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Properties of Recycled Aggregate Concrete

Master's Thesis, July 2017

DTU Civil Engineering
Department of Civil Engineering

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Preface

This project was made in the period of January 23 2017 to June 23 2017, and it represents the Master's Thesis done by Kristian Nyvang Jensen. This thesis constitutes to the work of 35 ECTS points at the Department of Civil Engineering of the Technical University of Denmark.

The recycled concrete aggregates, collected at Islevgård Alle 5, were shared with Louise Green Pedersen, where Louise Green Pedersen studied the aggregates of the 4-8 mm fraction and Kristian Nyvang Jensen studied the 8-16 mm fraction. This lead to cooperation in a lot of the experiments performed during this project.

I would like to thank supervisors Lisbeth M. Ottosen and Gunvor M. Kirkelund for great assistance during the project period. I would also like to thank Ebba Cederberg Schnell and Malene Grønvold for technical assistance during to experiments made in the laboratories in building 118 and to Per Leth for assistance in the concrete laboratory. Lastly, I would like to thank my fellow students, Mads Emil Herløv and Louise Green Pedersen.

Kristian Nyvang Jensen (s113804)

Abstract

This project focusses on determining the properties of recycled concrete aggregates (RCA) in the fraction 8-16 mm and the recycled aggregate concrete (RAC) made with this RCA. To determine the properties of RCA a series of experiments have been performed. These experiments include finding the porosity and density of RCA, since these properties have an influence on the performance of the RAC. The solid dry state density was found to be 2482.79 kg/m^3 by the use of a desiccator and was later confirmed to be 2484.10 kg/m^3 by the use of a pycnometer. The porosity of RCA is an important factor since the pores contributes to the water absorption of the RAC. The porosity was found by the use of desiccator, which resulted in a porosity of 29.8 volume percent, which is considered to be a high porosity.

The mortar attached to the RCA has an influence on the water absorption, since the attached mortar is porous. The amount of attached mortar was found to be 27.26 % by the means of immersing 20 gram RCA in acid, and determine how much mortar had reacted with the acid. To describe the distribution of the aggregate sizes, there were made grain-size distribution curves for the raw RCA material. These grain-size curves were compared to the requirements for a quality A (the best quality) material in respect to usage as road fill. This comparison lead to the RCA having the right amount of aggregates in all sizes except for aggregates below 0.063 mm, where the amount was not sufficient.

To examine the compressive strength of RAC, there were created 200x100 mm cylindrical concrete specimens where 50 % or 100 % of the natural aggregates in the fraction 8-16 mm were substituted with RCA. The first RAC samples cast were created with RCA that had been treated with washing through a sieve to remove the finer aggregates and this was followed by drying in a ventilated oven at 50 ºC. The first notable difference between natural concrete and RAC was the poor workability, which was caused by the high porosity of the RCA which leads to a high water absorption that causes less free water in the fresh concrete. There were made slump tests for each casting which showed that the RAC had slumps in the range 1-5 cm. At the same time the air content were measured with a pressure gauge, which showed that the air contents were in the range of 1.1 % - 2.2 %. In total there were made 96 cylindrical concrete specimens, which were divided into 24 samples of 4 concrete specimens. These samples were compressive strength tested with a Toni Technik 3000 machine, and the compressive strength results showed that the RAC with treated RCA had a higher compressive strength compared to the RAC with untreated RCA. The compressive strengths were compared to the theoretical compressive strengths predicted with Bolomey's formula, which showed that the 7 day specimens with treated RCA had a higher compressive strength compared to the theoretical prediction. The compressive strength tests of the RAC showed that it is possible to substitute all the natural aggregates in the 8-16 mm fraction with RCA in the 8-16 mm fraction.

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CHAPTER 1

Introduction

In 2015 there was a total production of 11,307,000 tons waste in Denmark. Out of the total waste construction is the biggest contributor with 4,162,000 tons of construction waste. Concrete waste is the biggest part of construction waste with 1,061,000 tons concrete waste. This means that 25 % of the construction waste is concrete waste, and 9 % of the total waste production in Denmark is concrete waste. (Miljøstyrelsen 2017)
Since concrete waste is such a big part of the total waste production, it has to be handled in the best and most productive way possible. In this project, a productive usage of concrete waste will be investigated, which is the usage of RCA in new concrete. By using RCA as a replacement for virgin aggregates in concrete, the amount of virgin aggregates used will be lowered, which will lower the amount of CO_2 emission from machines that extracts virgin aggregates. The RCA will also lower the CO_2 emission by lowering the amount of transport needed to either collect virgin aggregates to the construction site, or the amount of transport needed to carry the demolished concrete away from the construction site. An ideal scenario would be that the demolished concrete can stay at the construction site, and be reused in the new concrete in an eventual new building at the same construction site, or a construction site nearby.
The recycling of construction waste have traditionally been good in Denmark. In the nineties the recycling rate of construction waste was up to 90 % and this rate increase to 95 % in the year 2000. In 2015 the recycling of construction waste was at 87 %. (Miljøstyrelsen 2017)

1.0.1 Objective

The objective of this project is to study the properties of recycled concrete aggregates in the fraction 8-16 mm collected at a construction site on Islevgård Alle in Rødovre, and further examine the influence on the mechanical properties of recycled aggregate concrete based on the recycled concrete aggregates. Furthermore, the standard deviation and the reliability of the recycled aggregate concrete is examined. unknown source

CHAPTER **2**

Theory

2.1 Concrete

Concrete is the most used material for construction, which is partly because of its easy formability and its properties in hardened condition and partly because of the low production price. Concrete has a high compressive strength and a tensile strength that is ten times lower than the compressive strength, which can be improved by adding reinforcement, in form of steel, to the concrete. The constituents of concrete are mortar and gravel, where mortar is made from cement, water and sand. The mixing of cement and water forms a binding material called cement paste, this cement paste binds the sand and gravel together to create concrete. An overview of the constituents of concrete can be seen in Figure 2.1.

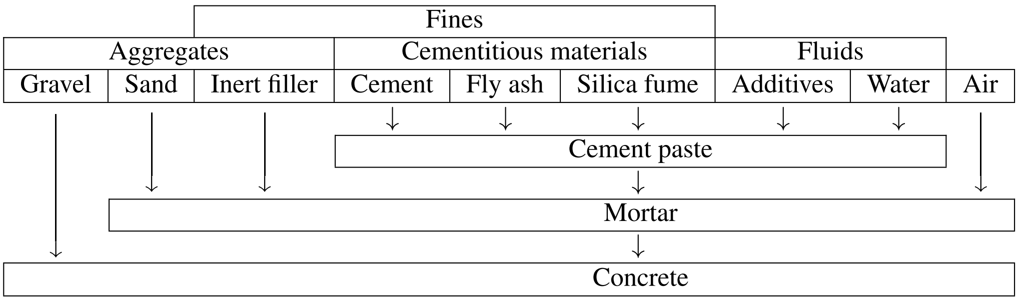

Figure 2.1: Constituents of concrete. Inspired by Table 5.2 in (Geiker and Nielsen 2012)

