECCO 1999). A higher RAC than NAC strength can also be achieved if

the concrete source of the RCA, was originally produced with a lower water to cement ratio than the new concrete (Padmini, Ramamurthy, and Mathews 2009).

CHAPTER 3
Materials and Methods

The RCA used in this project were collected from a construction site located in Herlev. The aggregates were from the demolition of the old hardware store "Elgiganten" located at Hørkær 19-21 in Herlev. Unfortunately there were no public records available as to when the building was built nor which concrete was originally used in the building. Aggregates were collected twice during the period from February to April, so the aggregates were fairly wet at the time of collection. The extraction was done by hand by simply shovelling aggregates into buckets of approximately 30kg per bucket. The pile of RCA was estimated to be approximately 15 m wide, 30 m long and 5-6 m tall. First time collecting aggregates 7 buckets were filled for a total of 214.87 kg and 2nd time 15 buckets of approximately 30kg each.

3.1 Preparation of Aggregates

In order to start experimenting with the RCA, there were some preparations that had to be done, before new concrete specimens could be cast. The preparations are described in section 3.1.1 and section 3.1.2.

3.1.1 Sieving

The collected material was a mix of all aggregate sizes, and it was therefore necessary to sieve it all in order to get the desired aggregate fractions, which were the fractions 4-8 mm and 8-16 mm. The sieving process was done manually by hand using sieve sizes of 16 mm, 8 mm and 4 mm respectively. The sieves used can be seen in Figure 3.1.

Figure 3.1: Sieves sizes 16 mm, 8 mm and 4 mm (from left to right).

First all the material was sieved using the 16 mm sieve, and everything above a diameter of 16 mm was tossed away. This procedure was repeated with the 8 mm sieve and the 4 mm sieve. All material above 16 mm and below 4 mm was tossed away, leaving only the aggregates of 4-8 mm and 8-16 mm. The procedure can be seen in Figure 3.2

Figure 3.2: Sieving the collected material.

Once all the material had been sieved, it had to be washed to remove sand and other material attached to the aggregates. This was done by stacking the 3 sieves and then re-doing the process with water to rinse the aggregates. During this process there was a tiny fraction of the aggregates that didn't go through the 16 mm sieve, this material was tossed. The process can be seen in Figure 3.3.
After the sieving and rinsing of all the material the original collection of aggregates was reduced by approximately 60% which which can be seen in Table 3.1.

3.1.2 Drying

After the materials had been sieved and rinsed they had to be dried in order to use it for new concrete castings. If the materials are not dry when casting new concrete, it is not possible to control the water to cement ratio, which will have an effect on the final compressive strength of the concrete. It is also necessary that the material is dry in order to determine the porosity and density of the aggregates, this will be described in section 3.2.
The drying process has to be done until a constant mass is achieved. The drying process is normally done at 105°C for normal aggregates, and at 50°C for concrete. The reason concrete has to dry at a lower temperature is that a higher temperature will make changes to the pore structure of the concrete (See Appendix B). Since this project is using reused aggregates, where the aggregates are still partially covered in old mortar

Figure 3.3: Rinsing the once sieved material.

the temperature of 50°C is used.
The aggregates were placed in metal trays with a layer thickness of approximately 2 cm and put into an oven at 50°C, in addition to this a smaller sample was placed in a smaller tray and weighed before and after in order to determine if constant mass had been achieved. The first batch of aggregates, 4-8 mm, were put in the oven for 27 hours at 50°C.
The sample weight was 1311 g before the drying process was started, and after 27 hours the sample weighed in at 1148 g, a reduction of 163 g ($\sim$ 12.5%). In the project group a test sample had previously been weighed after 24 hours, and again after an additional 20 hours of drying. The result showed a reduction of less than 2 g after another 20 hours of drying, it was therefore deemed acceptable with 27 hours of drying.
The same procedure was done for the 8-16 mm aggregates. These aggregates were dried for a longer time, due to the layer being thicker. This was done solely to save some time and speed up the process. The aggregates were placed in trays with a thickness of approximately 3.5cm and dried at 50°C for 42 hours. The sample weighed in at 1556 g before, and 1461 g after the process was complete, a reduction of only 95 g (6%). The larger aggregates were therefore holding close to 10% less water than the smaller aggregates. The procedure can be seen in Figure 3.4 and Figure 3.5. For a more detailed description of drying the aggregates see DS/EN1097-5 2013.

The final results of weights before sieving, before drying and after drying can be seen in Table 3.1.

Weighing of the aggregates before and after sieving was only done once in order to get an estimate about how much RCA had to be collected from the construction site, and there will be a more specific water contents experiment later on. This was so to speak only a screening in the very beginning of the project.

Figure 3.4: Aggregates placed in trays for drying.

Figure 3.5: Sample for drying procedure.

Table 3.1: Weights during sieving and drying process of the first collection of aggregates.

		Aggregates		
Size	Weight before sieving	Weight after sieving	Weight after drying	Reduction
4-8 mm	214.87 kg	31.53 kg	27.55 kg	3.98 kg (12.62%)
8-16 mm		56.19 kg	51.91 kg	4.28 kg (7.62%)

3.2 Porosity and Density of Aggregates

The porosity and density of the aggregates used is found using 2 different techniques. The first technique is done by using a desiccator and the other one is by using a gas pycnometer. These properties are important when creating the mix design in terms of final compressive strength and getting the desired water to cement ratio in the concrete mix.

3.2.1 Determination by desiccator (LBM-standard)

To determine the porosity and density of the aggregates using a desiccator, a small dry sample of each aggregate type was needed (m_{105}). The aggregates were placed in a small net and closed off with a rubber band, afterwards the samples were placed inside the desiccator. The desiccator was then connected to a vacuum pump for 3 hours, once that is done the desiccator was filled with distilled water and left for an other hour. Finally the valve to the desiccator was opened and the desiccator was then left overnight at atmospheric pressure.
The next day the samples were then first weighed below water (m_{sw}) and then dried with cloth and weighed above water (m_{ssd}). A more detailed description of the process can be found in (Appendix B).
This test was done twice to get as homogeneous results as possible, the results from the 2 tests can be found in chapter 4.

3.2.2 Determination by pycnometer

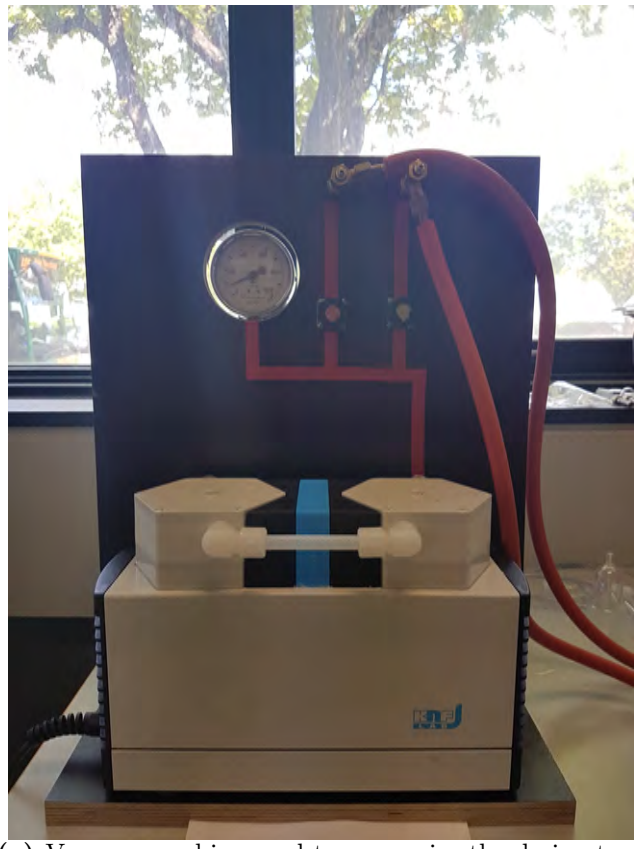
The pycnometer experiment is only used to determine the density of the aggregates. The experiment is performed using a vacuum machine, 2 desiccators, a large beaker and a pycnometer large enough to contain the sample you wish to test. The pycnometer has been calibrated beforehand and the weight of the pycnometer glass is known both with the lid on and filled with water.
A sample is weighed and put into the pycnometer which is filled approximately 75% with water, the beaker is just filled with water and both glasses are placed in the desiccator, one beaker for each. The vacuum machine is then started and has to run continuously for 2 hours and afterwards it is then turned on and off for an hour at a time, this is done for 24 hours. The following day the pressure is released from the desiccators and the pycnometer is then topped off with the water from the beaker.
The lid is then put on the pycnometer and any excess water is wiped off. The full pycnometer is then weighed again and it is then possible to determine the density. The equation used in order to determine the density can be seen in Equation 3.1 (found in DS/CEN ISO/TS 17892-3) and will be used later in chapter 4.

$$\rho_s = \frac{m_4}{\frac{m_1 - m_0}{\rho_{w;1}} - \frac{m_3 - m_2}{\rho_{w;3}}} \tag{3.1}$$

Where:

- ρ_s is the density of the soil particles
- m_0 is the dry mass of the pycnometer
- m_1 is the mass of the pycnometer completely filled with control liquid
- m_2 is the dry mass of the pycnometer filled with the dry sample
- m_3 is the mass of the pycnometer completely filled with the saturated sample and control liquid
- m_4 is the dry mass of the test sample
- $\rho_{w;1}$ is the density of the control liquid when m_1 is determined
- $\rho_{w;3}$ is the density of the control liquid when m_3 is determined

The test set-up used in this project can be seen in Figure 3.6 and a full detailed description of this method can be found in DS/EN1097-6 2013.



(a) Vacuum machine used to pressurize the desiccators.

(b) Desiccators and the test samples.

Figure 3.6: Apparatus and instruments used in the pycnometer experiment.

3.3 Attached mortar

When using RCA for new concrete, the aggregates will still be partially covered in old mortar. The old mortar can have an impact on the properties of the new concrete and it was therefore necessary to determine the amount of attached mortar on the aggregates used.
In order to do this a sample of approximately 5 grams of aggregates were weighed and put in a beaker, the sample was then mixed with 50 ml distilled water at approximately 50°C. This temperature was achieved by mixing distilled water from the tap with boiled distilled water 1:1. Once the sample is mixed with the distilled water 10 ml of concentrated nitric acid was poured into the sample and thoroughly mixed and left to react with the remaining mortar.
When the reaction has stopped (no more air development in the beaker) the sample was rinsed through a filter with distilled water and put in a Petri dish and put in the oven at 105°C for 24h. The following day the sample would be weighed once again and it is now possible to determine the amount of old mortar still attached to the aggregates. In order to do it this way, it is important that you weigh the filter and the Petri dish used for the sample in order to get the exact weights before and after the experiment.
A more detailed description of this method can be found in Appendix C, which is a part of the method to determine the chloride contents of a given sample. Since the attached mortar is the focus, the remainder of the experiment is not performed.
All aggregates in this experiment were pre-treated as previously described, it was performed on both 4-8 mm and 8-16 mm aggregates and it was also done on aggregates crushed to fine dust using a ring grinder. Finally the experiment was performed twice for both aggregate sizes, which will be further elaborated in chapter 4.

3.4 Particle size distribution

The aggregates used in this project are RCA, and the particle size distribution might therefore deviate from natural aggregates. It was therefore necessary to determine the particle size distribution of the collected aggregates.
This is done in a very low-practise way by sieving the aggregates by hand. With a maximum particle size of maximum 31.5 mm it is necessary to use atleast 10 kg of aggregates according to DS/EN-933-1 2007 to get a fair particle size distribution. The aggregates used were oven dried at 105ºC for 24 hours prior to the experiment. The aggregates were run through the following sieve sizes: 31.5 mm, 16 mm, 8 mm, 4 mm, 2 mm and 1 mm.
In order to not overfill the sieves, the sample was split into 2x5 kg. The sieving was then done for 5 kg at a time, and the material retained in each sieve was weighed. This experiment was also done twice, to get as homogeneous results as possible. The full description of this method can be found in DS/EN-933-1 2007.
The particle size distribution of the material with a diameter less than 1mm was found using laser diffraction, which will be described in the following section.

3.4.1 Laser diffraction

As previously described the smallest sieve used by hand was 1 mm, and to find the particle size distribution of the material with a diameter less than this laser diffraction was used. Laser diffraction works by measuring the pattern a particle scatters when passing through a beam of monochromatic light, usually a laser. Depending on the particle size the light is scattered in different patterns as can be seen in Figure 3.7.

Figure 3.7: The patterns created by 2 different spherical particles. The scattering pattern a) is twice as large as b). Found in DS-ISO13320 2009.

This technique can measure particles sizes ranging from 0.1 μm up to 3 mm, under certain conditions and with special instrumentation this technique can be extended even further. A much more detailed description of laser diffraction and its uses can be found in DS-ISO13320 2009.

3.5 Water content

When casting concrete using RCA the aggregates have normally been washed and dried. The dry aggregates make it harder to get the right water to cement ratio, because the dry aggregates absorb a lot of the mixing water. The water content was found using a very simple method by taking 3 samples from each of the size fractions used, i.e 4-8 mm and 8-16 mm.
Each sample was weighed in their air-dry state (AD) and then dried in an oven at 105ºC ± 5ºC for 24 hours to oven-dry state (OD). Afterwards the samples were weighed again, and the water content could be determined. A detailed description of the method can be found in DS/EN1097-5 2013. The results from this method can be found in chapter 4.

3.6 Casting of Concrete Specimens

Once the first batch of aggregates had been prepared as described in section 3.1, new concrete specimens using RCA were ready to be cast. The concrete mixture used in this project is the same as the one used in (Pepe et al. 2016) and is as follows:

- Cement: 344 $\frac{kg}{m^3}$ for w/c 0.5
- Cement: 287 $\frac{kg}{m^3}$ for w/c 0.6
- Water: 172 $\frac{kg}{m^3}$
- Sand: 742 $\frac{kg}{m^3}$
- Fine aggregates (4-8 mm): 554 $\frac{kg}{m^3}$
- Coarse aggregates (8-16 mm): 554 $\frac{kg}{m^3}$

This recipe was scaled down to a suitable size in order to be able to cast 4 concrete specimens for each cast, and to avoid excessive waste of materials. This was done by testing, and a suitable amount turned out to be 20 litres. The amounts of water, sand, cement, fine and coarse aggregates for all the casts performed during this project can be seen in Table 3.2.

Table 3.2: Concrete recipes used for every cast performed during the project.

	Specimen	w/c [-]	CEM I [kg]	Vand [kg]	Sand [kg]	NA 4-8 mm [kg]	NA 8-16 mm [kg]	RCA 4-8 mm [kg]	RCA 8-16 mm [kg]	Treatment [-]
Screening	Ref A	0,5	6,88	3,44	14,84	11,08	11,08	-	-	-
	A1	0,5	6,88	3,44	14,84	5,54	11,08	5,54	-	Washed/dried
	A2	0,5	6,88	3,44	14,84	11,08	5,54	-	5,54	Washed/dried
	Ref B	0,6	5,74	3,44	15,24	11,08	11,08	-	-	-
	B1	0,6	5,74	3,44	15,24	5,54	11,08	5,54	-	Washed/dried
	B2	0,6	5,74	3,44	15,24	11,08	5,54	-	5,54	Washed/dried
Further testing	B3	0,6	5,74	2,97	15,24	11,08	5,54	-	5,54	Saturated
	B4	0,6	5,74	2,62	15,24	11,08	-	-	11,08	Saturated
	B6	0,6	5,74	3,44	15,24	11,08	5,54	-	5,54	No treatment
	B7	0,6	5,74	3,44	15,24	11,08	-	-	11,08	Washed/dried
	B8	0,6	5,74	3,44	15,24	11,08	-	-	11,08	No treatment
	B9	0,6	5,74	3,44	15,24	-	-	11,08	110,8	No treatment

In Denmark normal practice when substituting NA with RCA, is to use aggregates that have been washes and dried or aggregates without any treatment at all. According to DS/EN-206-1 2011 the substitution of RCA is only allowed in a passive environment and the substitution limits are up to 30% for fine aggregates and up to 100% of the coarse aggregates. This corresponds very well with the very angular shape of the fine RCA and the increased amounts of attached mortar as previously described in section 2.2. It was therefore decided to experiment with substitution of different amounts of RCA and the treatment. The reason that the further experiments almost only substitute the coarse fraction, is that the amounts of fine aggregates (4-8 mm) was very limited in comparison to the coarse aggregates.

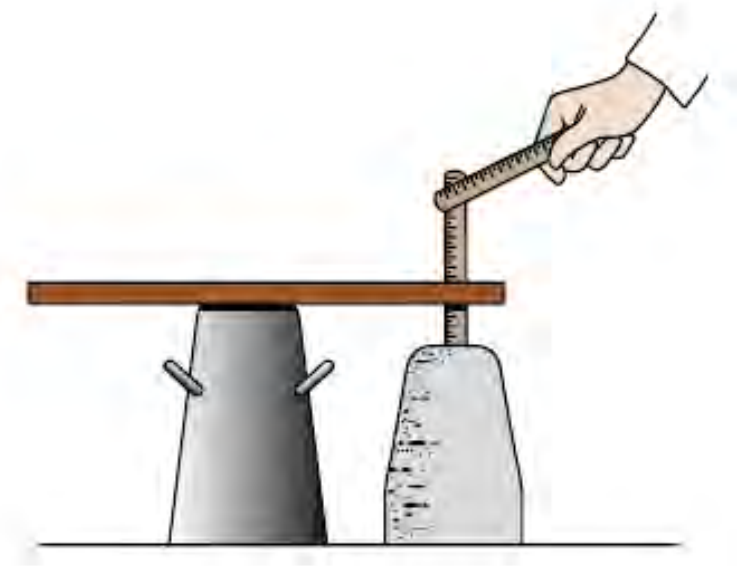
To start off the project a screening process was performed, this was done in order to as early as possible in the project to determine how the specimens would behave in terms of final compressive strength and early find a more specific path to investigate further. This was done by casting two reference mixtures using NA only, these were for the purpose of having something to compare the specimens using RCAs to.
The two first reference specimens, RefA and RefB, had a water to cement ratio of 0.5 and 0.6 respectively. For each reference specimen an additional two mixtures were cast, replacing either 50% of the fine aggregates or coarse aggregates with RCA, these were called A1, A2, B1 and B2.
These 6 mixtures were the initial screening process in the project and had a curing time of 7 days. This screening process showed that when casting with a w/c of 0.5, the slump of the mixtures was low and the workability rather poor, it was therefore decided to only cast concrete with a w/c of 0.6 further on. The slumps and air content of the casts can be seen later on in Chapter 4.
Afterwards different mixtures were cast with different variations in terms of different treatments of the aggregates, varying amounts of the aggregates replaced with RCA and curing times. The mixtures cast for further testing can also be seen in Table 3.2, it

turned out that the specimens cast using RCA that had had no treatment at all, other than being sieved, showed a surprisingly high compressive strength. It was therefore decided to cast more specimens using RCA without any treatment, to see if the strength development over time was as promising as the initial tests indicated, this is be further discussed in Chapter 4. It is also seen that the further testing was focused mostly on replacing 8-16 mm aggregates, because this showed the most promising results early on in the project.

The apparatus needed to cast the concrete specimens specified in Table 3.2 was a concrete mixer of suitable size, water, sand, fine and coarse aggregates and cement. The concrete mixer used in this project had a capability of approximately 30 litres, though this turned out to leave an excessive amount of unused concrete for every cast and in order to preserve material the 20 litres adjustment was done as previously described. The cement used in this project was CEM ll/A-LL 52,5 N (LA), which according to (EN-197-1 2000) means the cement is a Portland-limestone cement containing between 6% and 20% by mass of limestone with a total organic carbon content not exceeding 0.20% by mass (LL) of strength class 52.5 with an ordinary early strength and a low alkali content of $\leq 0.6\%$ by mass.
The materials displayed in Table 3.2 were weighed off in buckets and all the dry materials were added to the concrete mixer starting with the most coarse materials down to the finest. The materials were then dry mixed for approximately 1 minute before adding the mixing water slowly, the concrete was then allowed to mix for 5 minutes. Once the mixing process was complete a slump test was performed, the description of this can be found in section 3.6.1.
After the slump test the concrete was put into moulds measuring 200x100mm (HxD) according to (DS/EN12390-1 2013). The moulds were all lubricated using moulding oil, in order to make the de-moulding process easier. After filling the moulds they were placed on a vibration table and vibrated at approximately 60Hz somewhere in between 1 to 3 minutes depending on how wet or dry the concrete mix was. While vibrating the moulds were topped off and the top was levelled out to get a smooth top. Parallel to this the air content experiment was performed, the description to this experiment can be seen in section 3.6.2. Once the top of the moulds were levelled out nicely the lid was placed on the forms and the excess concrete was rinsed off and the moulds were set aside somewhere protected against shock, vibration and dehydration at a temperature of (20 $\pm$ 5^{o}C) for at least 16 hours but no more than 3 days. Once the specimens had been removed from the mould they were put in water at a temperature of (20 $\pm$ 2^{o}C) to cure until they were ready for compressive strength testing.
When casting the specimens using saturated aggregates a slightly different method was used. The desired amount of aggregates were weighed and put in water for 24h to achieve saturation (see Pepe et al. 2016). Before casting the saturated aggregates were taken out of the water and weighed once again, the mixture water was then corrected by the amount of water the aggregates had soaked during the 24h in water, hence less water was added to the concrete mixture. This can be seen for the specimens B3 and B4 in Table 3.2. A full description of the method can be found in DS/EN12390-2 2012.

3.6.1 Slump

When casting concrete you aim to reach a desired workability of the concrete, depending on what you need the concrete for. The workability of the concrete is a combination of the water to cement ratio and any additives added to the concrete mix. The workability of the concrete determines how much time and energy is needed when compacting the concrete, the lower the slump the more energy you need, and the other way around.
The workability of the concrete can be measured in 2 different ways, either using the slump test or the slump-flow test. In this project there is no need for a very high workability, and the slump test is therefore used, since a slump-flow test is usually first needed at slumps above approximately 200 mm. The slump test is performed using a frustum of a cone with a base diameter of 200 mm $\pm$ 2 mm, a top diameter of 100 mm $\pm$ 2 mm and a height of 300 mm $\pm$ 2 mm.
The cone is clamped at the bottom and then filled with concrete in 3 layers, where each layer compacted 25 times using a rounded steel rod with a diameter of 16mm (See Portland 2007 p. 85-86). Once the cone is filled it is released and slowly lifted up and concrete cone will collapse a bit. The difference between the top of the concrete cone and the height of the metal frustum of a cone is the slump. The apparatus and way to measure the slump can be seen in Figure 3.8.



(a) Slump test in theory.

(b) Slump test in practice.

Figure 3.8: Apparatus and measuring method for slump test.

3.6.2 Air content

The air content of the fresh concrete mixture is another property that has a influence on the final compressive strength. The higher the air content of the concrete mix, the higher is the porosity, which will lead to a decreased compressive strength in the end, each %-point increase in the air content will lead to a 4-5% decrease in compressive strength (See Portland 2007 p. 51). It is therefore important to control the amount of air in the fresh concrete. Depending of the use of the concrete there are different desired air contents, for instance if the concrete has to be frost resistant you need an air content of atleast 4.5%. In natural concrete the air content is usually around 1-2% (Portland 2007, K. K. Hansen 2012).
The air content can be measured using 2 different methods, one is the water column method and the other is the pressure gauge method. In this project the pressure gauge method was used. The details of the apparatus can be seen in Figure 3.9.

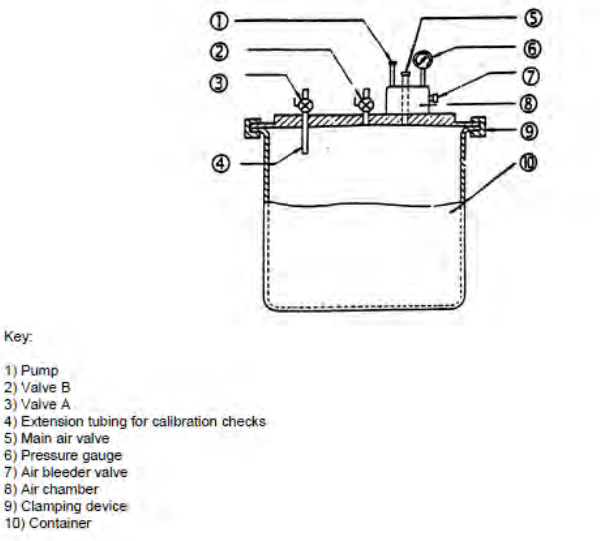


Figure 3.9: Pressure gauge method apparatus. Found in DS/EN12350-7 2009.

In this method the air content is measured using a pressure gauge meter. As seen in Figure 3.9 this consists of a container with a cover fitted with a pressure gauge that can be clamped to the container. The container is filled with concrete and vibrated on a vibration table capable of atleast 40Hz. In this project the concrete was vibrated at 60Hz. Once the vibration is complete the container is thoroughly sealed by clamping the cover on the container. The 2 valves, A and B, are opened and water is injected into either valve A or B using a syringe until water out of the other valve. The valves are then closed and air is pumped into the container until the pressure gauge reaches the original pressure (red line on Figure 3.10(a)), once that is done the main air valve is opened (green button seen in Figure 3.10(b)) and the air content can be read on the pressure gauge.
A full detailed description of this test method can be found in DS/EN12350-7 2009.

(a) Pressure gauge apparatus used.

(b) Pressure gauge on the container cover.

Figure 3.10: Apparatus and measuring method for slump test.

3.7 Compressive strength of specimens

Once the test specimens are hardened for either 1, 7 or 28 days they are ready to be tested for compressive strength, in this project only 7 and 28 day hardened specimens were tested. This was done using a Toni Technik 3000 machine. The specimens were placed in the center of the machine, topped off with a thin piece of spacing block to ensure that the pressure on the specimen would be even in case the top was uneven from the casting process. Figure 3.11(b) shows the display on the machine, here values such as diameter, height, weight, pressure rate and fracture detection % was inserted. The fracture detection % was set to 2.5% and is a value chosen based on previous experiments. This value gives a clear fracture that makes it possible to see the break pattern of the specimen. The pressure rate was chosen to 0.6 MPa per second according to DS/EN-12390-3 2009. Since the machine had a pressure rate of kN/s this had to be converted, which can be seen in equation 3.2.

$$P_{rate} = \pi \cdot \left(\frac{D}{2}\right)^2 \cdot 0.6 \cdot \left(\frac{N}{mm^2 \cdot s}\right) = \pi \cdot \left(\frac{100mm}{2}\right)^2 \cdot 0.6 \cdot \left(\frac{N}{mm^2 \cdot s}\right) = 4.71\frac{kN}{s} \quad (3.2)$$

The test set-up can be seen in Figure 3.11 and a full description of the compressive strength test method can be found in DS/EN-12390-3 2009.

(a) Toni Technik 3000.

(b) The display to edit the test values such as pressure rate and fracture rate.

Figure 3.11: Compressive strength test set-up.

CHAPTER 4

Results

4.1 Porosity and Density

4.1.1 Porosity and Density found with desiccator

The mean results for the determination of porosity and density of the aggregates can be seen in Table 4.1, whereas the results both of the 2 individual experiments can be found in Appendix A. The interesting part of these results are mostly the open porosity (P_{open}) and the saturated surface dry density of the aggregates (ρ_{ssd}). The reason for this is that these properties are most often tested, and these will therefore be the ones compared to results found by others.
It is seen that for the 4-8 mm aggregates the mean porosity is 19% and the density in ssd state is just below 2200 $\frac{kg}{m^3}$, for the 8-16 mm aggregates the mean porosity was slightly higher at 24.8% and a slightly higher ssd density of almost 2300 $\frac{kg}{m^3}$. These results will be further discussed and compared in chapter 5.

Table 4.1: LBM Standard test: Density and porosity found using a desiccator.

Samples		4-8 mm	8-16 mm
m_{105}	[Kg]	0,101	0,097
m_{ssd}	[Kg]	0,110	0,108
m_{sw}	[Kg]	0,059	0,061
V	[m3]	$5,07 \cdot 10^{-5}$	$4,72 \cdot 10^{-5}$
V_p	[m3]	$0,96 \cdot 10^{-5}$	$1,16 \cdot 10^{-5}$
P_{open}	[Kg/m3]	0,190	0,248
ρ_d	[Kg/m3]	1981,856	2051,378
ρ_f	[Kg/m3]	2447,945	2749,977
ρ_{ssd}	[Kg/m3]	2171,819	2299,009
u_{ssd}	[Kg/Kg]	0,096	0,120

4.1.2 Density found with pycnometer

As previously described the pycnometer experiment was only able to determine the density of the aggregates. The results from the experiment can be seen in Table E.1 (See Appendix E).

The results seen in Table E.1 are only for aggregates of the size 8-16 mm. The reasoning for only choosing the 8-16 mm fraction was because this was by far the most frequently used during the project. As seen the experiment was performed twice, and the mean density found using Equation 3.1 was:

$$\rho_s = 2.575\frac{g}{cm^3} = 2575\frac{kg}{m^3}$$

The result found using the desiccator experiment was just below $2750\frac{kg}{m^3}$ and is therefore only slightly lower at about 7%. The will be discussed further later in the report.

4.2 Attached mortar

The results from the experiments can be seen in Tables 4.2 and 4.3.

Table 4.2: Results from the 1st experiment of attached mortar.

Experiment 1	Sample before [g]	Sample after [g]	Reduction [%]	Average [%]
4-8 mm	4,96	3,32	33,06	29,27
4-8 mm (crushed)	5,26	3,92	25,48	
8-16 mm	5,77	5,00	13,34	15,12
8-16 mm (crushed)	5,33	4,43	16,89	

Table 4.3: Results from the 2nd experiment of attached mortar.

Experiment 2	Sample before [g]	Sample after [g]	Reduction [%]	Average [%]
4-8 mm	20,38	15,25	25,17	25,12
4-8 mm (crushed)	20,31	15,22	25,06	
8-16 mm	20,39	17,01	16,58	16,96
8-16 mm (crushed)	20,53	16,97	17,34	

It is seen in Tables 4.2 and 4.3 that despite the sample size, the amount of attached mortar for the 4-8 mm fraction is around 25 to 30% whereas the 8-16 mm fraction seems steady at approximately 15% attached mortar. The reason that the sample size in the 2nd experiment is approximately 4 times larger, was that with a sample size of only 5 g there was a rather large chance that the aggregates picked were pure mortar. For instance 5 g of the 8-16 mm aggregates were only 3-4 aggregates, if just one of those was pure mortar the reduction would already be at at least 25%.
It is also seen that the difference between having whole aggregates or crushing them beforehand had very little influence on the 4-8 mm fraction in experiment 2. The reason the difference is so much higher in experiment 1 can be due to the sample size as previously explained. For the 8-16 mm aggregates the reduction in both experiment 1

and 2 was slightly higher when crushing the aggregates. The reduction was expected to be higher when crushing the aggregates, due to the nitric acid having easier access to the mortar though the increased reduction was less than expected with only a few % increase.

4.3 Particle size distribution

The particle size distribution results from the first experiment can be seen in Table 4.4 and the graphic view of the results can be seen in Figure 4.1, Figure 4.2 and Figure 4.3 .

Table 4.4: Results of particle size distribution from the first experiment.

Particle size distribution: Experiment 1			
Fraction [mm]	Passing [g]	Passing [%]	Cumulative passing [%]
1	1357	15.20	15.20
2	1496	16.76	31.96
4	947	10.61	42.57
8	1367	15.31	57.88
16	2137	23.94	81.82
31.5	1623	18.18	100.00

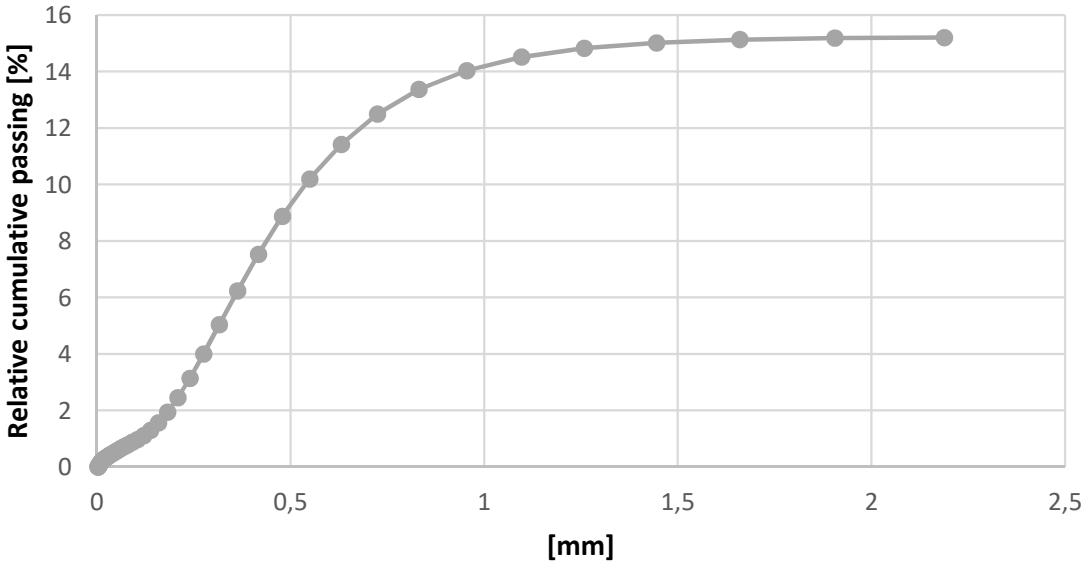


Figure 4.1: The particle size distribution from experiment 1 for aggregates below 1 mm found using laser diffraction.

It is seen in Figure 4.1 that the graph stops at 15.20% which is the cumulative passing value for aggregates less than 1 mm. The data below 1 mm is not included in the table

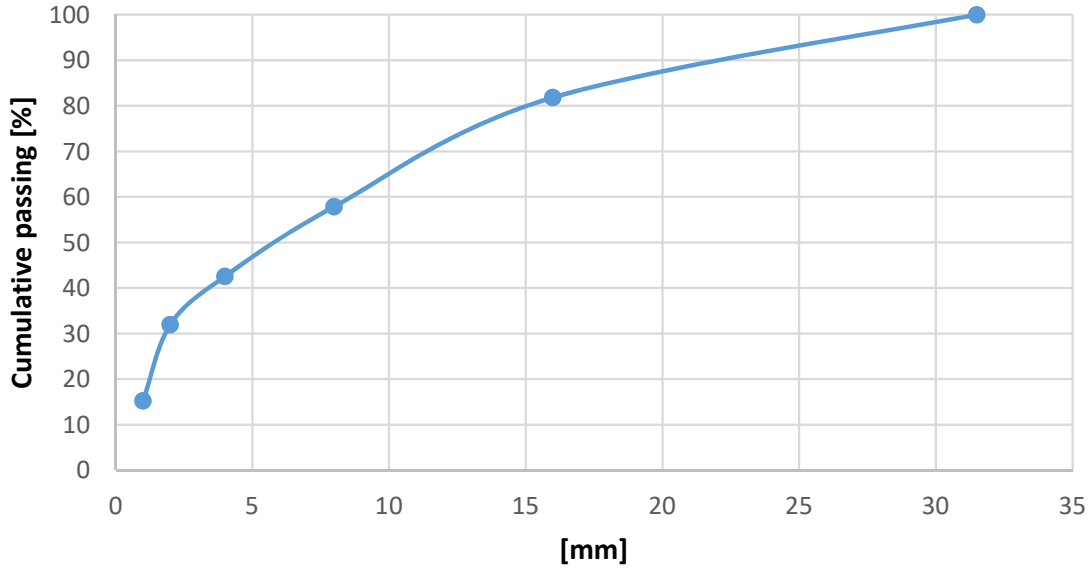


Figure 4.2: The particle size distribution from experiment 1 for aggregates above 1 mm found manually by hand.