2.1.1 Cement Paste

The most commonly used cement type is the Portland cement, which mostly consists of calcium oxides which originates from Limestone (CaO), silicate from sand (SiO_2) and aluminate (Al_2O_3) which originates from clay. When heating the raw materials cement clinker are formed. These cement clinker can be divided into four different clinker minerals:

Alite	$3CaO \cdot SiO_2$	short notation C_3S
Belite	$2CaO \cdot SiO_2$	short notation C_2S
Aluminate	$3CaO \cdot Al_2O_3$	short notation C_3A
Ferrite	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	short notation C_4AF

Portland cement is a hydraulic binder. The term hydraulic binder is used to describe a material that loses its formability and hardens with the presence of water. During this process, the clinker minerals is going through a hydration, where the clinker minerals make bindings with water with the means of various chemical reactions, which causes the hardening of concrete and the growth in strength. The two solid main products from the hydration process are calcium-silicate-hydrate (C-S-H) and calcium-hydroxide (CH), the reactions can be seen below, where H is the short notation for water:

$$\begin{array}{ccccccccc} 2C_3S & + & 7H & \rightarrow & C_3S_2H_4 & + & 3CH & & \\ \text{(alite)} & & & & & & & & \\ 2C_2S & + & 5H & \rightarrow & C_3S_2H_4 & + & 2CH & & \\ \text{(belite)} & & & & & & & & \\ C_3A & + & 6H & \rightarrow & C_3AH_6 & & & & \\ \text{(aluminate)} & & & & & & & & \\ C_4AF & + & 2CH & + & 10H & \rightarrow & 2C_3AH_6 & + & C_3FH_6 \\ \text{(ferrite)} & & & & & & & & \end{array}$$

2.1.2 Mechanical Properties of Concrete

Concrete is used for construction, which means the mechanical properties are highly relevant to investigate. An important factor for concrete is the compressive strength, which can be predicted with Bolomey's formula which can be seen below:

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

Where K and α are constants relying on the cement type used and the time the concrete has cured. w/c is the ratio between the weight of water and cement, and f_c is the compressive strength. Bolomey's formula can be used for concrete with a water-cement ratio in the range 0.45-1.25 and with an air content in the range 1.5 - 2.0 %. (Geiker and Nielsen 2012).

Another mechanical property that has to be taken into account is the shrinkage of concrete. The shrinkage can be expressed as the strain, which can be calculated as shown below:

$$\epsilon = \frac{l - L}{L} \tag{2.2}$$

Where ϵ is the strain, L is the original length of the material and l is the measured length of the material.

2.2 Recycled Concrete Aggregates

According to Table E.2 from (DS/EN-206-1 2011), which can be seen in Table 2.1, it is allowed to substitute up to 50 % natural aggregates with RCA from a known source (the original concrete) in exposure class X0. For concrete in exposure class XC1, XC2, XC3, XC4, XF1, XA1 and XD1 it is allowed to substitute 30 % of the natural aggregates with RCA from a known source, in all other exposure classes it is not allowed to use RCA. For all these cases the RCA can only be used if it is from a source that was designed for these exposure classes. RCA can be used in concrete with a strength up to C30/37. The RCA also has to comply with Table 2426-3 in (DS/EN-206-1 2011), which can be seen in Appendix A.1.

Table 2.1: Table E.2 from (DS/EN-206-1 2011)

Recycled aggregate type	Exposure classes			
	X0	XC1, XC2	XC3, XC4, XF1, XA1, XD1	All other exposure classes [a]
Type A: (Rc_{90}, Rcu_{95}, Rb_{10-}, Ra_{1-}, FL_{2-}, XRg_{1-})	50 %	30 %	30 %	0 %
Type B [b]: (Rc_{50}, Rcu_{70}, Rb_{30-}, Ra_{5-}, FL_{2-}, XRg_{2-})	50 %	20 %	0 %	0 %

[a] Type A recycled aggregates from a known source may be used in exposure classes to which the original concrete was designed with a maximum percentage of replacement of 30 %.
[b] Type B recycled aggregates should not be used in concrete with compressive strength classes > C30/37.

2.2.1 Production

The recycled concrete aggregates come from old concrete such as buildings, foundations, pavements or bridges that have been demolished. This old concrete is then crushed into smaller sizes, for example by the use of one of the two basic types of crushers - the compression crusher and the impact crusher. An illustration of the two types of crushers can be seen in Appendix A.1 Figure A.2. During the production of the RCA, it is important to remove any other materials than concrete to prevent contaminations from materials such as steel, gypsum and asphalt, especially if the RCA have to be used in RAC where the purity of the material is important. (ECCO 1999)

2.2.2 Shape and Texture

RCA have an angular shape, which is caused when the concrete is crushed. Usually the finer RCA will be more angular than the larger RCA, which causes a higher absorption and lower specific gravity, which has lead to a more restrictive use of finer RCA compared to the use of larger RCA. The finer material have more adhered mortar. (ECCO 1999)

2.2.3 Density

The density of RCA varies with the water-cement ratio of the old concrete it is produced from. As stated earlier in section 2.2.2, the density is usually lower for the smaller aggregates due to a higher percentage of adhered mortar, which is lighter than the original aggregates. (Hansen 1986)

In a Japanese investigation (BCSJ 1978) it was stated that the s.s.d. densities of coarse RCA are in the range 2,290 kg/m^3 - 2510 kg/m^3 and the s.s.d. densities of fine RCA are in the range 2190 kg/m^3 - 2320 kg/m^3.

2.2.4 Water Absorption

Finer particles usually have a higher water absorption due to the particle shape caused by the crushing of the old concrete. (ECCO 1999)

The high porosity and water absorption of RCA causes a hindering of the cementitious hydration process as the high water absorption modifies the amount of free water, which means the cement has less water to react with. This can in some degree be prevented by saturating the RCA. (Pepe et al. 2016)

The water absorption is dependent of the amount of mortar adhered to the aggregates, since the mortar have a higher porosity than natural aggregates. The increase in mortar and porosity also results in a lower density. The relation between the water absorption and the density can be seen in Figure 2.2 . (Hansen 1986)

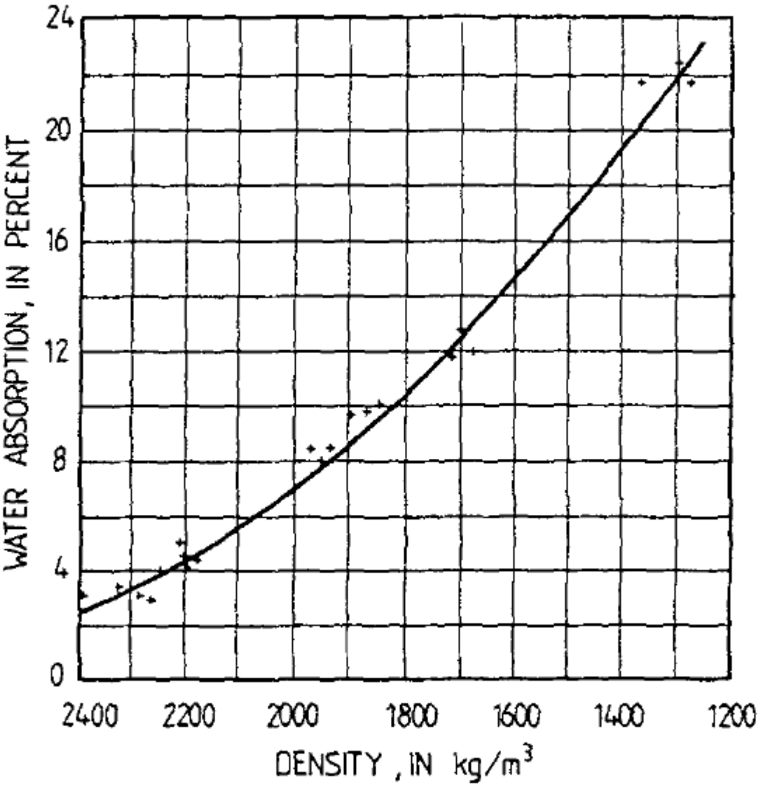

Figure 2.2: The water absorption in percent as a function of the density of RCA taken from (Hansen 1986).