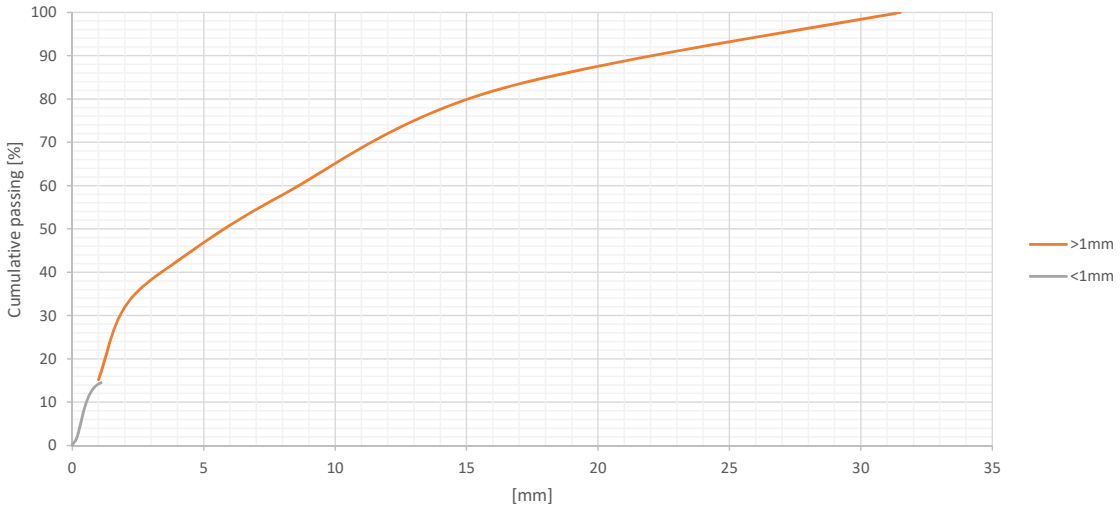


Figure 4.3: The combined particle size distribution from experiment 1.

because it is way too extensive and can be seen in Appendix F. Figure 4.2 shows the cumulative passing of the aggregates above 1 mm, and it therefore starts at 15.20% and ends at 100% passing.

Figure 4.3 shows a combination between Figure 4.1 and Figure 4.2. In order to make the 2 graphs properly connect the part of Figure 4.1 above 1 mm size is excluded, that way it can properly connect to the distribution found by hand starting at 1 mm. Right where the two graphs connect some of the data has been excluded to get a proper visualization of the result.
Likewise the results from the second experiment can be seen in Table 4.5 and the graphic view can be seen in Figure 4.4, Figure 4.5 and Figure 4.6.

Table 4.5: Results of particle size distribution from the second experiment.

Particle size distribution 2			
Fraction [mm]	Passing [g]	Passing [%]	Cumulative passing [%]
1	1278	15.13	15.13
2	1579	18.70	33.83
4	970	11.49	45.32
8	1356	16.06	61.37
16	1915	22.68	84.05
31.5	1347	15.95	100.00

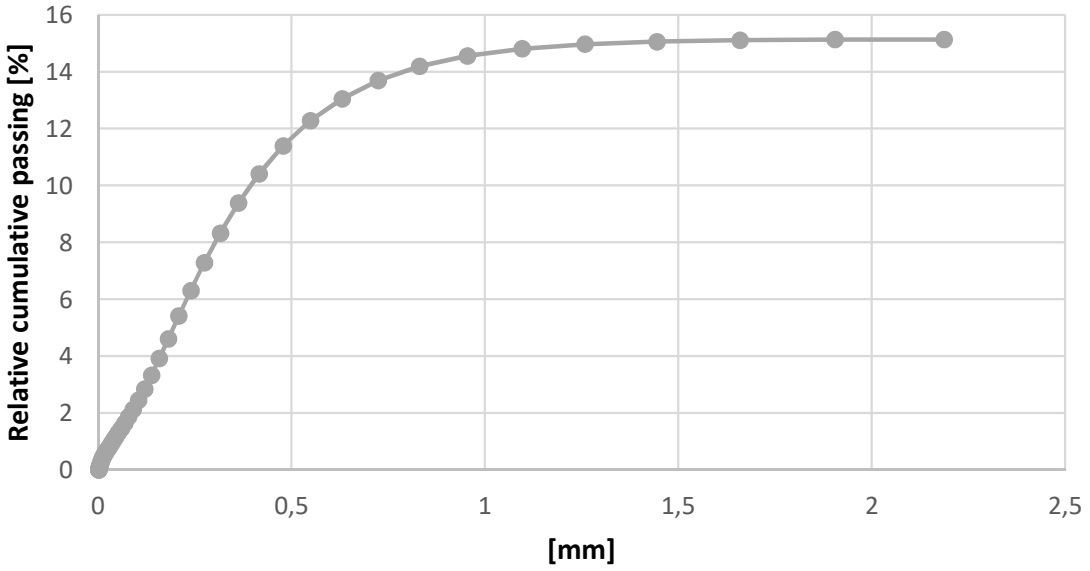


Figure 4.4: The particle size distribution from experiment 2 for aggregates below 1 mm found using laser diffraction.

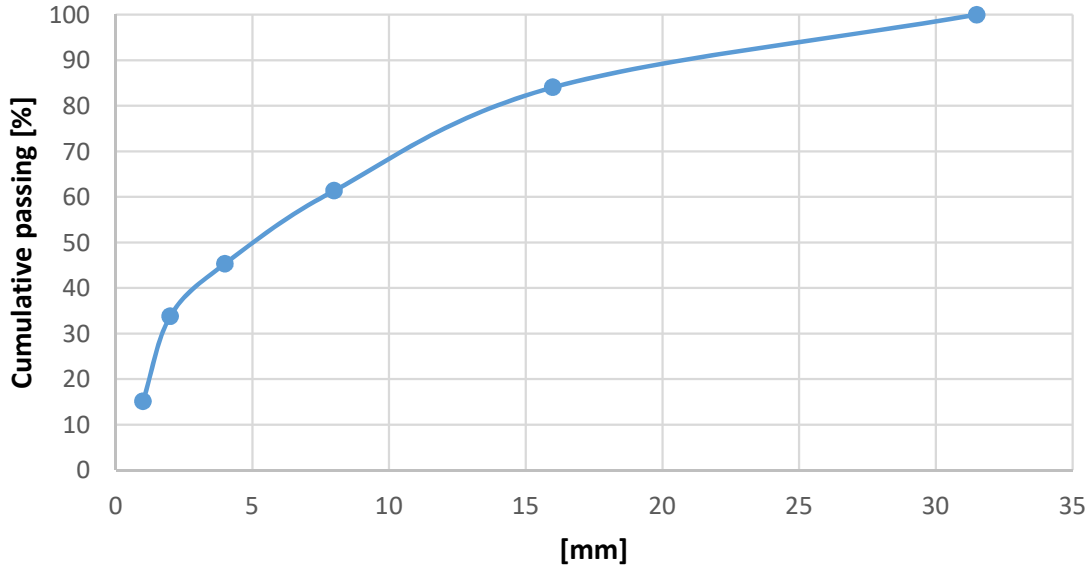


Figure 4.5: The particle size distribution from experiment 2 for aggregates above 1 mm found manually by hand.

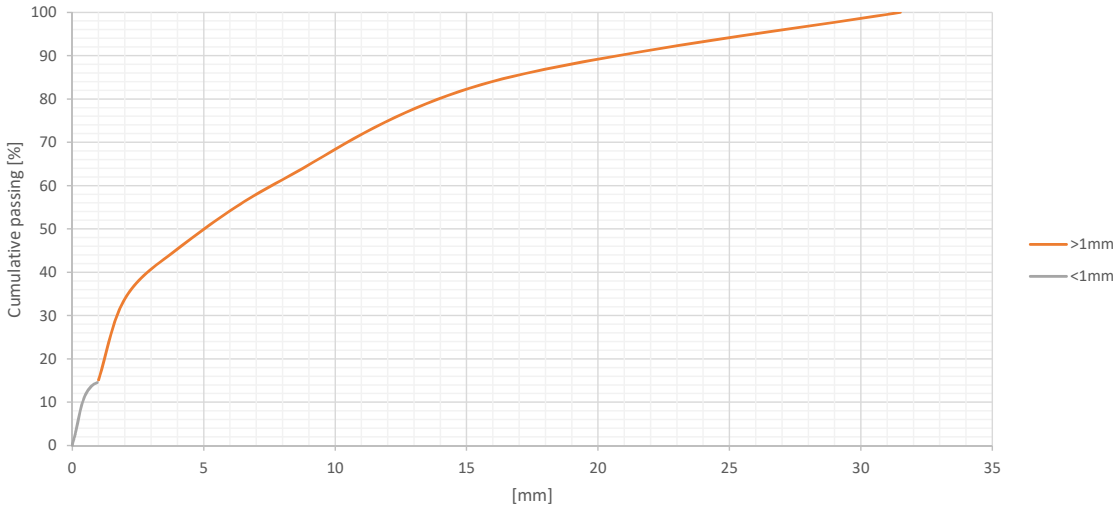


Figure 4.6: The combined particle size distribution from experiment 2.

Again it is seen that Figure 4.4 stops at the value of the passing for aggregates below 1 mm which in this experiment was 15.13% and like previously all the more specific data from the laser diffraction experiment can be seen in Appendix F. Figure 4.5 shows the passing above 1 mm starting at 15.13% up to 100% passing.
Figure 4.6 shows the combined graphic visualization of the passing from 0 up to 1 mm and from 1 mm to 31.5 mm, like previously described at the point where the two graphs meet, the data set had to be fitted to get a proper connection between the two.
Comparing the passing values from experiment 1 and 2 seen in Tables 4.4 and 4.5 it is seen that the values from the laser diffraction (<1mm) almost don't deviate.
When looking at the passing values above 1 mm we see approximately the same deviation for every sieve size. For every sieve size the difference between experiment 1 and 2 is approximately 2-3%, which isn't much and is therefore deemed acceptable.
Finally the combined graph from experiment 1 and 2 can be seen in Figure 4.7.

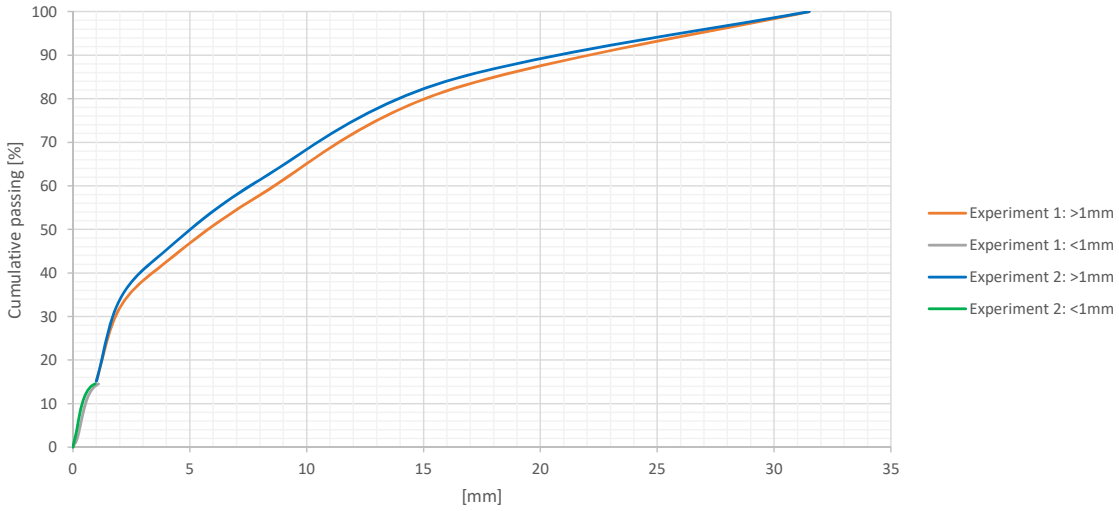


Figure 4.7: The combined particle size distribution from experiment 1 and 2.

It is clearly seen in Figure 4.7 that the results from the laser diffraction are almost identical and the distribution found by hand only slightly deviates from each other by a few %.

4.4 Water content

The results from the water content experiment can be seen in Table 4.6. It is seen that the water content in the 4-8 mm fraction was constant at a 7.5% and the 8-16 mm fraction contained slightly less water at a mean reduction of 6.5%.
Moisture content of natural aggregates can vary in between 1 percent in gravel and up to 40 percent in very porous sandstone (Pennstate 2017), so the values found here are acceptable. Since concrete is cast with gravel, the values might seem rather high which could be explained by the rather high amount of attached mortar on the aggregates which has a rather high porosity.

Table 4.6: Results from the water content experiment.

Fraction	Weight before [g]	Weight after [g]	Water content [%]	Mean water content [%]
4-8 mm	200	185	7.50	7,50
	200	185	7.50	
	200	185	7.50	
8-16 mm	200	188	6.00	6,50
	200	187	6.50	
	200	186	7.00	

4.5 Slump and air content

The slump and air content was measured and noted for every cast. The slump and air content has a great influence on the workability and properties of the hardened concrete. Higher slumps are usually seen when the concrete is very wet, and it will lead to a lower final compressive strength, likewise the air content has a influence on the properties, for instance if the concrete needs to be frost resistant the air content has to be at least 4.5%. The slump and air content measurements from all the concrete castings can be seen in Table 4.7.

Table 4.7: The slump and air content for every concrete casting performed, including the varying amounts of aggregates replaced and their treatment.

Specimen	w/c	RCA	Curing Length [Days]	Slump [mm]	Mean Slump [mm]	Air Content [%]	Mean Air Content [%]
RefA	0,5	None	7	40	44	1,50	1,65
			7	15		2,20	
			28	60		1,40	
			28	60		1,50	
A1	0,5	4-8mm, 50%	7	0	10	2,10	1,60
			28	20		1,10	
A2	0,5	8-16mm, 50%	7	20	20	2,00	1,55
			28	20		1,10	
RefB	0,6	None	7	30	63	1,70	1,63
			7	30		2,00	
			28	130		1,20	
B1	0,6	4-8mm, 50%	7	10	15	1,90	2,00
			28	20		2,10	
B2	0,6	8-16mm, 50%	7	20	15	1,80	1,95
			28	10		2,10	
B3	0,6	8-16mm, 50% saturated	7	5	5	1,90	1,90
B4	0,6	8-16mm, 100% saturated	7	5	5	1,50	1,50
B6	0,6	8-16mm, 50% no treatment	7	45	53	1,50	1,45
			28	60		1,40	
B7	0,6	8-16mm 100%	7	5	5	2,10	2,10
B8	0,6	8-16mm, 100% no treatment	7	15	38	2,10	1,90
			28	60		1,70	
B9	0,6	4-8mm and 8-16mm, 100% no treatment	7	0	18	1,90	1,85
			28	35		1,80	

It is seen in Table 4.7 that the slump for all the concrete castings ranges in between 0mm up to 130mm. Depending on the purpose of the concrete and how the vibration is performed the slump has to vary. On site the concrete will in most cases be vibrated using a stick and the slump should therefore normally be in the range between 60mm to 130mm (See Portland 2007). The air content of the concrete was rather constant for all the experiments performed ranging from 1.45-2.1%, which for RCA should range in between 1.1-2% according to (T. C. Hansen 1986 and Portland 2007).
The slumps for the casting performed in this project are mostly in the area of 30 mm and it is therefore on the lower side of the recommended. The reason the slump in this project was not adjusted was to maintain the water to cement ratio at either 0.5 or 0.6, in order to be able to properly compare the different mixture designs final compressive strength to each other.

4.6 Compressive strength of specimens

4.6.1 Initial testing

After hardening for either 7 or 28 days the concrete specimens were ready to be tested for their compressive strength. Every specimen was tested using the apparatus and pressure rate previously described in chapter 3. All raw test data for each concrete specimen can

be found in Appendix G. During the early stages of the project some of the data was unfortunately not noted, such as the fracture type and displacement.
The first specimens to be tested were the references RefA/RefB, A1/A2 and B1/B2, the specimens previously described as the screening specimens. The results of the compressive strength for these can be seen in Figure 4.8 and Figure 4.9.

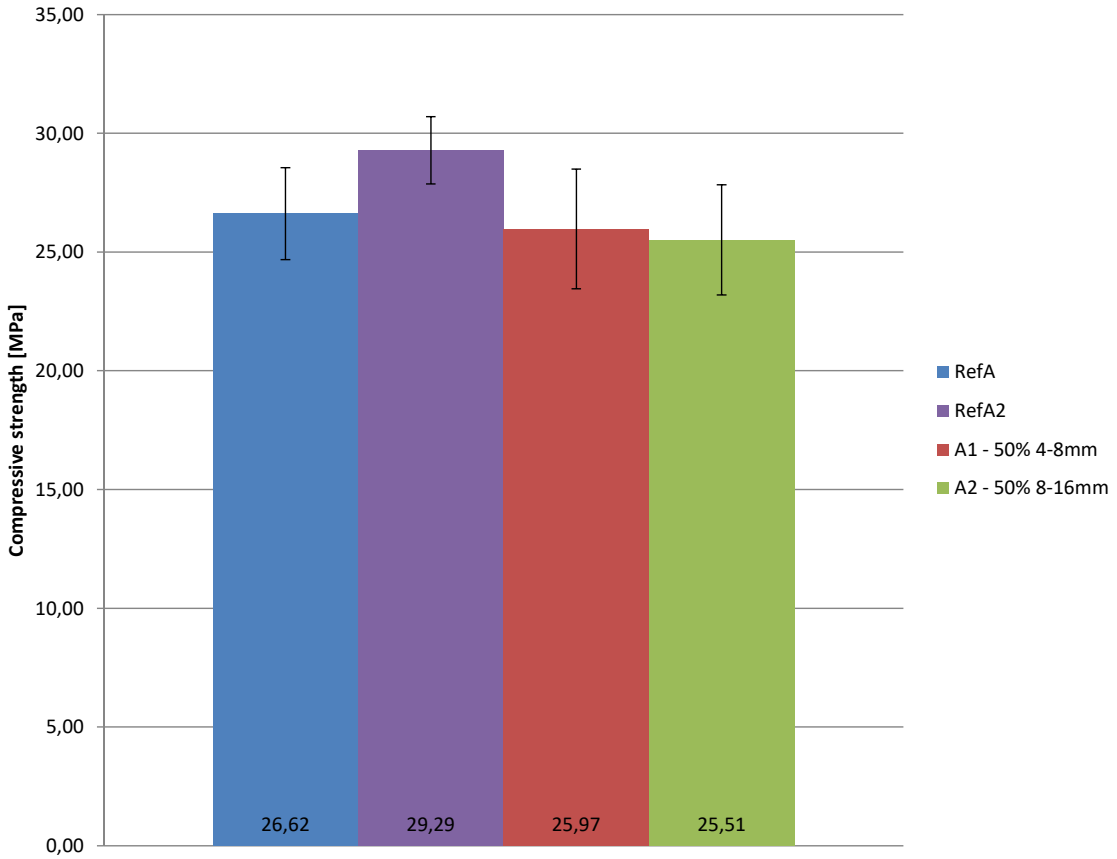


Figure 4.8: Results from the screening specimens that cured for 7 days with w/c = 0.5.

It is seen in Figure 4.8 that a reference RefA2 is also included. This reference was cast later on in the process because the strength of RefA was expected to be more than approximately 1 MPa stronger than A1/A2 (it should theoretically be 5-10% stronger (M. Safiuddin et al. 2013)), and it is therefore included here as well.
Figure 4.8 shows that substituting either 50% of 4-8 mm (A1) or 8-16 mm (A2) at a water to cement ratio of 0.5 resulted in almost identical strengths of 25.97 MPa and 25.51 MPa respectively. The first reference RefA showed only slightly higher strength

at 26.62 MPa, whereas RefA2 showed a compressive strength of 29.29 MPa which, as expected, is approximately 10% higher than when casting concrete using RCA.

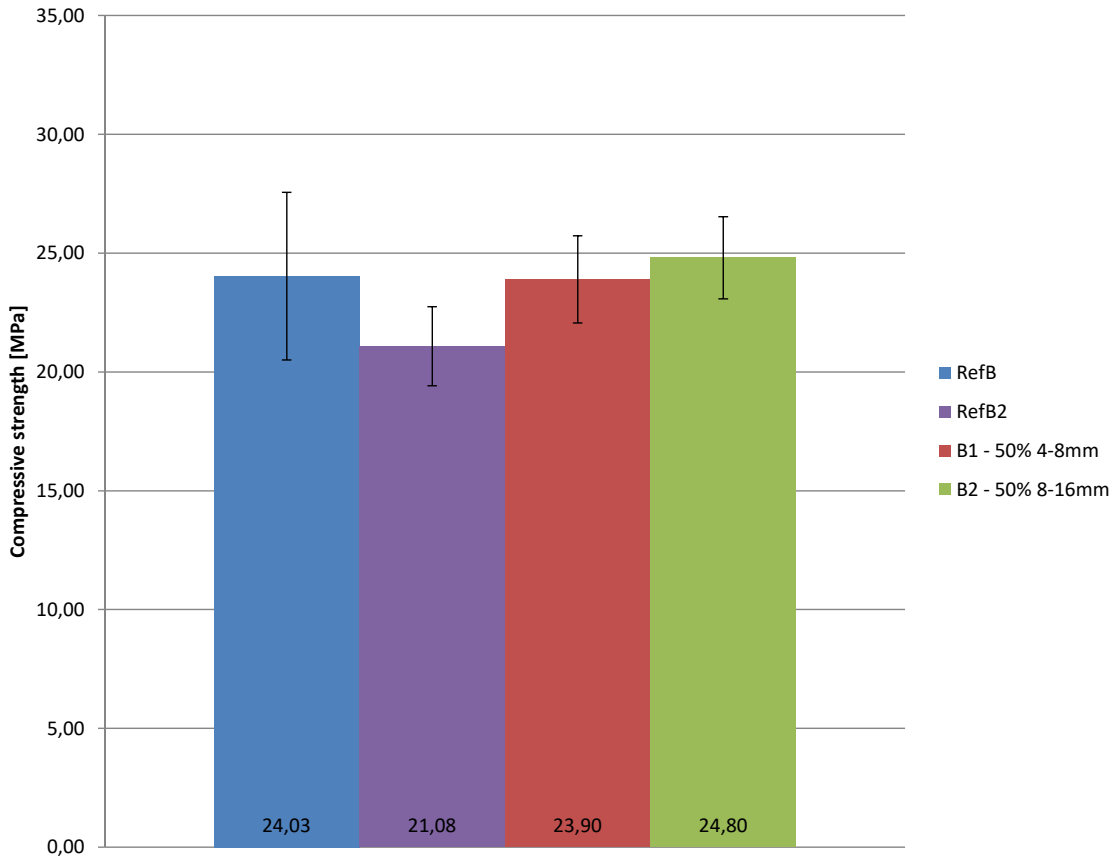


Figure 4.9: Results from the screening specimens that cured for 7 days with w/c = 0.6.

Figure 4.9 shows the results from the screening of specimens with a water to cement ratio of 0.6. Here it is also seen that a RefB2 has been added, this was due to the very high standard deviation of the first reference RefB. The 2nd cast RefB2 successfully managed to decrease the standard deviation, but the strength was unfortunately lower than the first reference.
Figure 4.9 shows, that substituting 50% of either 4-8 mm (B1) or 8-16 mm (B2) at a water to cement ratio of 0.6 also yield very similar compressive strengths at 23.90 MPa and 24.80 Mpa respectively. The first reference RefB showed a strength of 24.03 MPa and RefB2 showed a strength of only 21.08 MPa, both of which were lower than expected.

The results from the screening specimens that were allowed to cure for 28 days can be seen in Figure 4.10 and Figure 4.11

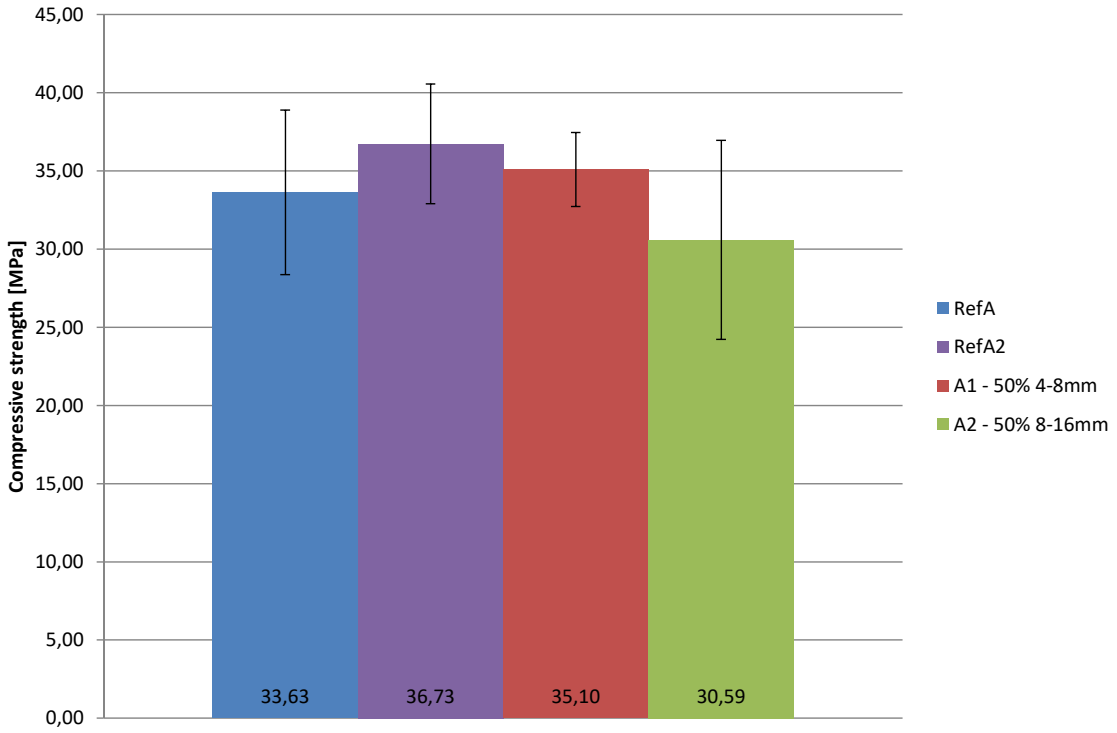


Figure 4.10: Results from the screening specimens that cured for 28 days with w/c = 0.5.

Figure 4.10 shows the results from the screening specimens that were allowed to cure for 28 days having a water to cement ration of 0.5. Again an additional reference specimen RefA2 is seen, this was due to a combination of the compressive strength of the first reference RefA being low and having a high standard deviation.
The new reference specimen managed to have an increased strength, but only slightly decreased the standard deviation. It is seen that RefA and RefA2 achieved a strength of 33.63 MPa and 36.73 MPa while the specimens with 50% RCA of either 4-8 mm (A1)or 8-16 mm (A2) achieved a strength of 35.10 MPa and 30.59 MPa respectively.
RefA2 was therefore 5-10% stronger than the specimens with RCA which was as expected, RefA on the other hand only managed to be stronger than the RCA specimen with 50% 8-16 mm replaced.

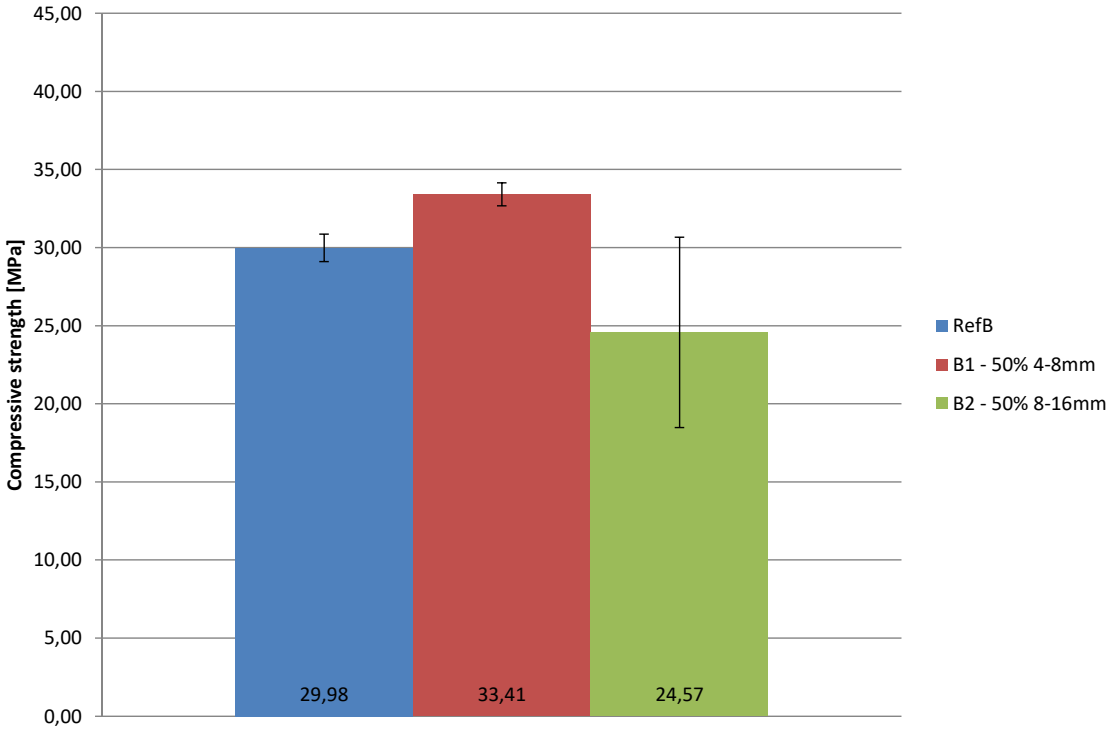


Figure 4.11: Results from the screening specimens that cured for 28 days with w/c = 0.6.

Figure 4.11 shows the results from the screening specimens that cured for 28 days with a water to cement ratio of 0.6. Here it wasn't deemed necessary to cast a second reference since the standard deviation of RefB was very low. RefB achieved a compressive strength of 29.98 MPa and the specimens with 50% RCA of 4-8 mm (B1) and 8-16 mm (B2) achieved strengths of 33.41 MPa and 24.57 MPa respectively. Specimen B1 was therefore approximately 10% stronger than the reference specimen as expected, meanwhile B2 turned out to be about 10% weaker.

4.6.2 Further testing

After the initial screening tests were done and it was decided to only cast using w/c=0.6, it was time to start experimenting more with varying RCA contents and treatments of the aggregates. The specimens B3, B4, B6 and B7 were therefore cast, the amounts of RCA replaced and the treatment used for the aggregates have previously been displayed in Table 3.2. The specimens had either 50% or 100% of the coarse aggregates replaced with RCA, and the treatments were either saturated, washed and dried or no treatment at all. The results from the compressive strength of these specimens can be seen in Figure 4.12.

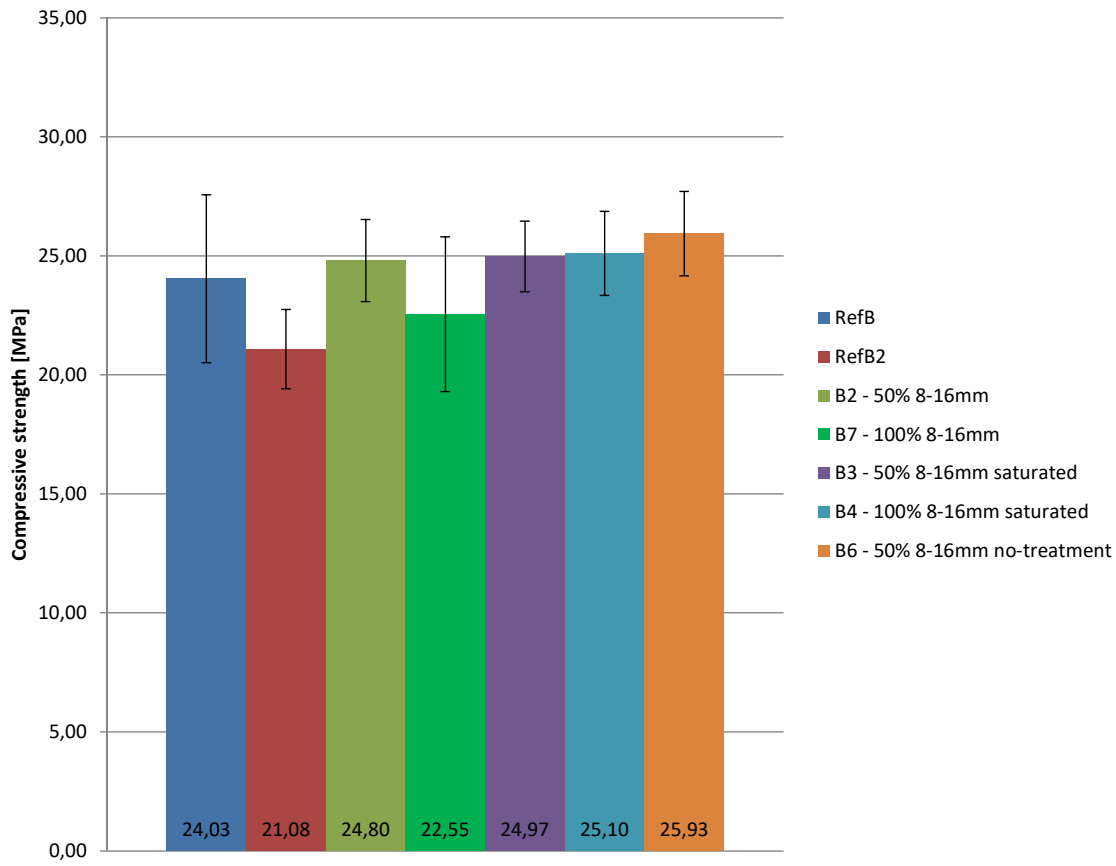


Figure 4.12: Results from the further tests of varying RCA amounts and treatments cured for 7 days with w/c = 0.6.

In Figure 4.12 the reference specimens RefB/RefB2 and specimen B2 are included as well to better compare the results. It is seen that when replacing either 50% or 100%

aggregates with a normal treatment (B2 and B7), the compressive strength decreases. With 50% replacement a strength of 24.80 MPa was achieved and only 22.55MPa when replacing 100% (B7). When replacing 50% and 100% of the aggregates with RCA that were saturated (B3/B4) almost no difference in the compressive strength was detected. The strength when replacing 50% (B3) was 24.97 MPa and when replacing 100% (B4) 25.10 MPa. Finally when replacing 50% of the coarse aggregates with RCA that had had no treatment, a surprisingly high compressive strength was achieved. The compressive strength of this mixture (B6) was 25.93 MPa which even exceeded the compressive strengths of the reference specimens (RefB/RefB2) at 24.03 MPa and 21.08 MPa respectively.
The surprisingly high compressive strength achieved with coarse aggregates without any treatment, therefore became the focus of the final tests performed during the project. The last specimens cast were therefore testing further replacement of aggregates with RCA, both replacing fine and coarse aggregates (B8/B9) and the long term strength development was tested by casting specimens B6, B8 and B9 once more and letting these cure for 28 days. The first results from the specimens cast without any treatment can be seen in Figure 4.13.

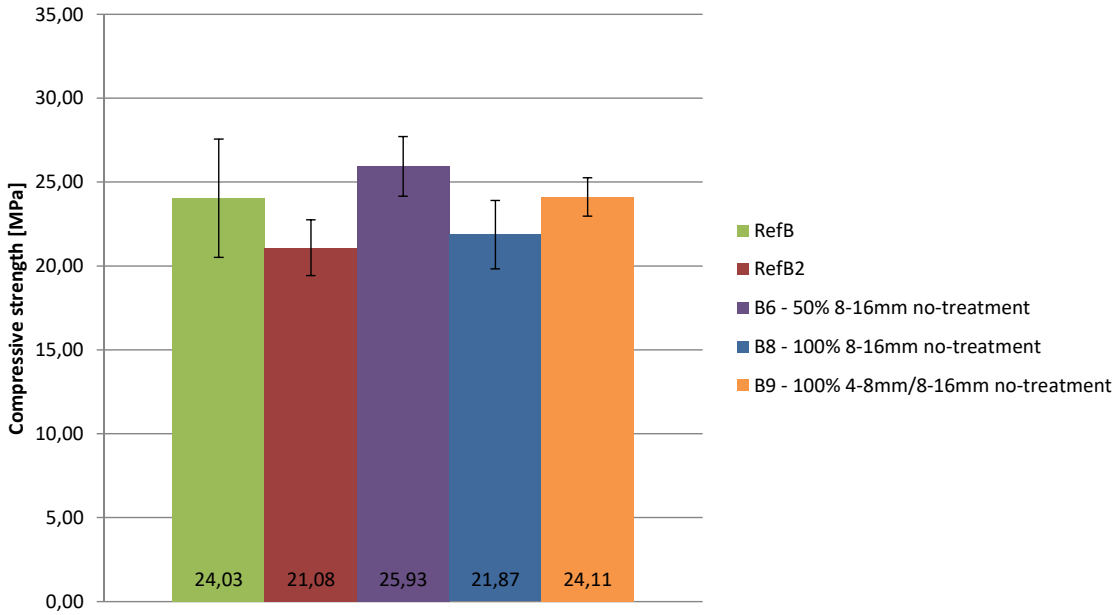


Figure 4.13: Results from the further testing of specimens cast with varying amounts of RCA without any treatment cured for 7 days with w/c = 0.6.

The results from the two reference specimens RefB/RefB2 and B6 shown in Figure 4.13 have already previously been described. The 2 new specimens B8 and B9 had 100% RCA content of either only coarse aggregates (B8) or both fine and coarse aggregates (B9). It is seen in Figure 4.13 that the compressive strength achieved by 100% replacement of the coarse aggregates (B8) was 21.87 MPa, and for 100% replacement of both fine and coarse aggregates (B9) a strength of 24.11 MPa was achieved. The compressive strength when replacing 100% coarse aggregates was therefore lower than when only replacing 50%, but even though the compressive strength of 100% replacement was low it still had approximately the same strength as the reference specimens. When replacing all aggregates in the cast with RCA the strength appeared to land in between replacing 50% and 100% of the coarse aggregates only, and slightly higher than the reference specimens.