2.2.5 Abrasion Value

The abrasion value can be tested with the Los Angeles abrasion test which is used to describe the materials toughness and abrasion characteristics. In (Hansen 1986) the Los Angeles abrasion loss was found to be 29.2 % for 8-16 mm RCA and 32.6 % for 4-8 mm RCA were the aggregates were from old concrete with a 0.70 water-cement ratio. This is a little higher than the corresponding natural aggregates which were found to have a Los Angeles abrasion loss of 22.7 % for 8-16 mm natural aggregates and 25.9 % for 4-8 mm natural aggregates.

2.3 Recycled Aggregate Concrete

2.3.1 Workability

The workability of fresh concrete can be described by measuring the slump. In (Topcu and Güncan 1995) several mix designs were cast with varying RCA content, which showed that an increase in RCA would result in a decrease in slump, e.g. a mix design with no RCA had a slump of 100 mm, a mix design with 50 % RCA had 80 mm slump and a mix design with 100 % RCA had 75 mm slump. In (Yrjanson 1989) it is stated that a greater angularity and surface roughness of the RCA results in a worse workability.

2.3.2 Density

The density of fresh RAC is reported to always be lower than the density of natural concrete. The reduction in density is between less than 5 % to more than 15 % according to (Hansen 1986). The reduction in density is dependent on the mix design and on the type of RCA used.

2.3.3 Porosity

In (Thomas et al. 2013) it is reported that the porosity of the RAC increases as the water-cement ratio increases, and similarly increases as the RCA-content increases. This is illustrated in Figure 2.3 taken from (Thomas et al. 2013).

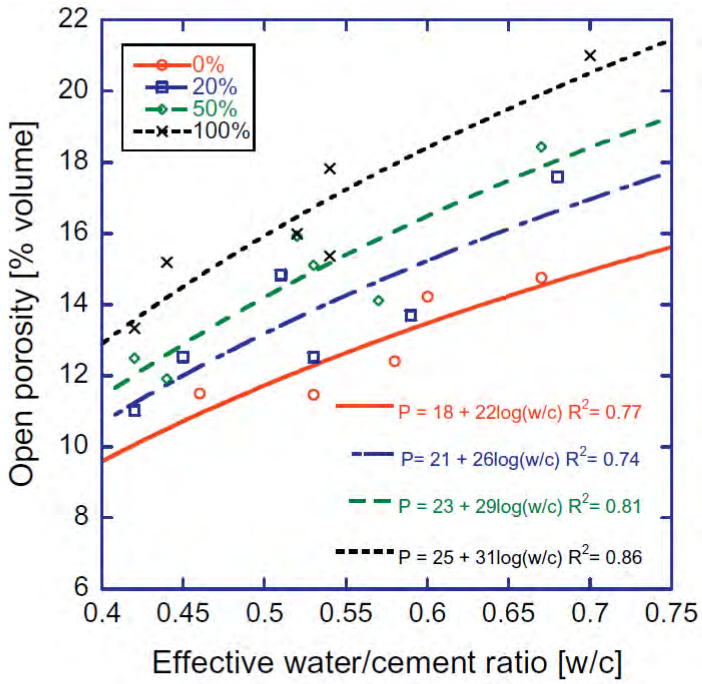

Figure 2.3: Open porosity as a function of the effective water-cement ratio of cured for 28 days from (Thomas et al. 2013).

2.3.4 Compressive Strength

The compressive strength of RAC decreases with the increase in RCA added to the concrete. This is illustrated in Figure 2.4 taken from (Safiuddin et al. 2013).

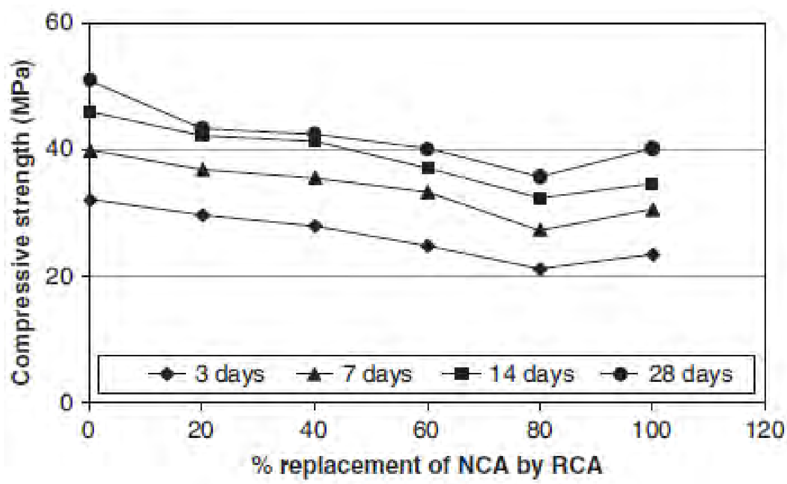

Figure 2.4: Compressive strength of concrete as a function of the percentage of NA substituted with RCA.

In Figure 2.4, it can be seen that an increase in natural aggregates replaced with RAC results in a decrease in compressive strength. Looking at the 28 days results, the compressive strength is 51 MPa at no RCA added and decreases to 41 MPa at 100 % RCA - a decrease of 19.6 %. Looking at the 7 days results, the compressive strength is reduced with 25 % by going from no RCA to 100 %. In (Hansen 1992) it is reported that the compressive strength can be decreased with up to 25 % depending on the RCA quality. According to (ACPA 2009) the compressive strength of RAC is 0 % - 24 % lower with coarse RCA and 15 % - 40 % lower with both coarse and fine RCA.

2.3.5 Air Content

Air content of fresh RAC is reported to be slightly higher than air content of natural concrete, which normally is in the range of 1 % to 2 %. The RAC can be produced with little to no reduction of air content. (Hansen 1986)

2.3.6 Drying Shrinkage

A concern regarding concrete in construction, that has to be addressed is shrinkage, since it affects the length of the concrete which can cause concrete beams to fall down in extreme cases and causes tension within beams or other parts of the construction made with concrete. In (Hansen 1986) an experiment with drying shrinkage was reported, which can be seen in Table 2.2, where H means high strength (0.40 w/c), M means medium strength (w/c=0.70) and L means low strength (w/c=1.20). The combinations indicate the strength of the concrete made and the second strength level indicates the strength of the concrete that the RCA is produced from, e.g. H/L means a high strength concrete produced with RCA from a low strength concrete.

Table 2.2: Drying shrinkage of samples after 13 weeks of drying taken from (Hansen 1986) Table VIII.6.

Item	Shrinkage after 13 weeks of drying at 40% RH and 25° C of original and recycled aggregate concretes											
	H	H/H	H/M	H/L	M	M/H	M/M	M/L	L	L/H	L/M	L/L
Total shrinkage x 10^4	3.4	5.1	4.9	5.3	3.5	4.9	5.3	5.2	4.5	6.8	5.7	6.8
% increase in shrinkage above controls	0	50	44	56	0	40	51	49	0	51	27	51

As it is seen in Table 2.2, the drying shrinkage is between 40 % and 56 % except for one case which was described as "erratic" by (Hansen 1986).

CHAPTER **3**

Materials and Methods

3.1 Description of Material

The material used through the entirety of this project was recycled concrete aggregates collected at a construction site on Islevgård Alle 5 in Rødovre. There were made a total of 3 trips to collect materials since the amount of material needed was underestimated in the beginning of the project. The total amount collected was 28 buckets of 20 liter each with approximately 30 kg in each - so a total amount of approximately 840 kg RCA were used. The RCA were collected with the use of shovels, where at least two persons collected RCA at different sites of the RCA pile. Thereafter, the RCA was transported to DTU with a transporter vehicle. The focus in this project was on RCA in the fraction 8-16 mm, which there were used 125 kg of to create concrete specimens, which means approximately 15 % of the raw RCA collected could be used as a 8-16 mm RCA fraction.

3.2 Characterization of Material

3.2.1 Porosity and Density

To examine the porosity and density of the RCA, two different experiments were done. An experiment with RCA in an desiccator and an experiment with RCA in a pycnometer in an desiccator.

Desiccator

In the desiccator experiment, the dried RCA were weighed and placed in nets, so the RCA could freely interact with water while the sample simultaneously could be controlled. The RCA were placed in an desiccator with a lid on, and the desiccator was connected with a vacuum pump for 3 hours to extract air from the desiccator. After the 3 hours had passed, distilled water was lead into the desiccator through a hose due to suction. After the RCA had been under water and pressure for one hour the air was lead back into the desiccator, and was left for 24 hours. The RCA which was still covered in water was then taken out of the desiccator the next day, where it was weighed above water and under water. The experiment can be seen in Figure 3.1. The guideline followed can be seen in Appendix B.1.

(a) The aggregates placed in nets. 4-8 mm in red nets and 8-16 mm in black nets.

(b) The desiccator filled with water and the RCA.

Figure 3.1: The desiccator experiment.

Pycnometer

A sample of approximately 100 gram of recycled concrete aggregates were weighed in a pycnometer, and then topped 3/4 off with water and put in an desiccator along with a glass of water in another desiccator to have air free water later in the experiment. Hereafter the desiccator was pumped down to a constant pressure of 30 mbar and left in the desiccator for 24 hours. The next day, the pycnometer was topped off with air free water and the lid was put on and the pycnometer, lid, water and RCA was weighed together. This experiment description can be found in (DS-CEN-ISO-TS-17892-3 2004).

3.2.2 Attached Mortar

A sample of approximately 5 gram of recycled concrete aggregates were weighed in a beaker and then filled with 50 ml 50 ℃ water. Hereafter 10 ml concentrated HNO_3 acid was added to the sample. The experiment was complete when no more reaction could be visibly spotted in the beaker, which could be tested by adding 1 ml concentrated HNO_3. Thereafter, the sample was put through a filter and put on a Petri dish and put in the oven at 105 ℃ for 24 hours followed by a weighing the next morning. This experiment was later done with 20 gram RCA to create a larger sample size. The guideline followed can be seen in Appendix B.3

Figure 3.2: The pycnometer experiment. The pycnometers are placed in the desiccator in the back. In the desiccator in the front there is a glass of water.

Figure 3.3: The RCA reacts with acid during the attached mortar experiment.

3.2.3 Grain-Size Distribution Curve

A gran-size distribution curve was made by following (DS/EN-933-1 2007). A sample of 10 kg RCA were put through sieves of the sizes 1 mm, 2 mm, 4 mm, 8 mm, 16 mm and 31.5 mm, which can be seen on Figure 3.4. The distribution was found by weighing the sieves after thoroughly shaking the RCA through the sieves. The experiment was performed twice. The distribution of RCA smaller than 1 mm was saved for analysis through a laser diffractometer.

Figure 3.4: The sieves used to perform the sieving experiment. The aggregates can be seen in front of the sieves, going from small aggregates to the left to large aggregates to the right.

Laser Diffraction

A small sample was put in the Mastersizer 2000 laser diffractometer, which can be seen on Figure 3.5. The Mastersizer 2000 provided a grain-size distribution curve for the RCA that had passed through the 1 mm sieve in the previously described sieving experiment. This experiment was done 3 times for each grain-size distribution curve where the grain-size distribution curve represented the mean of the three experiments. A total of two grain-size distribution curves were made.

Figure 3.5: The laser diffractometer, Mastersizer 2000, used to create grain-size distribution curves for the smaller aggregates.

3.2.4 Water content

The water content of the 8-16 mm RCA was found by making 3 samples of 200.00 gram and then drying them at 105 ºC for 24 hours followed by another hour to make sure the weight was constant. This experiment were performed by following (DS/EN-1097-5 2008).

3.3 Casting and Testing of Recycled Aggregate Concrete

3.3.1 Sieving

To separate the RCA into the desired intervals of 4-8 mm and 8-16 mm three sieves were used. To start of the sieving process a sieve of 16 mm was used to separate the RCA larger than 16 mm from the rest, since they were not needed in this project. Afterwards the sieves of 8 mm and 4 mm were used to separate the RCA smaller than 4 mm and to create the two intervals of 4-8 mm and 8-16 mm.
The sieving process mentioned above is not effective enough to stand alone in the treatment of the concrete, so another sieving process was applied to get a much cleaner material. This time the same sieves were used, but water through a hose was applied to get the aggregates to pass through the sieve, and to wash the finer aggregates off. After the aggregates were washed, they were placed in the oven at 50 ºC for approximately one day. It was secured that the aggregates were dry by weighing them with intervals of one hour until constant mass.

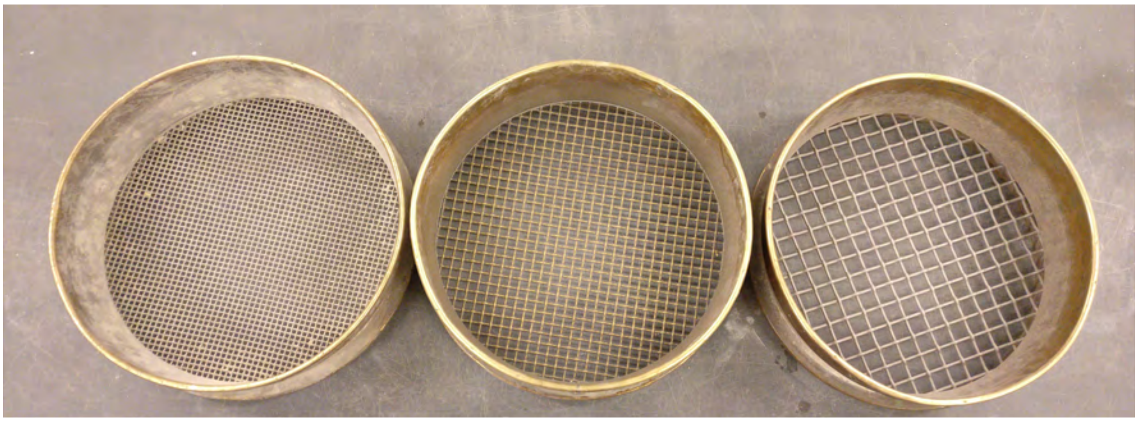

Figure 3.6: The three sieves used. From left to right: 4 mm, 8 mm and 16 mm.