The long term strength specimens B6, B8 and B9 can be seen in Figure 4.14.

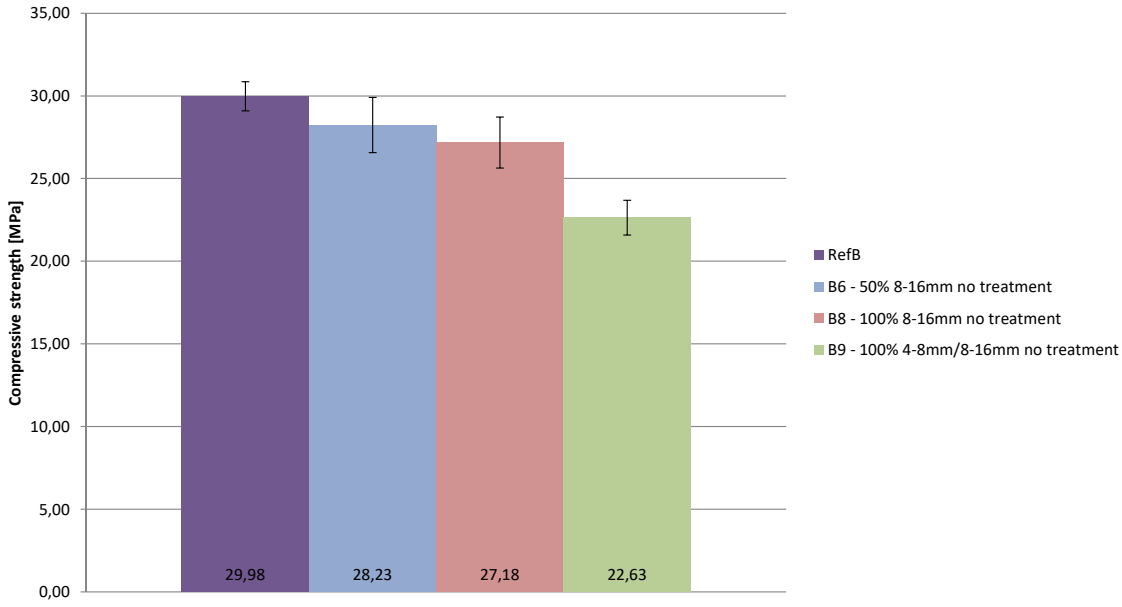


Figure 4.14: Results from the further testing of specimens cast with varying amounts of RCA without any treatment cured for 28 days with w/c = 0.6.

Figure 4.14 shows that replacing either 50% (B6) or 100% (B8) of the coarse aggregates has very low impact when the specimens are allowed to cure for 28 days. The strengths detected were for 50% replacement 28.23MPa and for 100% replacement 27.18 MPa, both of which were lower than the reference at 29.98 MPa. Replacing 100% of both fine and coarse aggregates (B9) on the other hand show a significant decrease of around 25% in compressive strength at 22.63 MPa compared to the reference at 29.98 MPa.

CHAPTER 5

Discussion

5.1 Porosity, density and water content

The results found in chapter 4 can be compared to the results Poon et al. 2004 have found in their study of the moisture content in natural and recycled concrete aggregates. The results from Poon et al. 2004 can be seen in Figure 5.1 and 5.2.

Type	Nominal size (mm)	Density (kg/m^3)	Water absorption (%)	Strength (10% fine value) KN	Porosity (%)
Crushed granite	10	2620	1.25	159	1.60
	20	2620	1.24		
Recycled aggregate	10	2330	7.56	117	10.45
	20	2370	6.28		

Figure 5.1: Moisture contents of aggregates..

Mix	Moisture content (%)				
	Sand	Crushed granite		Recycled aggregate	
		10 mm	20 mm	10 mm	20 mm
AD1	0.61	0.70	0.66	3.70	2.90
OD1	0.61	0.00	0.00	0.00	0.00
SSD1	0.40	1.25	1.24	7.16	6.14
AD2	0.76	0.78	0.85	3.84	3.22
OD2	0.82	0.00	0.00	0.00	0.00
SSD2	0.82	1.25	1.24	7.16	6.14
AD3	0.45	0.72	0.42	3.28	3.15
OD3	0.45	0.00	0.00	0.00	0.00
SSD3	0.76	1.25	1.24	7.16	6.14
AD4	0.40	0.65	0.48	3.65	3.02
OD4	0.42	0.00	0.00	0.00	0.00
SSD4	0.42	1.25	1.24	7.16	6.14

Figure 5.2: Properties of natural and recycled aggregates..

To quickly summarize the results found previously in chapter 4 the open porosity was found to be 19% for fine aggregates and 24.8% for coarse aggregates. The ssd density of fine aggregates was 2171 $\frac{kg}{m^3}$ and coarse aggregates was 2299 $\frac{kg}{m^3}$. The particle density found with the pycnometer was 2575 $\frac{kg}{m^3}$. Finally the water content of the fine aggregates was 7.5% and coarse aggregates 6.5%

Starting off looking at the fine aggregates the porosity in Poon et al. 2004 was unfortunately only tested for a nominal size of 10mm, and their test showed a porosity of 10.45% as seen in Figure 5.2. This porosity is about 50% lower than what was detected using the desiccator experiment during this project, unfortunately there is no description of the method used to find the porosity in Poon et al. 2004. On the other hand the water content found for the fine aggregates are very similar, Poon et al. 2004 found the aggregates with a nominal size of 10 mm had a water content of about 4-7% whereas the fraction tested in this project showed a water content of 7.5%. This could indicate that Poon et al. 2004 either used a different method to find the porosity, or there might have been made a mistake during the experiment performed during this project.

The ssd density of 2171 $\frac{kg}{m^3}$ appears to be fairly accurate since the density found by Poon et al. 2004 was 2330 $\frac{kg}{m^3}$ (See Figure 5.1). The same ssd density was found in another study performed by T. C. Hansen 1986 where the density for 4-8 mm aggregates was found between 2340-2350 $\frac{kg}{m^3}$ depending on the water to cement ratio. Reasons that the density found was slightly lower than this could be, that the aggregates in this project might have had a higher amount of attached mortar, which automatically would lead to a lower density.

For the coarse aggregates Poon et al. 2004 did no investigation to find the porosity and can therefore not be compared, but since the porosity for the fine aggregates had such a high deviation the coarse aggregates would probably have showed the same tendency. The water content found for the coarse aggregates of 6.5% matches Poon et al. 2004 pretty well, since they found the water content of coarse RCA to be 3-6%. The ssd

density of 2299 $\frac{kg}{m^3}$ also matches very well since Poon et al. 2004 found the ssd density of coarse aggregates to be 2370 (See Figure 5.1). The study performed by T. C. Hansen 1986 found the density of 8-16mm RCA to be between 2440-2450 $\frac{kg}{m^3}$, which is slightly higher than the density found in both Poon et al. 2004 and this study.
Finally no studies has been found where the particle density was investigated, but since the particle density does not take account for the porosity it can approximately be compared to the density of NA, since NA has a very low porosity. Both Poon et al. 2004 and T. C. Hansen 1986 investigated the density of the NA used, and they found the density to be 2620 $\frac{kg}{m^3}$, which matches the found density of 2575 $\frac{kg}{m^3}$ very well.

5.2 Particle size distribution

The results found in chapter 4 can be compared to Fuller's ideal grain size distribution curve (Munch-petersen 2013) and to the passing values used to classify RCA in Pihl, Berg, and Milvang-Jensen 2004. Fuller's ideal grain distribution is defined by the following equation:

$$p = 100 \cdot \sqrt{\frac{d}{d_{max}}} \tag{5.1}$$

Where p is the ideal passing value, d the particle size and d_{max} is the maximum particle size. The maximum particle size in this project was 31.5 mm and the Fuller ideal passing values have been calculated and summarized in Table 5.1 together with the results previously found.
It is seen that sieve sizes 0.5 mm and 0.063 mm has been added, these can be found in the raw data of the laser diffraction found in Appendix F. These points were added to compare the results to Pihl, Berg, and Milvang-Jensen 2004 which will be done later.

Table 5.1: Summarized results together with Fuller's ideal values.

Fraction [mm]	Experiment 1 Cumulative passing [%]	Experiment 2 Cumulative passing [%]	Combined Average passing [%]	Fuller's ideal Passing [%]	Deviation [%]
31,5	100	100	100	100,00	0,00
16	81,82	84,05	82,93	71,27	11,66
8	57,88	61,37	59,63	50,40	9,23
4	42,57	45,32	43,94	35,63	8,31
2	31,96	33,83	32,89	25,20	7,70
1	15,20	15,13	15,17	17,82	2,65
0,5	10,20	12,28	11,24	12,60	1,36
0,063	0,65	1,46	1,05	4,47	3,42

Table 5.1 shows that the passing values found by hand and laser diffraction deviate from Fuller's ideal distribution by 1-10%. It is seen that the passing values deviate more for the larger aggregates than the smaller aggregates. This indicates that the fraction of small aggregates has been too large. If the fraction of smaller aggregates is too large, the degree of packing of the aggregates become worse, which leads to decreased workability of the concrete which could be an explanation to the low workability experienced when

casting the concrete specimens.
This is due to the smaller aggregates will "push" the larger aggregates apart, likewise if the amount of fine aggregates is too small the larger aggregates will end up rubbing against each other, which also leads to decreased workability.

The values displayed in Table 5.1 can also be compared to the passing value requirements used to classify RCA from Pihl, Berg, and Milvang-Jensen 2004. The classification values can be seen in Table 5.2.

Table 5.2: Value requirements in order to classify the RCA as class A, found in Pihl, Berg, and Milvang-Jensen 2004.

Sieve mm	Passing [%]		Deklaration values		Tolerance
	Min.	Max.	Min.	Max.	
63	100	-	-	-	
31,5	75	99	-	-	
16	50	90	61	79	± 11
8	30	75	41	64	± 11
4	20	60	31	49	± 11
2	13	45	22	36	± 9
1	8	35	13	30	± 5
0,5	5	25	10	20	± 5
0,063	2	5	2	5	-

It is seen that the passing values found in Table 5.1 almost all lie within the intervals required to classify the RCA as class A seen in Table 5.2. The only value that doesn't meet the requirement is the 0.063 mm fraction. The passing value found using laser diffraction averaged at 1.05% which is 1% lower than what is required, but since deviation is so small it is deemed acceptable to classify the RCA used in the project class A.

5.3 Attached mortar

The averaged values of attached mortar previously detected for the coarse and fine aggregates used in this project are summarized in Table 5.3.
It is seen in Table 5.3 that the averaged amount of attached mortar for fine aggregates was 27.19% and 16.04% for coarse aggregates. The amount of attached mortar on RCA has previously been studied by T. C. Hansen 1986, and the results reported can be seen in Figure 5.3.
Since the water to cement ratio of the original concrete is not known, it is assumed to be in the range of 0.4 to 0.7 to compare the results to the ones reported by T. C. Hansen 1986. Figure 5.3 shows that the amounts of attached mortar for fine aggregates (4-8 mm) ranges from 50% (w/c = 0.4) to 64% (w/c = 0.7) and coarse aggregates (8-16

Table 5.3: Averaged values of attached mortar for coarse and fine aggregates used.

Aggregates	Experiment 1 Average [%]	Experiment 2 Average [%]	Mean [%]
4-8mm 4-8mm (crushed)	29,27	25,12	27,19
8-16mm 8-16mm (crushed)	15,12	16,96	16,04

Type of Aggregate	Size Fraction in mm	Specific Gravity SSD cond.	Water Absorption in percent	Los Angeles Abrasion Loss Percentage (L500)	Los Angeles Uniformity Number L100/L500 Ratio	B.S. Aggregate Crushing Value in percent	Volume percent of mortar attached to natural gravel particles
Original natural gravel	4- 8 8-16 16-32	2500 2620 2610	3.7 1.8 0.8	25.9 22.7 18.8	0.28 0.22 0.20	21.8 18.5 14.5	0 0 0
Recycled aggregate (H) (w/c = 0.40)	4- 8 8-16 16-32	2340 2450 2490	8.5 5.0 3.8	30.1 26.7 22.4	0.30 0.25 0.24	25.6 23.6 20.4	58 38 35
Recycled aggregate (M) (w/c = 0.70)	4- 8 8-16 16-32	2350 2440 2480	8.7 5.4 4.0	32.6 29.2 25.4	0.31 0.28 0.25	27.3 25.6 23.2	64 39 28
Recycled aggregate (L) (w/c = 1.20)	4- 8 8-16 16-32	2340 2420 2490	8.7 5.7 3.7	41.4 37.0 31.5	0.38 0.39 0.38	28.2 29.6 27.4	61 39 25
Recycled aggregate (M) (w/c = 0.70)	< 5	2280	9.8	-	-	-	-

Figure 5.3: Properties of NA and RCA including attached mortar, found in T. C. Hansen 1986.

mm) ranges from 38% (w/c = 0.4) to 39% (w/c = 0.7). The result achieved in this project of 27.19% for fine aggregates and 16.04% for coarse aggregates are therefore significantly lower than what T. C. Hansen 1986 has reported. This significantly lower amount of attached mortar unfortunately doesn't correspond very well to the densities found previously. The densities were all matching the densities found in other studies, and should according to this discovery be higher due to a significantly lower amount of attached mortar.

5.4 Slump and air content

The slumps and air contents found in this project has previously been shown in Table 4.7. The slumps were varying in between 0-130 mm, but if focused on the specimens cast with coarse RCA the slump varied between 0-60 mm, and the air content was ranging between 1.45-2.1%. The slump values for RAC has by M. Safiuddin et al. 2013 been reported to range in between 70-255 mm, which is a lot higher than what was achieved during this project. M. Safiuddin et al. 2013 unfortunately did not report anything

about the distribution of the aggregates nor if the slump was adjusted in any way.
Padmini, Ramamurthy, and Mathews 2009 has studied the influence of moisture states on slumps and compressive strengths of concrete cast with RCA, the moisture states they tested were air dry, oven dry and saturated surface dry. In Padmini, Ramamurthy, and Mathews 2009 the initial slump was reported for recipes using 50% crushed granite and 50% RCA and for recipes using 100% RCA, at the 3 moisture states mentioned. The result found by Padmini, Ramamurthy, and Mathews 2009 can be seen in Figure 5.4.

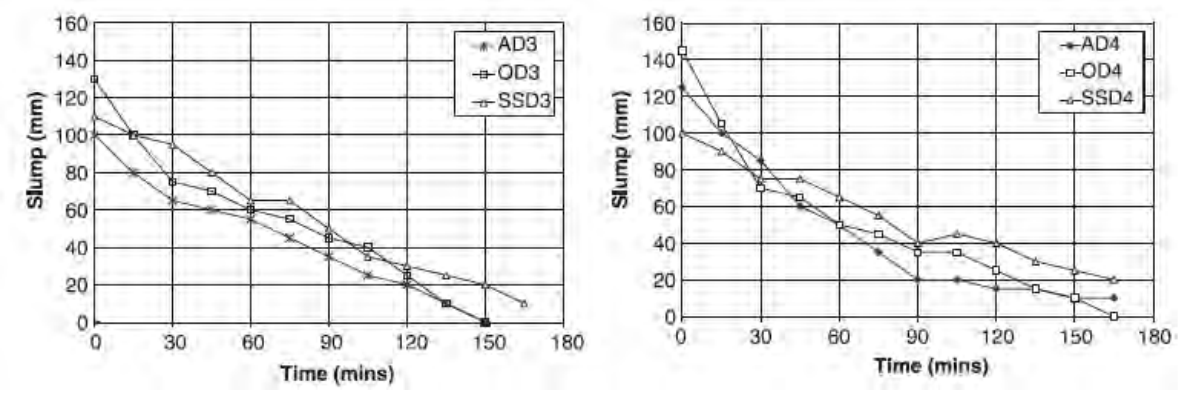


Figure 5.4: The slumps reported by Padmini, Ramamurthy, and Mathews 2009. Left figure is 50% granite + 50% RCA and right figure is 100% RCA.

Figure 5.4 shows the concrete cast with 50% RCA had initial slumps of 100-140 mm, where the oven dried sample achieved the highest slump. The concrete cast with 100% RCA showed initial slumps of 100-145 mm and once again the oven dried RAC had the highest slump.
These slumps are also higher than the ones experience during this project, but an interesting observation is that the concrete cast in this project with RCA that had no treatment (AD) generally had higher slumps (0-60 mm) compared to the concrete cast with either saturated or oven dried aggregates that had a very low slump (5-20 mm), which is opposite of what Padmini, Ramamurthy, and Mathews 2009 reported.

The air content of fresh RAC has been reported by T. C. Hansen 1986 to be in the range of 1-2% and M. Safiuddin et al. 2013 has reported air contents of 1.3-6.3% for NAC and 1.5-6.9% for RAC. The values ranging from 1.45-2.1% detected during this project are therefore perfectly normal and has been verified by other studies.

5.5 Compressive strength

The compressive strengths can first be compared to the theoretical strength calculated using Bolomey's equation and the constants found in Appendix D. This can be seen in Table 5.4.

Table 5.4: Measured compressive strengths compared to the predicted values from Bolomey's equation.