3.3.2 Casting of Concrete Specimens

The concrete was cast in accordance to (DS/EN-12390-2 2012). The procedure was started by weighing the of the desired amount of 8-16 mm aggregates (NCA and RCA), 4-8 mm aggregates, sand and cement. These were then put in the mixer, and mixed for approximately 1 minute, after the dry mixing, the water was added and the mixing continued for approximately 5 minutes where the mixer was tilted as close to horizontal as possible without spilling the fresh concrete. After the mixing was done, the slump of the concrete was measured, and then the concrete was cast in 4 cylindrical moulds with a diameter of 100 mm and a height of 200 mm on a vibration table (in accordance with EN 12390-1). The cylinders were then vibrated at 60 Hz, which causes the concrete to settle. Due to this settling of the concrete, they would have to be topped off with more fresh concrete. During this procedure an apparatus used to measure the air content was filled with concrete and vibrated together with the moulds. After the vibration process the lids to the moulds were applied and they were stored between 16 and 72 hours. This is followed by de-moulding the cylindrical concrete specimens and storing them in water for 7 or 28 days from the casting process.

The different recipes used can be seen on Figure 3.7 below.

				NCA		RCA	
				4-8 mm	8-16 mm	8-16 mm	
	Cement [kg]	Water [kg]	Sand [kg]	aggregates [kg]	aggregates [kg]	aggregates [kg]	Treatment of RCA
Ref A	6.88	3.44	14.84	11.08	11.08	-	-
A2	6.88	3.44	14.84	11.08	7.756	3.324	Standard washing and drying
Ref B	5.74	3.44	15.24	11.08	11.08	-	-
B2	5.74	3.44	15.24	11.08	5.54	5.54	Standard washing and drying
B4	5.74	3.44	15.24	11.08	5.54	5.54	Standard washing and drying and saturated
B6	5.74	3.44	15.24	11.08	-	11.08	Standard washing and drying
B8	5.74	3.44	15.24	11.08	-	11.08	Standard washing and drying and saturated
B10	5.74	3.44	15.24	11.08	5.54	5.54	No treatment
B12	5.74	3.44	15.24	11.08	-	11.08	Standard washing and drying, saturated and floating aggregates removed

Figure 3.7: The different concrete recipes used.

All the different types of specimen were inspired by the mix design used in (Pepe et al. 2016). All the recipes were made by following the method described above, but B4 and B8 had an additional treatment in the saturating of the RCA. This is done by putting them in a bucket and filling it with water, and let them stay in the water for at least 24 hours, as it is done in (Pepe et al. 2016). To make sure the water-cement ratio stay at the wanted ratio, the water and the saturated RCA is put through a 8 mm sieve to separate the saturated RCA from the free water. Then the saturated RCA is weighed and the extra amount of weight due to the water in and on the aggregates is subtracted from the amount of water added during the mixing process. The B10 recipe is made without treating the RCA at all - no washing or drying of the aggregates. The B12 recipe is done by saturating the RCA for at least 24 hours, and then remove the RCA that is floating in the water. To make sure all the floating aggregates were removed the RCA was mixed around to get the lightweight aggregates which were stuck under heavier aggregates to float on top of the water. To find the amount of extra water in and on the RCA the saturated RCA is weighed together with the removed floating aggregates. The cement type used to all recipes is Aalborg Portland Basis cement CEM II/A-LL 52.5 N (LA), which means the following according to (DS/EN-197-1 2000):

- CEM II means it is a Portland-composite cement.
- A/LL: A means it has additives and LL means it is limestone based in which the total organic carbon content does not exceed 0.20 % by mass.
- 52.5 means it has a strength of 52.5 MPa after 28 days of curing determined in accordance with EN 196-1.
- N means it has a normal strength development.
- LA means it has a low alkali content ($\leq$ 0.6 %).

3.3.3 Slump

The slump was measured by following (DS/EN-12350-2 2009), which states that a standard sized cone shall have a base diameter of 200 mm $\pm$2 mm, a top diameter of 100 mm $\pm$2 mm and shall have a height of 300 mm $\pm$2 mm. This cone was filled one third and then stomped 25 times with a metal rod, and hereafter another third of the cone was filled and the newly filled concrete shall be stomped 25 times as well, lastly the last third of the cone was filled and stomped 25 times. This was followed by lifting the cone off, and measuring how much the concrete had fallen down. The measuring of the slump can be seen on Figure 3.8.

Figure 3.8: Measuring of the slump.

3.3.4 Air Content

The air content of the concrete samples was measured with a pressure gauge method, which is stated in (DS/EN-12350-7 2009). The pressure gauge designed to measure air content in concrete can be seen on Figure 3.9. The container was filled with concrete and vibrated on the vibration table at 60 Hz. Afterwards the lid was applied on top of the bucket and secured with hinges. Then it was topped of with water through the pipes on the side of the lid, followed by pumping it full with air with the red handle on top. Then the green button was pushed and the air content could be read on the display.

Figure 3.9: Pressure gauge used to measure the air content.

3.3.5 Strength Test

The cylindrical concrete samples' compressive strength was measured with a Toni Technik 3000 machine, where the machine was set to pressure with 4.71 kN/s, which is taken from (DS/EN-12390-3 2009), where it is stated that the specimen should be pressured with 0.6 ± 0.2 MPa/s which is converted to kN/s like shown below:

$$A \cdot 0.6 \text{ MPa/s} = r^2 \cdot \pi \cdot 0.6 \text{ MPa/s} = (50mm)^2 \cdot \pi \cdot 0.6 \text{ MPa/s} = 4712 \text{ N/s} = 4.71 \text{ kN/s}$$

The fracture detection parameter was set to 2.5 %, which is a parameter mainly decided with experience. A larger fracture detection would lead to further fractures in the specimen before the pressure was removed. The specimen was placed in the center of the square testing area, and the compressive strength test could be initiated. After the test was done, the compressive strength and displacement could be read from the machine's display.

Figure 3.10: The test machine and a test specimen after compression test.

CHAPTER **4**

Results and Discussion

4.1 Porosity and Density

To determine the porosity and density of the recycled aggregate concrete there have been performed two different types of experiments - an experiment where the RCA was placed in an desiccator and an experiment where the RCA was placed in a pycnometer and then placed in a desiccator.

4.1.1 Desiccator

The desiccator experiment have been performed two times - the 8th of February and the 5th of May, the results can be seen in Table 4.1 below.

Table 4.1: The results from the desiccator experiments.

		Date		
		08-02-2017	05-05-2017	Mean
m_{105}	$[kg]$	0.10423	0.10000	
m_{ssd}	$[kg]$	0.11680	0.11515	
m_{sw}	$[kg]$	0.06767	0.07066	
V	$[m^3]$	$4.913 \cdot 10^{-5}$	$4.449 \cdot 10^{-5}$	
V_{po}	$[m^3]$	$1.257 \cdot 10^{-5}$	$1.515 \cdot 10^{-5}$	
P_o	$[m^3/m^3]$	0.25585	0.34053	0.29819
ρ_d	$[kg/m^3]$	2121.51	2247.70	2184.61
ρ_f	$[kg/m^3]$	2850.93	3408.32	3129.62
ρ_{ssd}	$[kg/m^3]$	2377.37	2588.22	2482.79
u_{ssd}	$[kg/kg]$	0.12060	0.15150	0.13605

Both experiments were done with approximately 100 gram of RCA and the formulas used to calculate the volume of open pores (V_{po}), the open porosity (P_o), the dry density (ρ_d), the solid density (ρ_f), the solid state dry density (ρ_{ssd}) and the water dry ratio (u_{ssd}) can be found in Appendix B.1. The mean of the two experiments can also be seen in Table 4.1, where it can be seen that ρ_{ssd} has been found to be 2482.79 kg/m^3, which is fairly close to the one found in Table VII.1 in (Hansen 1986) which state that the density (in solid dry state) for 8-16 mm RCA with a water-cement ratio of 0.70 is 2440 kg/m^3. The result can also be compared to (Safiuddin et al. 2013) which claims that the density of RCA is in the range of 2100-2500 kg/m^3, which the experiment confirmed. In (Safiuddin et al. 2013) it is also stated that the density of NCA is in the range 2400-2900 kg/m^3, which is higher than the density of RCA. The lower density of RCA is because of the adhered mortar which have a lower density than gravel.

The open pore volume, V_{po} have been found to be 0.298, which is high compared to (Safiuddin et al. 2013) where it is stated that the pore volume is in the range 5.0-16.5 volume percent. The high pore volume results in a higher water absorption, which could be an explanation to the low workability of the fresh concrete.

4.1.2 Pycnometer

The density of the RCA was measured two times by using a pycnometer. This resulted in a average density of 2484.1 kg/m^3. This can be compared to the density found with the use of desiccator, which was found to be 2482.79 kg/m^3, which means the results deviate 0.05 % from each other. The results of the pycnometer experiments can be seen in Table C.1.

4.2 Attached Mortar

The amount of mortar attached to the recycled concrete aggregates has been measured. The results can be seen in Table 4.2.

Table 4.2: The amount of attached mortar on the 8-16 mm RCA

	RCA weight [g]	Filter weight [g]	Total weight after drying [g]	Cement content [g]	Cement content [%]
05-04-2017					
8-16 mm	5.51	2.48	7.36	0.63	11.43
8-16 mm crushed	5.11	2.41	6.65	0.87	17.03
04-05-2017					
8-16 mm	20.38	1.94	16.01	6.31	30.96
8-16 mm crushed	20.33	1.86	17.40	4.79	23.56

The experiments were done with RCA that had been treated with washing and drying, and as it can be seen in Table 4.2 the experiments was performed with crushed RCA and non-crushed RCA. The experiments was done two times - the first time with approximately 5 gram RCA, which was later decided to not be enough since it corresponds to about 3-5 aggregates, which is not a big enough sample size. Therefore the experiment was done again May 4th where approximately 20 gram RCA were used. The first experiment lead to cement content of 11.43 % for non-crushed RCA and 17.03 % for crushed concrete, where the crushed concrete has to be considered the more reliable result since crushed concrete has far more surface area and will easier react with the acid. In the later experiment it was found that the crushed RCA had a cement content of 23.56 % and the non-crushed RCA had a cement content of 30,96 %. Since the crushing of the RCA should have contributed to a more complete reaction with the acid. This was not the case, since it has lost less mass than the non-crushed RCA, but it also has to be taken into consideration that all the aggregates are different, and the 20 gram maybe isn't enough to create a solid sample size. Therefore it was decided to take the mean of the two results from May 4th, and consider it the final result. The mean of the two results is 27.26 %. This result can be compared to Table VII.1 from (Hansen 1986), which can be seen on Figure 4.1.

Is it can be seen on the figure, the percentage of attached mortar is found to be 39 % for 8-16 mm RCA with a water-cement ratio of 0.70. By comparing this to the achieved result of 27.26 % it can be seen that there is a deviation of 30.1 %, which is quiet a lot, and probably tells that the RCA studied in (Hansen 1986) is different from the RCA studied in this project.

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 4.1: Properties of RCA taken from (Hansen 1986)

4.3 Grain-Size Distribution Curve

To describe the RCA used, the grain-size distribution can be measured by creating a grain-size distribution curve. This has been done two times by following (DS/EN-933-1 2007). The measurements were split into two, by measuring the aggregates larger than 1 mm first with sieve method and then measuring the smaller aggregates with a laser diffractometer. On Figure 4.2 the measurements from the laser diffractometer can be seen, while the measurements from the sieving method can be seen on Figure 4.3.

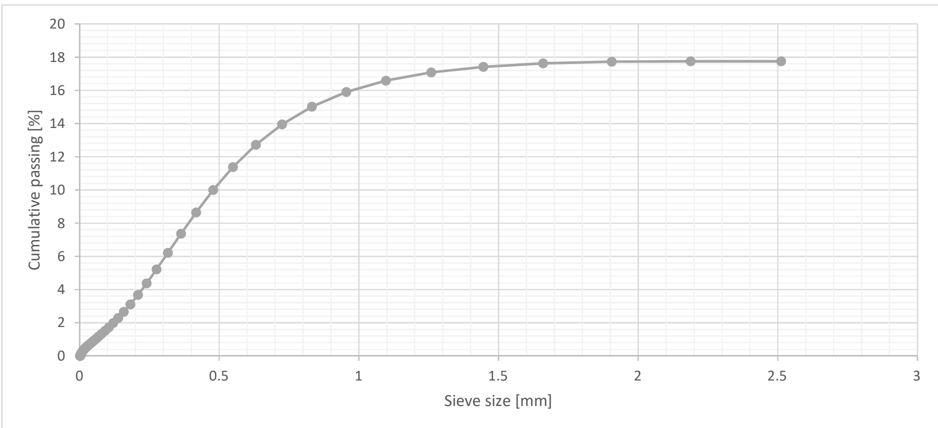

Figure 4.2: Measurements for grain-size distribution curve 1 provided by using a laser diffractometer.

As it can be seen on Figure 4.2 the measurements from the laser diffractometer exceeds 1 mm, so the measurements have been cropped to only cover sizes up to 1 mm. Then the two measurements have been combined on Figure 4.4, which can be seen below.

As it can be seen on Figure 4.4 the two different measurements fit quiet nicely together. And it can be considered as a complete grain-size distribution curve from 0.01 μm to 31.5 mm.