Mix	7 day			28 day		
	Measured strength [MPa]	Prediction [MPa]	Percentage [%]	Measured strength [MPa]	Prediction [MPa]	Percentage [%]
RefA	26,62	31,20	85,31	33,63	40,60	82,84
RefA2	29,29	31,20	93,87	36,73	40,60	90,48
A1	25,97	31,20	83,25	35,10	40,60	86,45
A2	25,51	31,20	81,77	30,59	40,60	75,34
RefB	24,03	23,20	103,60	29,98	30,93	96,91
RefB2	21,08	23,20	90,88	-	30,93	-
B1	23,90	23,20	103,00	33,41	30,93	108,01
B2	24,80	23,20	106,91	24,57	30,93	79,43
B3	24,97	23,20	107,63	-	30,93	-
B4	25,10	23,20	108,20	-	30,93	-
B6	25,93	23,20	111,79	28,23	30,93	91,27
B7	22,55	23,20	97,20	-	30,93	-
B8	21,87	23,20	94,26	27,18	30,93	87,88
B9	24,11	23,20	103,93	22,63	30,93	73,16

It is seen in Table 5.4 that the screening specimens with a water to cement ratio of 0.5 all achieved approximately 80% of the predicted value found using Bolomey's equation for both 7 and 28 days of curing. Though the references did achieve a slightly higher compressive strength which was to be expected.
The screening specimens with a water to cement ratio of 0.6 on the other hand performed much better, and almost every specimen cured for 7 days exceeded the predicted strength by up to 6%. It is seen that specimen RefB2 only achieved 90% of the predicted value, which is suspicious since there were no anomalies detected when testing the strength of this mix. The water to cement ratio 0.6 screening specimens that cured for 28 days on the other hand showed mixed results. One of the specimens achieved a strength 10% stronger than the predicted value, whereas the remaining 2 either performed decent or poor. It is seen that RefB reached almost 97% and B2 only reached near 80% of the predicted value.
The specimens cast for further testing that cured for 7 days almost all exceeded the predicted strength, by up to 11%. The only specimens that didn't reach the predicted value were B7 and B8, both of which had 100% of the coarse aggregates replaced (B7 washed/dried and B8 no treatment). These specimens reached 97.20% and 94.26% of the predicted strength respectively. The same specimens that were allowed to cure for 28 days on the other hand had far from reached the predicted value. Specimen B6 (50% coarse no treatment) performed the best and reached 91% of the predicted value, whereas B8 (100% coarse no treatment) reached 88% and B9 (100% fine/coarse no treatment) reached only 73% of the predicted strength.
Since Bolomey's equation doesn't take into consideration the nature of the aggregates used, recycled or natural, the specimens cast for further testing that cured for 7 days must be deemed to have performed very well, since the predicted value is expected to

be cast with NA only.

The compressive strength of concrete cast using RCA has also been investigated by Pepe et al. 2016, Poon et al. 2004 and Safiuddin et al. 2011. The compressive results from the screening specimens cured for 7 and 28 dayss can be seen in Figure 5.5 and Figure 5.6. The results from casts using different saturations of the RCA can be seen in Figure 5.7 The results from the further test specimens can be seen in Figure 5.8

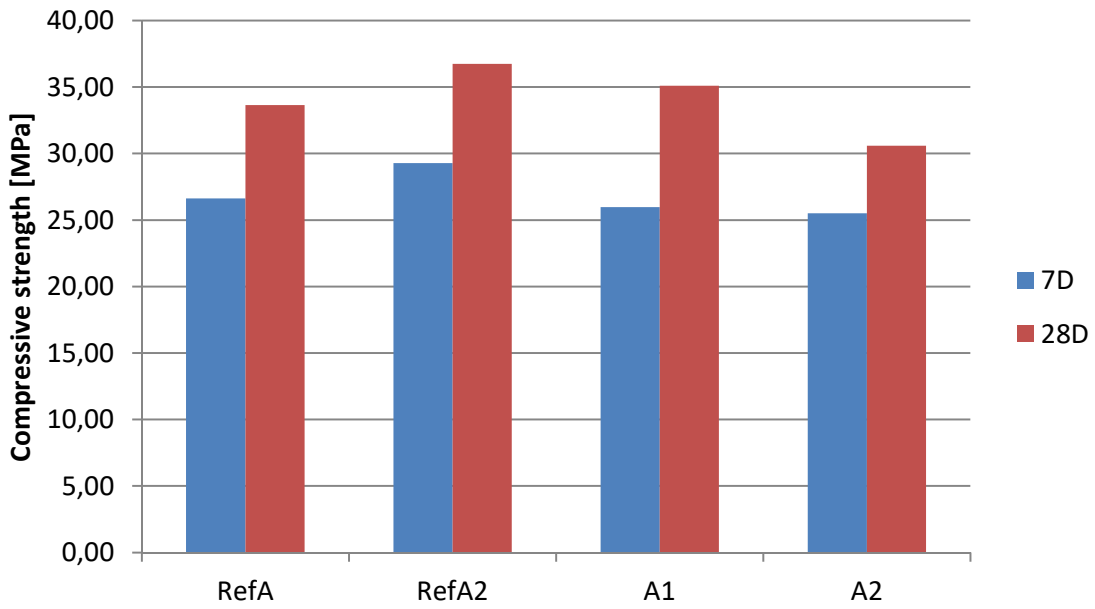


Figure 5.5: Comparison of results from compressive test performed on screening specimens with a water to cement ratio of 0.5.

It is seen in Figure 5.5 that the compressive strength for 28 day curing were all higher than the 7 day compressive strength for screening specimens with w/c = 0.5. Though the compressive strength reached at 28 days was not very significant. The concrete recipe was identical to the one used in Pepe et al. 2016 which was designed to reach a 28 day compressive strength of 50 MPa.
It is seen that the 28 day strength of all specimens lie just around 35 MPa which is about 30% lower than what has been reported by Pepe et al. 2016. The results reported by Pepe et al. 2016 can be found in Appendix H. Specimens A1 and A2 on the other hand almost reached the same compressive strength reported by Pepe et al. 2016 when replacing 60% RCA at w/c = 0.5 (DRY). Pepe et al. 2016 reported a 28 day strength of 38.57 MPa whereas A1 and A2 lie at 30-35 MPa, which is only a slight deviation.
The reference from Pepe et al. 2016 reached a 28 day strength of 49 MPa where the reference specimens in cast in this project only reached approximately 35 MPa. An explanation for this could be that Pepe et al. 2016 maybe used aggregates of a higher

original strength or from a concrete with a lower w/c ratio in the original cast. Figure 5.5 also shows that there was no clear loss in compressive strength when replacing aggregates with RCA, both in terms of the 7 and 28 days of curing.

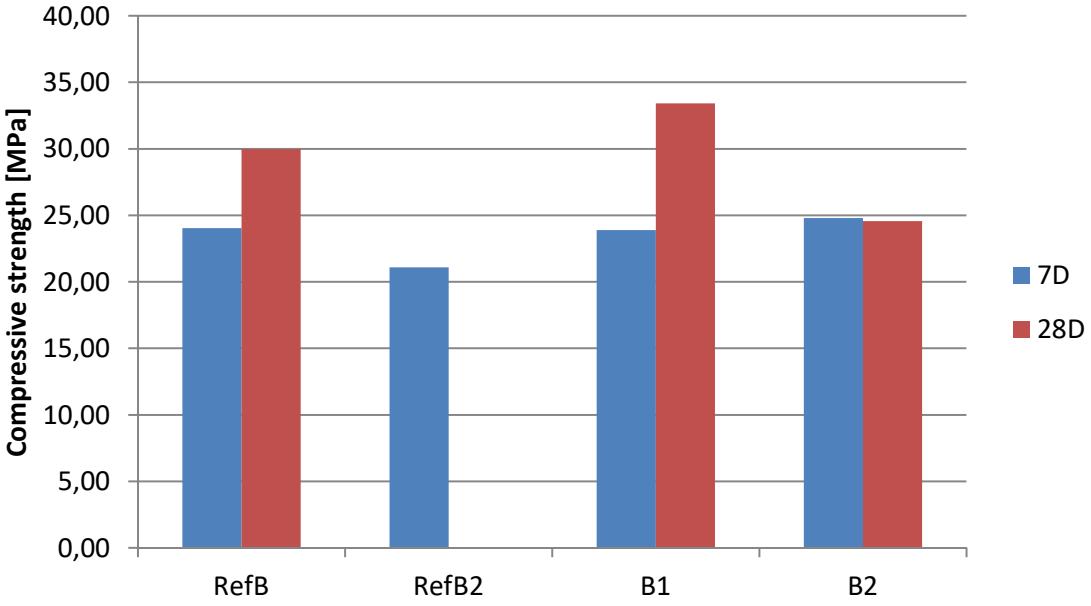


Figure 5.6: Results from compressive test performed on screening specimens with a water to cement ratio of 0.6.

Figure 5.6 shows the screening specimens with a w/c ratio of 0.6, though a 28 day specimen of cast RefB2 is missing because this was not cast unfortunately. Assuming the strength development of RefB2 28 day would follow Refb the strength could be expected to be approximately 25% higher at ∼25 MPa. If this is assumed it is seen that again almost all 28 strengths are higher than the 7 day strength. The only one not following the same tendency is B2, which actually reached a lower 28 day strength than 7 day strength. This is highly suspicious, since there wasn't detected any abnomalies during the cast or the compressive test of B2. Pepe et al. 2016 unfortunately do not have any casts using NA at w/c = 0.6 so the reference specimens cast in this project can not be compared. Pepe et al. 2016 did report that specimens with w/c of 0.6 and 60% RCA reached a 28 day compressive strength of 36 MPa, which is close to what was detected for B1 (34 MPa at 50% RCA). Since there must have some kind of error with B2 it is unfortunately not possible to compare this specimen to the results reported by Pepe et al. 2016.

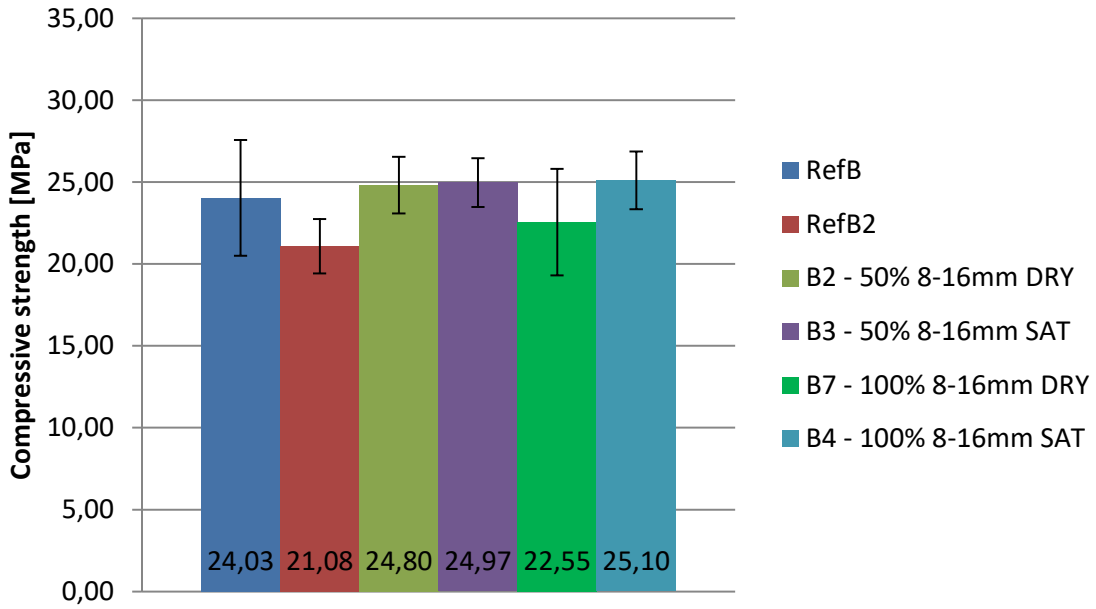


Figure 5.7: Results from compressive test performed on specimens with different saturations with a water to cement ratio of 0.6.

Figure 5.7 shows the specimens with varying degree of saturation, either oven dry or SSD. These specimens were only cast with a curing time of 7 days. It is seen that when casting with 50% there was no difference seen in compressive strength when using dry or saturated aggregates. When casting with 100% RCA the saturated concrete reached a slightly higher compressive strength. This has been investigated by Poon et al. 2004 and their results for 50% and 100% replacement at either dry or saturated state can be seen in Table 5.5.

Table 5.5: Results from specimens cast with 50% and 100% RCA at either air dry, oven dry or saturated state. Values from Poon et al. 2004.

Mix	Compressive strength [MPa]	
	7 days	28 days
AD 50%	32.2	44.7
AD 100%	33.9	46.8
OD 50%	29.2	39.7
OD 100%	32.1	43.3
SSD 50%	27.0	38.1
SSD 100%	28.5	39.1

The results detected in this project are interesting since the SSD casts both display either the same or a higher compressive strength than the OD casts. The results reported by

Poon et al. 2004 in Table 5.5 shows the exact opposite, there the SSD casts all display a slightly lower compressive strength at both 7 and 28 days of curing.

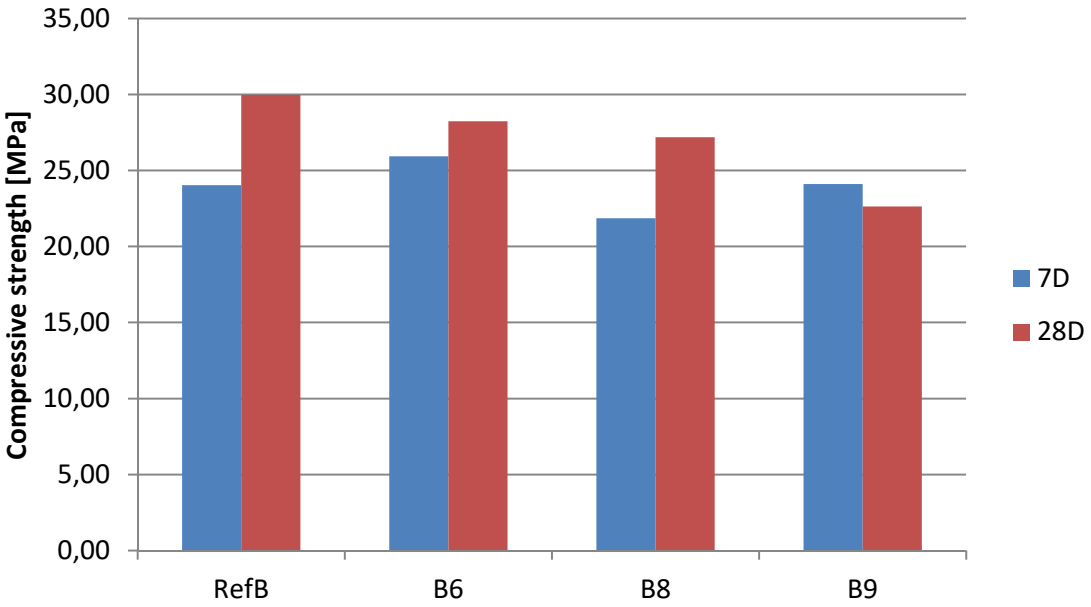


Figure 5.8: Results from compressive test performed on specimens for further testing with a water to cement ratio of 0.6.

Figure 5.8 shows the specimens cast for further testing with either 50% coarse RCA (B6), 100% coarse RCA (B8) or 100% of both fine and coarse RCA (B9) content at air dry state. It seen that for almost every cast the 28 day compressive strength exceeds the 7 day compressive as should be expected. Though one specimen, B9, actually had a lower 28 day strength than 7 day strength. With a standard deviation of only ± 1 MPa for that specimen, it can't even be explained by having a few very bad specimens pulling down the average compressive strength for the mixture. It is generally seen that increasing the RCA content decreases the compressive strength reached for both 7 and 28 days, again with the exception of the B9 7 day specimen which achieved a surprisingly high strength compared to the other mixtures.
Comparing these to the results reported by Poon et al. 2004 in Table 5.5 it is seen that they contradict each other. Poon et al. 2004 achieved a higher compressive strength at both 7 and 28 days of curing when increasing the amounts of RCA from 50% to 100% in every moisture state, whereas the compressive strengths in this project only decreased. Safiuddin et al. 2011 also investigated the compressive strength when replacing various amounts of the NA with RCA, their results can be seen in Figure 5.9.

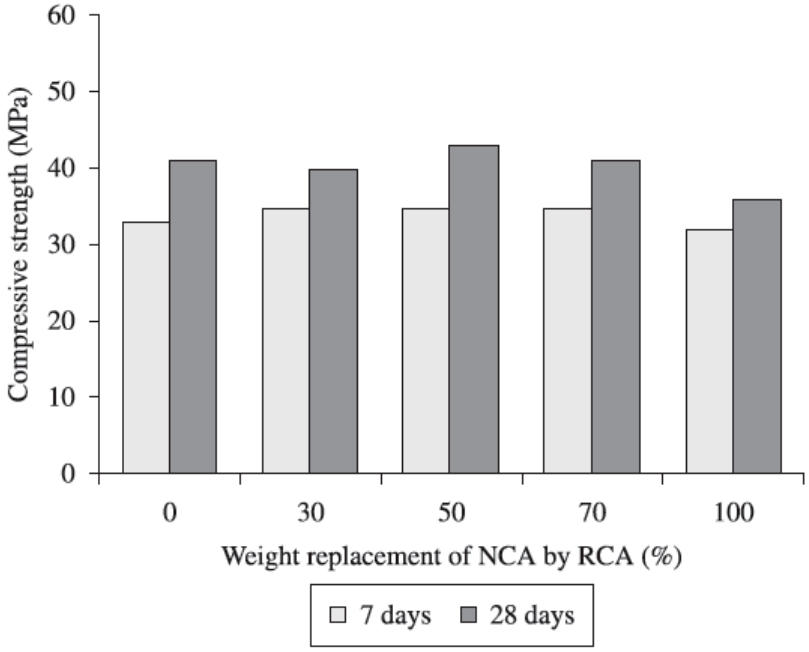


Figure 5.9: The compressive strengths reported by Safiuddin et al. 2011.

The results from Safiuddin et al. 2011 confirms the tendency seen in this project. It is seen in Figure 5.9 that when increasing the RCA content from 50% up to 100% the compressive strength decreases, which is the same tendency shown in Figure 5.8.

CHAPTER 6

Conclusions

The recycling of concrete aggregates can be used to overcome the shortage and increasing demands of NA, meanwhile decreasing the environmental impact and transportation costs of both the importation of NA and the disposal of waste. This project used RCA to either partially or fully replace NA in the casting of new RAC specimens.
Besides replacing, the RCA had been treated in various ways, either washed and dried, saturated or non-treated to investigate the influence this would have on the workability, air content and compressive strength of the RAC. The properties of the RCA were also investigated in terms of porosity, density, attached mortar, particle distribution and natural water content. Based on the experimental work performed in this project the following conclusions can therefore be drawn:

1. The ssd density of the RCA used in the project was found to be just below $2200\frac{kg}{m^3}$ and $2300\frac{kg}{m^3}$ for fine and coarse aggregates respectively. This was slightly lower than what had been found in other studies, that reported densities of RCA in the range of $2300 - 2450\frac{kg}{m^3}$.

2. The porosities found were 19% and 24.8% for the fine and coarse RCA respectively. These values were significantly higher than the porosities reported in other studies, and this might have been one of the main reasons of the poor workability experienced during the casting process. The increased water absorption will make it hard to control the mixing water to achievez the desired water to cement ratio. When casting concrete with RCA it is therefore very important to know this property.

3. The amounts of attached mortar found on the fine and coarse RCA was 27.19% and 16.04% respectively. This finding was significantly lower than what other studies have reported at up to 64% for fine RCA and 39% for coarse RCA.It is therefore surprising that the low amounts of attached mortar found didn't show a increased density or decreased open porosity compared to those studies.