In Table C.2 the results from the sieve method can be seen, and the results from the laser diffraction can be

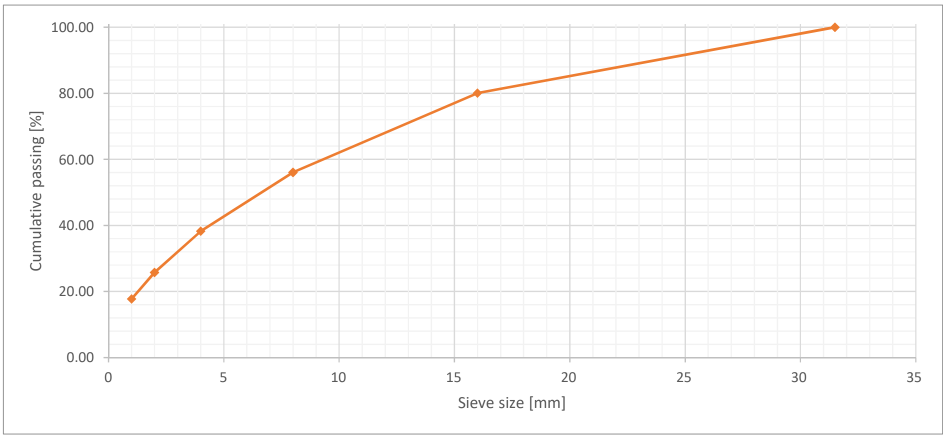

Figure 4.3: Measurements for grain-size distribution curve 1 provided by using sieving method.

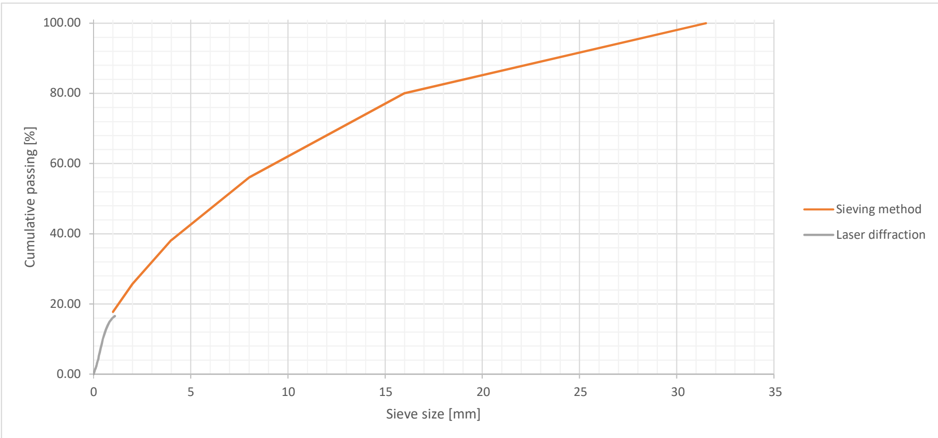

Figure 4.4: The complete grain-size distribution curve for the first measurements.

seen in Table C.3 in Appendix B.
The same procedure has been made to create a second grain-size distribution curve to have more data to back up the measurements. The results the laser diffraction method can be seen on Figrue 4.5 and the sieve method for grain-size distribution curve 2 can be seen on Figrue 4.6.

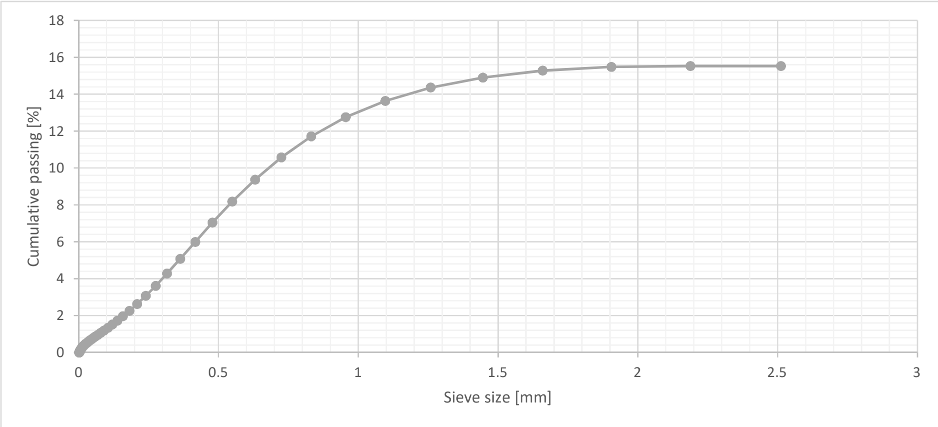

Figure 4.5: Measurements for grain-size distribution curve 2 provided by using a laser diffractometer.

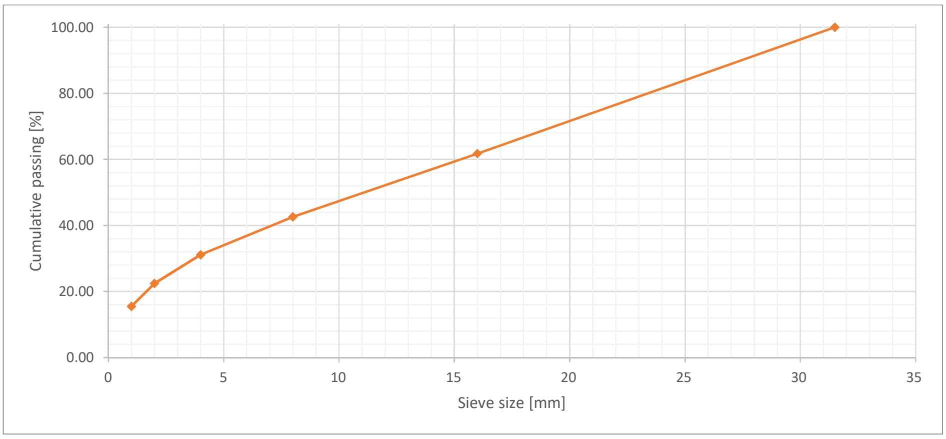

Figure 4.6: Measurements for grain-size distribution curve 2 provided by using sieving method.

These two methods have again been combined to create a complete grain-size distribution curve, which can be seen on Figure 4.7.

To compare the two grain-size distribution curves, they have been plotted on the same chart, which can be seen on Figure 4.8.

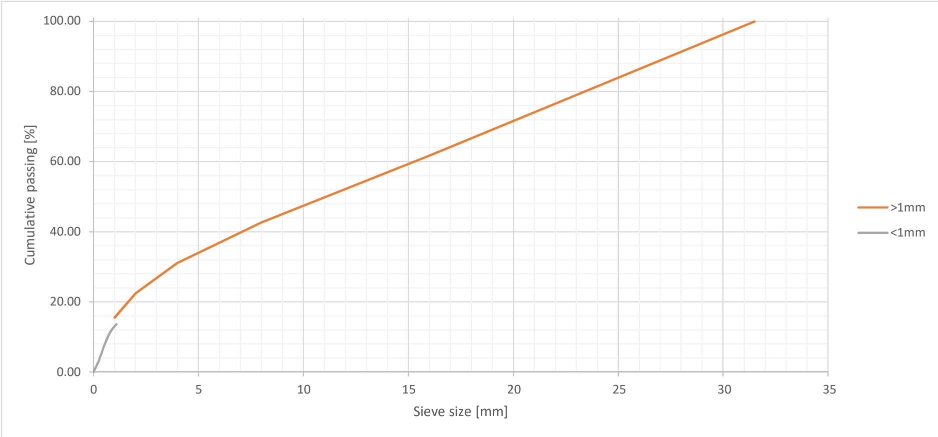

Figure 4.7: The complete grain-size distribution curve for the second measurements.