4. The natural water content of the RCA was found to e approximately 7% for both RCA fractions used. This corresponds well with other studies performed, though this property wont have quite the same influence on the water to cement ratio and workability, since some of this water wont be available for the hydration process.

5. The particle distribution was found to deviate approximately by 10% from the ideal grain distribution defined by Fuller. It was found that the passing values

were slightly higher than what is ideal, which resulted in a decreased packing of the aggregates. Decreased packing of the aggregates will result in a decrease in workability, which was the case during the project.

6. RCA was found to decrease the workability of the concrete, this decrease became greater the higher RCA contents were used, especially with a high content of fine RCA. The combination of a high porosity, poor grading and the angular shaping of RCA resulted in slump measurements varying from 0-60 mm. It is therefore necessary to make adjustments in either the water to cement ratio or add additives to the concrete if a specific workability is required for the purpose of the concrete.

7. The air content found during the casting of RAC, were all found to match what other studies have reported of somewhere in between 1-6%. This was acceptable since there were no requirements of the concrete being frost resistant.

8. Generally no significant decrease in compressive strength was detected, when casting with RCA compared to casting with NA. The difference in casting with saturated or washed and dried aggregates was also insignificant. It was found that casting with increasing amounts of RCA did decrease the compressive strength achieved after 28 days, whereas the 7 day compressive strength at increasing amounts of RCA varied very little. This could be due to the concrete being very dry, which could result in a lack of water present in the concrete, therefore most of the hydration might already have taken place after only 7 days.

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APPENDIX A

Density and Porosity

The results from the 2 desiccator experiments to determine the porosity and density.

Table A.1: Test 1: Density and porosity found using a desiccator.

Samples		4-8mm	8-16mm
m_{105}	[Kg]	0,098	0,09609
m_{ssd}	[Kg]	0,109	0,10594
m_{sw}	[Kg]	0,059	0,05604
V	[m3]	$5,03 \cdot 10^{-5}$	$4,99 \cdot 10^{-5}$
V_p	[m3]	$1,09 \cdot 10^{-5}$	$0,99 \cdot 10^{-5}$
P_{open}	[Kg/m3]	0,217	0,197
ρ_d	[Kg/m3]	1945,924	1925,651
ρ_f	[Kg/m3]	2486,789	2399,251
ρ_{ssd}	[Kg/m3]	2163,419	2123,046
u_{ssd}	[Kg/Kg]	0,112	0,103

Table A.2: Test 1: Density and porosity found using a desiccator.

Samples		4-8mm	8-16mm
m_{105}	[Kg]	0,103	0,097
m_{ssd}	[Kg]	0,112	0,110
m_{sw}	[Kg]	0,060	0,066
V	[m3]	$5,12 \cdot 10^{-5}$	$4,46 \cdot 10^{-5}$
V_p	[m3]	$0,83 \cdot 10^{-5}$	$1,33 \cdot 10^{-5}$
P_{open}	[m3/m3]	0,162	0,298
ρ_d	[Kg/m3]	2017,787	2177,104
ρ_f	[Kg/m3]	2409,102	3100,703
ρ_{ssd}	[Kg/m3]	2180,219	2474,972
u_{ssd}	[Kg/Kg]	0,080	0,137

APPENDIX B

Density and Porosity (LBM-standard)

Porøsitet og densitet (LBM-standard)

A Princip

Porøsiteten i et materiale fortæller hvor porøst materialet er, dvs. hvor skrøbeligt det er. Jo højere porøsiteten er, des større evne har materialet til at optage vand. Det betyder også at en god evne til at optage vand. Densiteten er materialets masse pr. volumenenhed. Massen af et porøst materiale kan være en tør masse eller en masse med vand i de åbne porer, dvs. ved at finde densiteten kan man udregne massen ved forskellige forhold.

B Specielt apparatur

Til målingen benyttes vakuumpumpe, teknisk vægt med mulighed for at veje under vand.

C Analysens udførelse

Prøven tørres ved 105°C til prøven er hel tør dvs. ved kontant vægt.

Hvis der er tale om en betonprøve skal denne tørres ved 50°C i min 3 uger, da en tørring ved høj temperatur vil medføre ændring i porestrukturen.

Prøven vejes på teknisk vægt og vægten noteres som (m_{105})

Prøven placeres i en eksikator med låg og hane. Eksikatoren tilsluttes vakuumpumpen og pumpes ned i minimum 3 timer.

Destilleret vand med rumtemperatur ledes ind i eksikatoren vha en slange og undertrykket i eksikatoren. Hanen lukkes lige så snart vandstanden er 3 cm over prøvelegemet. Derefter skal den stå lukket i 1 time.

Herefter lukkes luften ind og prøven skal stå under vand natten over ved atmosfæretryk.

Den vandmættede prøve vejes først under vand på en teknisk vægt med ophæng under. Vandet i karret skal have rumtemperatur. Vægten noteres som (m_{sw}).

Prøven duppes med en hårdt opvredet klud inden den vejes over vand. Vægten noteres som (m_{ssd}).

For at kontrollere om der er sket en udvaskning af prøven ved vandmætning tørres prøven ved 105°C og kontrolvejes.

D Beregning af resultat

Rumtemp: °C	Vandtemp: °C	Vanddensitet ρ_w= kg/m^3		
Kontrollod: Før: kg Efter: kg				
Prøvelegement nr:				
m_{105}	Kg			
m_{ssd}	Kg			
m_{sw}	Kg			
$V = (m_{ssd}-m_{sw})/\rho_w$	m^3			
$Vpå = (m_{ssd}-m_{105})/\rho_w$	m^3/m^3			
$P_å = V_{på}/V$	Kg/m^3			
$\rho_d = m_{105}/V$	Kg/m^3			
$\rho_f = m_{105}/(V-V_{på})$	Kg/m^3			
$\rho_{ssd} = m_{ssd}/V$	Kg/m^3			
$u_{ssd} = (m_{ssd}-m_{105})/m_{105}$	Kg/kg			

Definitioner, begreber og symboler

m_{105} Masse af prøvelegemet efter tørring ved 105°C (kg)
m_{ssd} Masse af prøvelegemet over vand efter vakuumvandmætning (kg)
m_{sw} Masse af vakuumvandmættet prøvelegeme vejet i vand (kg)
V Prøvelegemets volumen (m^3)
$V_{på}$ Volumen af åbne porer (m^3)
ρ_f Faststofdensitet (kg/m^3)
ρ_d Tørdensitet (kg/m^3)
ρ_{ssd} Densitet af prøvelegeme i vakuumvandmættet overfladetør tilstand (kg/m^3)
$p_å$ Prøvelegemets åbne porøsitet (m^3/m^3)
u_{ssd} Vandtørstofforhold i vakuumvandmættet overfladetør tilstand (kg/kg)

APPENDIX C

Attached Mortar

Syreoplukning af beton

A Princip

Betonprøven knuses og cementpastaen opløses i salpetersyre. Alle chlorider vil Herefter være opløst. Uopløselige dele filtreres fra, og mængden af chlorid i væskefasen bestemmes ved titrering med sølvnitrat.

Metoden bestemmer ikke på hvilken form chloriden findes i betonprøven. Den siger ikke, om chloriden findes som natriumchlorid (almindelig salt), calciumchlorid eller andre chlorider.

B Specielt apparatur

Titrator 716 DMS Titrino

C Kemikalie sikkerhed

Salpetersyre - Brandnærende; Ætsende; Brandfarlig ved kontakt med brandbare stoffer. Alvorlig ætsningfare. Undgå indånding af dampe. Brug syrehandsker, plastikforklæder, sikkerhedsbriller og stinkskab ved afmåling.

Læs kemikaliebrugsanvisningen før arbejdet begynder.

D Reagenser

1) Salpetersyre 1% HNO_3:
17 mL koncentreret HNO_3 overføres med måleglas til en 1000,00 mL målekolbe som er ½ fyldt med destilleret vand. Der blandes godt og tilsættes vand til mærket. Efter blanding overføres opløsningen til en plastikflaske og mærkes.

E Analysens udførelse

5 g tørret knust prøve afvejes på teknisk vægt til en konisk kolbe. Der tilsættes ca. 50 mL varmt destilleret vand og det blandes.

Derefter tilsættes der langsomt 10 mL konc. HNO_3 til opslemningen som derefter

blandes godt og stilles til afkøling til stuetemperatur (skal foregå i stinkskab).

Der tilsættes ca. 1mL konc. HNO_3 for at kontrollerer at alt materiale er opløst (luftudvikling). Fortsæt med at tilsætte HNO_3 indtil der ikke er mere luftudvikling.

Filtrer opløsningen gennem alm filter ned i et bægerglas. Skyl filtreret med 1% HNO_3 Tilsæt destilleret vand til ca. 150 mL volumen.

Titrer prøven – se vejledning for chlorid titrering

F Affaldshåndtering

Ekstrakerne hældes i affaldsdunk mærket X 4.41 (tungmetaller).

Filterpapiret bortkastes i skraldespanden i stinkskabet.

APPENDIX D

Bolomey Constants

Table D.1: Guiding values for the constants K and α.

Cement type	Curing days	K	alpha
Basis Cement	1	17	0.9
	7	26	0.6
	28	30	0.5
Rapid Cement	1	13	0.9
	7	24	0.6
	28	30	0.5
Low Alkali Sulfate resistant Cement	1	5	0.8
	7	19	0.8
	28	29	0.7
Aalborg White	1	14	1.0
	7	25	0.8
	28	35	0.7
Basis Aalborg Cement	1	13	1.0
	7	24	0.7
	28	29	0.6

APPENDIX E

Density found with pycnometer

Table E.1: Test results from the pycnometer experiment.

				1	2	3
Fra kalibrering af pyknometer						
Pyknometer nummer				30	30	
Pykn. + prop (tomt)		m_0	g	363,19	363,19	
Pykn. + prop (vandfyldt)	W_2	m_1	g	943,06	943,06	
Temperatur ved kalibrering	T_k	T_1	°C	22	22	
Densitet af vand ved T_k *	$\rho_{w,k}$	$\rho_{w;1}$	g/cm^3	0,9978	0,9978	
Måling						
Pykn.+ prop + jord		m_2	g	463,74	462,6300	
Pykn.+ prop + jord + vand	W_1	m_3	g	1004,45	1004,16	
Temperatur	T	T_3	°C	22	22	
Densitet af vand ved T *	$\rho_{w,t}$	$\rho_{w;3}$	g/cm^3	0,9978	0,9978	
Jord - masse	W_s	m_4	g	100,55	99,44	
Jord - volumen	V_s		cm^3	39,246342	38,424534	
Korndensitet	ρ_s	ρ_s	g/cm^3	2,56202222	2,58792989	
Resultat - middel	ρ_s	ρ_s	g/cm^3	**2,5750**		
Betegnelser fra	dgf15	DS				

APPENDIX F

Raw data from laser diffraction

Table F.1: Raw data from experiment 1 of laser diffraction.

Raw data		Laser diffractometer 1			
µm	mm	Passing [%]	Cumulative passing [%]	Relative passing [%]	Relative cumulative passing [%]
2,51189	0,00251	0	0	0	0
2,88403	0,00288	0,014879	0,014879	0,002261768	0,0022618
3,31131	0,00331	0,058652	0,073531	0,008915735	0,0111775
3,80189	0,0038	0,078277	0,151808	0,011898946	0,0230764
4,36516	0,00437	0,091526	0,243334	0,013912936	0,0369894
5,01187	0,00501	0,103707	0,347041	0,015764579	0,052754
5,7544	0,00575	0,11843	0,465471	0,018002634	0,0707566
6,60693	0,00661	0,131852	0,597323	0,020042922	0,0907995
7,58578	0,00759	0,144542	0,741865	0,021971938	0,1127715
8,70964	0,00871	0,155798	0,897663	0,023682971	0,1364544
10	0,01	0,16484	1,062503	0,025057453	0,1615119
11,4815	0,01148	0,171472	1,233975	0,026065588	0,1875775
13,1826	0,01318	0,175389	1,409364	0,026661014	0,2142385
15,1356	0,01514	0,177213	1,586577	0,026938282	0,2411768
17,378	0,01738	0,178193	1,76477	0,027087252	0,268264
19,9526	0,01995	0,180621	1,945391	0,027456334	0,2957204
22,9087	0,02291	0,187372	2,132763	0,028482559	0,3242029
26,3027	0,0263	0,201593	2,334356	0,030644304	0,3548472
30,1995	0,0302	0,225142	2,559498	0,034224005	0,3890712
34,6737	0,03467	0,258326	2,817824	0,03926833	0,4283396
39,8107	0,03981	0,298546	3,11637	0,045382203	0,4737218
45,7088	0,04571	0,34156	3,45793	0,051920793	0,5256425
52,4807	0,05248	0,382319	3,840249	0,058116599	0,5837591
60,256	0,06026	0,417493	4,257742	0,063463426	0,6472226
69,1831	0,06918	0,448963	4,706705	0,068247204	0,7154698
79,4328	0,07943	0,486414	5,193119	0,073940159	0,7894099
91,2011	0,0912	0,550403	5,743522	0,083667175	0,8730771
104,713	0,10471	0,66937	6,412892	0,101751438	0,9748285
120,226	0,12023	0,883582	7,296474	0,134313966	1,1091425
138,038	0,13804	1,229576	8,52605	0,186908775	1,2960513
158,489	0,15849	1,755614	10,281664	0,266872208	1,5629235
181,97	0,18197	2,471983	12,753647	0,375767999	1,9386915
208,93	0,20893	3,401651	16,155298	0,517087533	2,455779
239,883	0,23988	4,482769	20,638067	0,681429095	3,1372081
275,423	0,27542	5,672236	26,310303	0,862240871	3,999449
316,228	0,31623	6,829418	33,139721	1,038144979	5,037594
363,078	0,36308	7,843092	40,982813	1,192234328	6,2298283
416,869	0,41687	8,554477	49,53729	1,300372498	7,5302008
478,63	0,47863	8,860109	58,397399	1,346831849	8,8770326
549,541	0,54954	8,691919	67,089318	1,32126516	10,198298
630,957	0,63096	8,054937	75,144255	1,224437046	11,422735
724,436	0,72444	7,03124	82,175495	1,068824093	12,491559
831,764	0,83176	5,757138	87,932633	0,875146888	13,366706
954,993	0,95499	4,399892	92,332525	0,6688309	14,035537
1096,48	1,09648	3,128406	95,460931	0,475551355	14,511088
1258,93	1,25893	2,055012	97,515943	0,312383923	14,823472
1445,44	1,44544	1,229033	98,744976	0,186826233	15,010298
1659,59	1,65959	0,766493	99,511469	0,116515179	15,126813
1905,46	1,90546	0,400156	99,911625	0,060828015	15,187641
2187,76	2,18776	0,088377	100,000002	0,013434254	15,201076

Table F.2: Raw data from experiment 2 of laser diffraction.

Raw data		Laser diffractometer 2			
µm	mm	Passing [%]	Cumulative passing [%]	Relative passing [%]	Relative cumulative passing [%]
1,44544	0,00145	0	0	0	0
1,65959	0,00166	0,028442	0,028442	0,004304189	0,0043042
1,90546	0,00191	0,072238	0,10068	0,010931932	0,0152361
2,18776	0,00219	0,088304	0,188984	0,013363234	0,0285994
2,51189	0,00251	0,107457	0,296441	0,016261699	0,0448611
2,88403	0,00288	0,126893	0,423334	0,01920299	0,064064
3,31131	0,00331	0,147336	0,57067	0,022296674	0,0863607
3,80189	0,0038	0,167909	0,738579	0,02541003	0,1117707
4,36516	0,00437	0,188432	0,927011	0,02851582	0,1402866
5,01187	0,00501	0,208568	1,135579	0,031563044	0,1718496
5,7544	0,00575	0,227649	1,363228	0,034450612	0,2063002
6,60693	0,00661	0,245596	1,608824	0,037166571	0,2434668
7,58578	0,00759	0,261775	1,870599	0,039614973	0,2830818
8,70964	0,00871	0,276498	2,147097	0,041843037	0,3249248
10	0,01	0,28964	2,436737	0,043831844	0,3687566
11,4815	0,01148	0,302322	2,739059	0,045751038	0,4145077
13,1826	0,01318	0,315431	3,05449	0,047734851	0,4622425
15,1356	0,01514	0,331292	3,385782	0,05013513	0,5123777
17,378	0,01738	0,351934	3,737716	0,053258929	0,5656366
19,9526	0,01995	0,380648	4,118364	0,05760428	0,6232409
22,9087	0,02291	0,419559	4,537923	0,063492765	0,6867336
26,3027	0,0263	0,471464	5,009387	0,07134766	0,7580813
30,1995	0,0302	0,536684	5,546071	0,081217543	0,8392988
34,6737	0,03467	0,615569	6,16164	0,09315538	0,9324542
39,8107	0,03981	0,706306	6,867946	0,106886805	1,039341
45,7088	0,04571	0,808516	7,676462	0,122354464	1,1616955
52,4807	0,05248	0,924041	8,600503	0,13983711	1,3015326
60,256	0,06026	1,059502	9,660005	0,160336715	1,4618693
69,1831	0,06918	1,228813	10,888818	0,185958912	1,6478282
79,4328	0,07943	1,448816	12,337634	0,219252439	1,8670807
91,2011	0,0912	1,742931	14,080565	0,263761494	2,1308422
104,713	0,10471	2,124476	16,205041	0,321501519	2,4523437
120,226	0,12023	2,611142	18,816183	0,395149731	2,8474934
138,038	0,13804	3,190822	22,007005	0,482873951	3,3303674
158,489	0,15849	3,861373	25,868378	0,584349875	3,9147172
181,97	0,18197	4,571548	30,439926	0,691822184	4,6065394
208,93	0,20893	5,294244	35,73417	0,801189323	5,4077287
239,883	0,23988	5,948387	41,682557	0,900182189	6,3079109
275,423	0,27542	6,488155	48,170712	0,98186644	7,2897774
316,228	0,31623	6,839691	55,010403	1,035065139	8,3248425
363,078	0,36308	6,965711	61,976114	1,054136016	9,3789785
416,869	0,41687	6,839933	68,816047	1,035101761	10,41408
478,63	0,47863	6,46254	75,278587	0,977990067	11,39207
549,541	0,54954	5,865242	81,143829	0,887599677	12,27967
630,957	0,63096	5,092149	86,235978	0,770605852	13,050276
724,436	0,72444	4,213583	90,449561	0,637650571	13,687926
831,764	0,83176	3,301572	93,751133	0,499633987	14,18756
954,993	0,95499	2,429508	96,180641	0,367662667	14,555223
1096,48	1,09648	1,664492	97,845133	0,251891152	14,807114
1258,93	1,25893	1,046081	98,891214	0,158305686	14,96542
1445,44	1,44544	0,595878	99,487092	0,090175498	15,055595
1659,59	1,65959	0,324535	99,811627	0,049112579	15,104708
1905,46	1,90546	0,148778	99,960405	0,022514894	15,127223
2187,76	2,18776	0,039593	99,999998	0,005991694	15,133215

APPENDIX G

Raw data from compressive strength tests

7 day specimens														
w/c	Mix	Date	Weight	Diameter	Height	Load	Fracture	Displacement	Area	Slump	Air	Compressive strength	Average	STDEV2
[-]	[-]	[-]	[kg]	[mm]	[mm]	[kN]	[-]	[mm]	[mm^2]	[mm]	[%]	[MPa]	[MPa]	[-]
0,5	RefA-1	28-02-2017	3,728	101	200	226	1	x	8011,85	40,00	1,50	28,21	26,62	1,93
	RefA-2		3,706	101	199	231	3	x	8011,85			28,83		
	RefA-3		3,733	101	199	195	J	x	8011,85			24,34		
	RefA-4		3,681	100,5	198	199	4	x	7932,72			25,09		
0,5	RefA2-1	11-04-2017	3,746	100	200	238	I	1,8	7853,98	15,00	2,20	30,30	29,29	1,42
	RefA2-2		3,745	99	200	233	4	1,7	7697,69			30,27		
	RefA2-3		3,744	99,5	200	231	E	1,5	7775,64			29,71		
	RefA2-4		3,712	100	200	211	I	1,6	7853,98			26,87		
0,5	A1-1	28-02-2017	3,609	100	199	189	J	5,2	7853,98	0,00	2,10	24,06	25,97	2,52
	A1-2		3,645	100	198	222	A/D	3,5	7853,98			28,27		
	A1-3		3,690	100	200	225	J	1,9	7853,98			28,65		
	A1-4		3,662	100	200	180	3	1,6	7853,98			22,92		
0,5	A2-1	28-02-2017	3,675	99	198	220	4	2,8	7697,69	20,00	2,00	28,58	25,51	2,32
	A2-2		3,653	100	197	175	I/J	2,0	7853,98			22,28		
	A2-3		3,647	100	199	208	I/4	2,2	7853,98			26,48		
	A2-4		3,686	100	199	194	4	2,3	7853,98			24,70		
0,6	RefB-1	01-03-2017	3,692	105	199	164	3	1,7	8659,01	30,00	1,70	18,94	24,03	3,53
	RefB-2		3,712	99,5	199,5	181	I	2,0	7775,64			23,28		
	RefB-3		3,693	100	198,5	198	3	2,4	7853,98			25,21		
	RefB-4		3,667	99	200	221	4	2,4	7697,69			28,71		
0,6	RefB2-1	11-04-2017	3,733	100	200	165	E	1,3	7853,98	30,00	2,00	21,01	21,08	1,66
	RefB2-2		3,727	98,5	200	175	I	1,3	7620,13			22,97		
	RefB2-3		3,732	100	200	145	E	1,3	7853,98			18,46		
	RefB2-4		3,709	100	200	172	E	2,5	7853,98			21,90		
0,6	B1-1	01-03-2017	3,666	100	200	199	3/4	1,5	7853,98	10,00	1,90	25,34	23,90	1,84
	B1-2		3,637	99	200	189	4	1,5	7697,69			24,55		
	B1-3		3,644	99	200	192	4	1,6	7697,69			24,94		
	B1-4		3,624	100	200	163	4	1,3	7853,98			20,75		
0,6	B2-1	01-03-2017	3,675	99	199	206	3	1,7	7697,69	20,00	1,80	26,76	24,80	1,73
	B2-2		3,679	100	200	175	4	1,6	7853,98			22,28		
	B2-3		3,687	99	199	200	I	1,7	7697,69			25,98		
	B2-4		3,671	100	199	190	4	1,6	7853,98			24,19		
0,6	B3-1	09-03-2017	3,664	100	201	209	E	1,9	7853,98	5,00	1,90	26,61	24,97	1,49
	B3-2		3,689	99	201	175	H	1,7	7697,69			22,73		
	B3-3		3,674	101	200	208	E	1,8	8011,85			25,96		
	B3-4		3,647	100	200	193	3	1,5	7853,98			24,57		
0,6	B4-1	10-03-2017	3,680	99	200	178	2	1,8	7697,69	5,00	1,50	23,12	25,10	1,77
	B4-2		3,657	100	199	203	E	1,6	7853,98			25,85		
	B4-3		3,679	100	200	217	E	1,7	7853,98			27,63		
	B4-4		3,660	100	200	187	I	2,4	7853,98			23,81		
0,6	B6-1	13-03-2017	3,695	100	200	187	E	1,5	7853,98	45,00	1,50	23,81	25,93	1,77
	B6-2		3,687	99	200	214	I	1,4	7697,69			27,80		
	B6-3		3,701	99	199	189	I	1,5	7697,69			24,55		
	B6-4		3,710	98	201	208	E	1,3	7542,96			27,58		
0,6	B7-1	16-03-2017	3,571	100	201	170	E/I	1,2	7853,98	5,00	2,10	21,65	22,55	3,25
	B7-2		3,566	99	200	216	4	1,3	7697,69			28,06		
	B7-3		3,587	100	200	163	3	1,2	7853,98			20,75		
	B7-4		3,584	99	200	152	E/I	1,3	7697,69			19,75		
0,6	B8-1	11-04-2017	3,627	100	200	169	E	1,8	7853,98	15,00	2,10	21,52	21,87	2,04
	B8-2		3,617	100	200	195	4	2,7	7853,98			24,83		
	B8-3		3,606	100	200	150	I	1,7	7853,98			19,10		
	B8-4		3,638	100	200	173	E	1,4	7853,98			22,03		
0,6	B9-1	11-04-2017	3,573	100	200	189	2	1,8	7853,98	0,00	1,90	24,06	24,11	1,14
	B9-2		3,560	99,5	200	202	4	1,4	7775,64			25,98		
	B9-3		3,545	99,5	200	182	4	1,6	7775,64			23,41		
	B9-4		3,555	99	200	177	2	1,7	7697,69			22,99		

Figure G.1: Raw data from 7 day strength tests..

28 day specimens														
w/c	Mix	Date	Weight	Diameter	Height	Load	Fracture	Displacement	Area	Slump	Air	Compressive strength	Average	STDEV2
[-]	[-]	[-]	[kg]	[mm]	[mm]	[kN]	[-]	[mm]	[mm^2]	[mm]	[%]	[MPa]	[MPa]	[-]
0,5	RefA-1	13-02-2017	3,762	100	200	278	3/4	1,6	7853,98	60,00	1,40	35,40	33,63	5,26
	RefA-2		3,753	100	199	300	3/4	1,6	7853,98			38,20		
	RefA-3		3,722	100	200	194	D	2,2	7853,98			24,70		
	RefA-4		3,751	99	200	279	4	1,5	7697,69			36,24		
0,5	RefA2-1	11-04-2017	3,744	100	200	237	3	1,6	7853,98	60,00	1,50	30,18	36,73	3,82
	RefA2-2		3,740	100	199,5	301	I	1,6	7853,98			38,32		
	RefA2-3		3,749	100	200	312	J	2,1	7853,98			39,73		
	RefA2-4		3,754	100	200	304	4	1,7	7853,98			38,71		
0,5	A1-1	14-02-2017	3,705	99	200	282	-	1,7	7697,69	20,00	1,10	36,63	35,10	2,37
	A1-2		3,685	99	199	247	-	1,5	7697,69			32,09		
	A1-3		3,676	99	200	293	-	1,4	7697,69			38,06		
	A1-4		3,642	100	199	264	-	1,7	7853,98			33,61		
0,5	A2-1	14-02-2017	3,688	100	200	272	-	1,3	7853,98	20,00	1,10	34,63	30,59	6,36
	A2-2		3,648	100	199	184	-	1,1	7853,98			23,43		
	A2-3		3,677	101	200	204	-	1,3	8011,85			25,46		
	A2-4		3,711	100	200	305	-	1,3	7853,98			38,83		
0,6	RefB-1	13-02-2017	3,717	99	200	237	4	1,6	7697,69	130,00	1,20	30,79	29,98	0,88
	RefB-2		3,716	100	200	240	H	1,5	7853,98			30,56		
	RefB-3		3,702	100	199	236	4	1,6	7853,98			30,05		
	RefB-4		3,708	100	199	224	3/4	1,5	7853,98			28,52		
0,6	B1-1	15-02-2017	3,649	100	200	254	4	x	7853,98	20,00	2,10	32,34	33,41	0,74
	B1-2		3,643	100	200	263	3	x	7853,98			33,49		
	B1-3		3,626	99	199	265	4	x	7697,69			34,43		
	B1-4		3,654	99	200	257	3	x	7697,69			33,39		
0,6	B2-1	15-02-2017	3,677	99,5	200	246	-	x	7775,64	10,00	2,10	31,64	24,57	6,09
	B2-2		3,628	99	199	156	-	x	7697,69			20,27		
	B2-3		3,640	99	198	226	-	x	7697,69			29,36		
	B2-4		3,635	99	197	131	-	x	7697,69			17,02		
0,6	B6-1	04-05-2017	3,644	100	199	229	4	1,5	7853,98	60,00	1,40	29,16	28,23	1,67
	B6-2		3,651	100	199	236	E	1,6	7853,98			30,05		
	B6-3		3,665	100	200	201	I	1,3	7853,98			25,59		
	B6-4		3,664	100	199	221	I	1,3	7853,98			28,14		
0,6	B8-1	04-05-2017	3,596	100	200	212	2/3	1,2	7853,98	60,00	1,70	26,99	27,18	1,54
	B8-2		3,607	100	200	232	4	1,3	7853,98			29,54		
	B8-3		3,606	100	201	212	I	1,3	7853,98			26,99		
	B8-4		3,588	100	200	198	I	1,1	7853,98			25,21		
0,6	B9-1	04-05-2017	3,456	100	201	188	4	1,3	7853,98	35,00	1,80	23,94	22,63	1,05
	B9-2		3,436	100	199	173	4	1,2	7853,98			22,03		
	B9-3		3,463	100	200	183	I	1,2	7853,98			23,30		
	B9-4		3,447	100	200	167	I	1,3	7853,98			21,26		

Figure G.2: Raw data from 28 day strength tests..

APPENDIX H

Compressive strengths from Pepe et al.

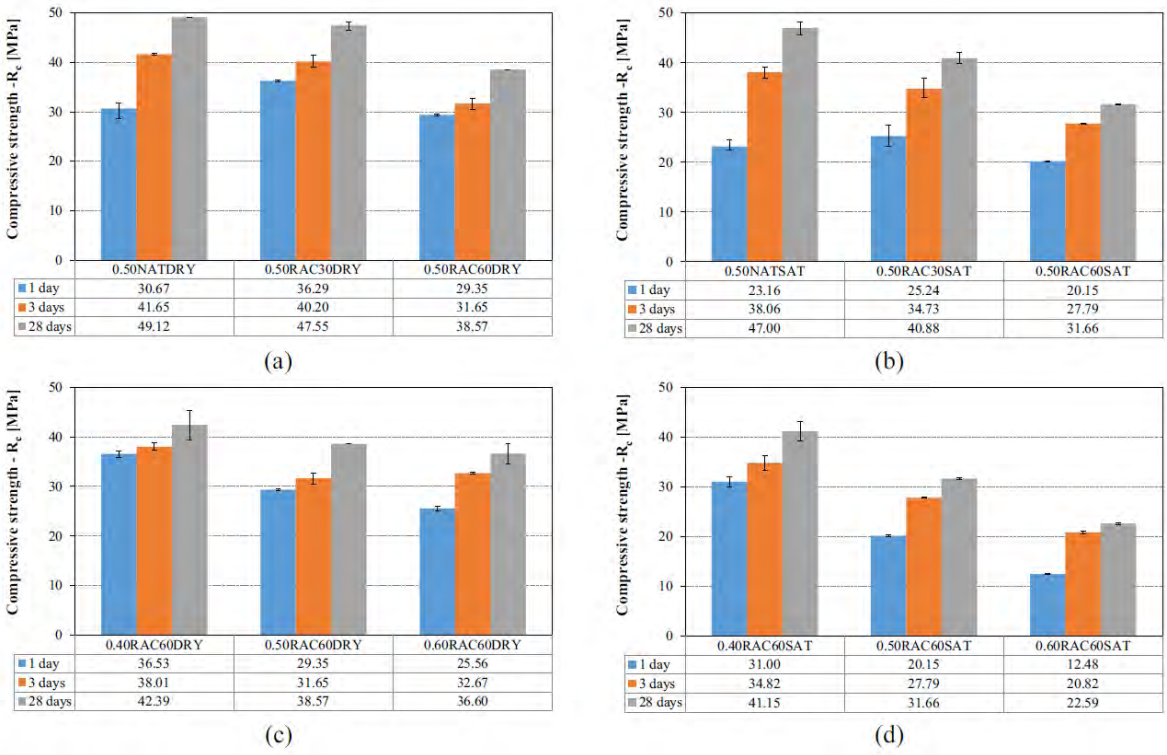

Figure H.1: Compressive strengths of RAC reported by Pepe et al. 2016.

APPENDIX I

Poster presentation

Reuse of concrete aggregates

Mads Emil Herløv

Introduction:

This project is being made in cooperation with DTU Byg, and its purpose is to check the useability of new concrete cast using recycled concrete aggregates. We're furthermore interested in investigating how large a proportion of the aggregates can be replaced, while keeping a reasonable workability and strength of the concrete.

Method:

The aggregates used in this specific project were aquired from a construction site in Herlev. In order to get the desired aggregate fractions to cast new concrete, the aggregates had to be sieved. This process was done through sieves of 16mm, 8mm and 4mm, dividing the aggregates in 16-8mm and 8 -4mm frations. Afterwards the aggregates were washed to remove excess particles and dried in an oven at 50Cº for 24 hours. This treatment is the "standard treatment" referred to later in table 1.

Figure 1: Sieves used to divide aggregates into 16-8mm and 8-4mm fractions. (From left: 16mm, 8mm and 4mm)

Mix designs:

The mix design used in this project is the same as the one used in [Pepe et al. 2016]. The specimens hardened for 28 and 7 days were cast with a w/c ratio of 0.5 and 0.6 with a reference for each of these. Afterwards a w/c ratio of 0.6 was used, because the workability of w/c 0.5 was not very good. Figure 2 shows the difference in workability for some of the concrete mixes.

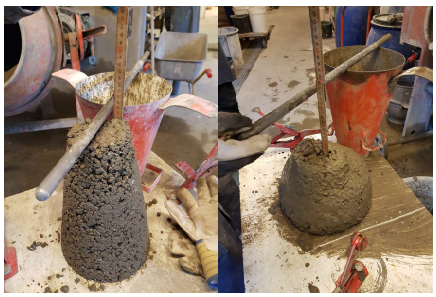

Figure 2: The difference in slumps depending on the mix design, lef picture shows mix design B7 with a slump of 5mm and the right picture shows mix B1 with a slump of 130mm. There is clearly a huge difference if the aggregates are dried in the oven or simply surface dry.

The different concrete mixes can be seen in Table 1:

Name	w/c ratio	8-16mm RCA	4-8mm RCA	Treatment
RefA	0.5	-	-	None
A1	0.5	-	50%	Standard
A2	0.5	50%	-	Standard
RefB	0.6	-	-	None
B1	0.6	-	50%	Standard
B2	0.6	50%	-	Standard
B3	0.6	50%	-	Saturated
B4	0.6	100%	-	Saturted
B6	0.6	50%	-	None
B7	0.6	100%	-	Standard

Table 1: The different mixes cast in this project, the percentge of aggregates replaced and which treatment had been used.

Results:

The results so far in the project can be seen in figure 3 and figure 4. It is clearly shown in both the case of 28 days of hardening and 7 days of hardening that the specimens with a w/c of 0.5 (RefA, A1 and A2) has a higher compressive strength than the ones with a w/c ratio of 0.6 (RefB, B1 and B2). The standard deviations on the first specimens cast (RefA, A1 and A2) are all fairly large, which most likely is a result of having very limited experience casting concrete, since the following specimens all have a reasonable deviation.

Looking at the specimens hardened for 7 days the same pattern is seen looking at the references and their corresponding specimens. The difference between replacing 50% and 100% saturated aggregates (B3 and B4) show little to no difference in compressive strength. The specimens cast with 50% RCA without any kind of treatment show a higher compressive strength than any of the other mix designs, which is surprising since it was expected that the excess particles on the aggregates would create a weaker interface between the concrete and aggregates. The last specimen cast with 100% RCA was the one to perform the worst. The mixture was very dry, and this has clearly had an impact on the compressive performance.

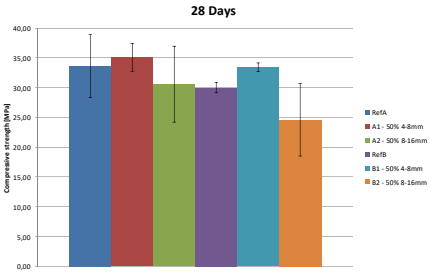

Figure 3: The results from compression tests on the specimens hardened for 28 days. Specimen RefA through A2 has a w/c ratio of 0.5 and the specimens RefB through B2 has a w/c rtio of 0.6.

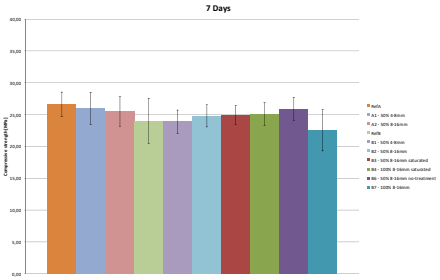

Figure 4: The results from compression tests on the specimens hardened for 7 days. Specimen RefA through A2 has a w/c ratio of 0.5 and the remaining specimens RefB through B7 has a w/c ratio of 0.6.

Conclusion:

Looking at the results so far it is possible to conclude that the development in compressive strength is as it should be when comparing 28 days and 7 days of hardening. The difference between the mix designs has not been very big, and the most surprising is that the specimen with aggregates that recieved no kind of treatment at all performed the best. It would therefore be of interest to further investigate the properties of these specimens, when increasing the amounts of RCA that has recieved no kind of treatment at all.

Figure I.1: Poster presentation.

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