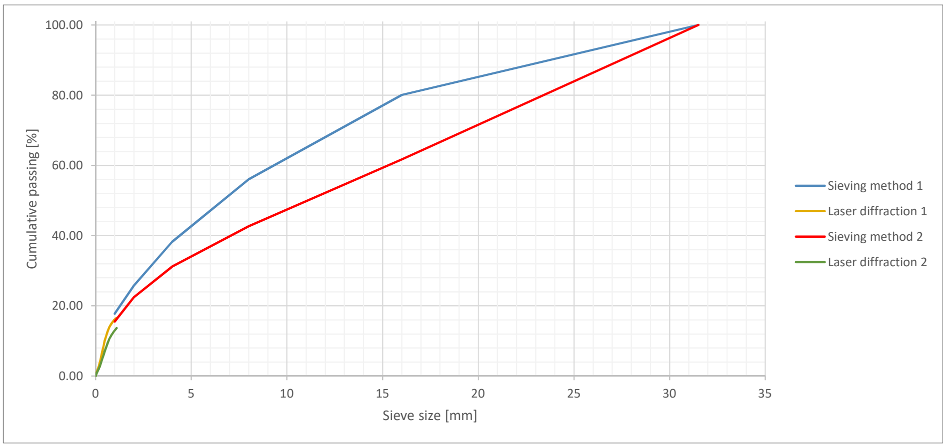

Figure 4.8: The two grain-size distribution curves.

It can be seen on Figure 4.8 that the first diffraction curve have more aggregates larger than 0.5 mm and smaller than 1 mm compared to the second diffraction curve. By comparing the two sieving methods, it can be seen that the first sieving curve have more aggregates from 1 mm to 16 mm because of the steeper curve, whereas the second sieving curve have more aggregates larger than 16 mm.
The mean of the two measurements have been found, which can be seen in Table 4.3.
According to (Pihl et al. 2004) the requirements in Table 4.4 will qualify the recycled concrete aggregates to a quality A material:

Table 4.3: The mean cumulative passing percentages from the two grain-size distribution curves.

Fraction [mm]	Mean cumulative passing [%]
31.5	100.00
16	70.90
8	49.36
4	34.68
2	24.10
1	16.64
0.5	9.15
0.063	0.96

Table 4.4: Requirements from Vejdirektoratet to achieve a quality A RCA materiel.

Recycled concrete aggregates quality A					
Sieve [mm]	Passing [%]				Tolerance
	Min	Max	Declaration values		
			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	

By comparing the mean cumulative passing from Table 4.3 with the requirements from (Pihl et al. 2004) in Table 4.4 it can be seen that the measurements exceeds the cumulative passing percentage for 31.5 mm, but this can be explained by having only measured up to 31.5 mm which of course results in a cumulative passing percentage of 100 %. The table from (Pihl et al. 2004) also shows that there isn't enough aggregates smaller than 0.063 mm. The demand is a cumulative passing percentage between 2 % and 5 %, whereas the measurements showed 0.96 %. It will not qualify for the lower quality classes in the report from (Pihl et al. 2004), since the cumulative passing percentage for 0.063 mm is at least 2 % for all quality classes. To have a insufficient amount of small aggregates can result in a poor packing of the concrete.

4.4 Water Content

It is important to know the water content of the RCA (and natural aggregates), since the water content has a influence on the effective water-cement ratio of the concrete. To measure the water content, three samples of 200 gram was dried in an oven for 25 hours - 24 hours plus one extra hour to make sure it was constant mass. The results of these measurements can be seen in Table 4.5 below.

Table 4.5: Water content in the RCA.

Weight before drying [g]	Weight after drying [g]	Water content [%]	Mean water content [%]
200.0	182.0	9.0	
200.0	183.0	8.5	8.7
200.0	183.0	8.5	

4.5 Slump and Air Content

During the casting of all the concrete specimens there were performed tests of the slump and air content, which can be seen in Table 4.6.

Table 4.6: The measured slump and air content.

Specimen type	Date	Curing length [Days]	Slump [cm]	Mean slump [cm]	Air content [%]	Mean air content [%]
Ref A	13-02-2017	28	6	4.50	1.4	1.65
	28-02-2017	7	4		1.5	
	11-04-2017	7	2		2.2	
	01-05-2017	28	6		1.5	
A2	14-02-2017	28	2	2.00	1.1	1.55
	28-02-2017	7	2		2.0	
Ref B	13-02-2017	28	13	6.33	1.2	1.63
	01-03-2017	7	3		1.7	
	11-04-2017	7	3		2.0	
B2	15-02-2017	28	1	1.75	2.1	1.88
	01-03-2017	7	2		1.8	
	07-05-2017	7	2		1.8	
	07-05-2017	28	2		1.8	
B4	09-03-2017	7	1	2.33	1.6	1.80
	13-05-2017	7	3		1.9	
	13-05-2017	28	3		1.9	
B6	10-03-2017	7	1	1.00	1.7	1.70
	09-05-2017	7	1		1.7	
	09-05-2017	28	1		1.7	
B8	14-03-2017	7	1	1.67	1.2	1.47
	13-05-2017	7	2		1.6	
	13-05-2017	28	2		1.6	
B10	13-03-2017	7	4	4.00	1.4	1.40
B12	10-06-2017	7	5	5.00	1.6	1.60

As it can be seen in Table 4.6 all the air contents measured is in the range 1.1-2.2 %. In (Geiker and Nielsen 2012) it is stated that the air content is in the range 1-2 % and in (Safiuddin et al. 2013) it is stated that the air content is in the range 1.3-6.3 % for NCA concrete and in the range 1.5-6.9 % for RCA concrete. The slumps measured is in the range 1-13 cm, where the RCA concrete is in the range 1-5 cm. This highlights the problem with the workability of the RCA concrete since the slump is so low. In (Safiuddin et al. 2013) it is stated that the slump is 7-25.5 cm for RCA concrete, which has not been achieved with the concrete specimens cast. The high open pore volume found in section 4.1.1 could be the reason for the low slump, since a higher pore volume results in a higher water absorption, which causes the fresh concrete to feel more dry.

4.6 Compressive Strength

All results from compressive strength tests, including dimension, weight and additional comments of the specimens can be seen in Appendix D. There are two variations of the reported results - one variation where the average and standard variation is calculated for each sample, and another variation where the average and standard variation are grouped together for recipes that has been cast two times. In Appendix D the graphic used to categorize the failure types indicated in the result sheet can be seen.

4.6.1 Initial Compressive Strength Tests

The project were started with a screening phase, where specimens with a water-cement ratio of 0.5 and 0.6 were made. First, there were made references for the two different water-cement ratios, and thereafter specimens with 50 % of the natural aggregates substituted with RCA were made.
The results of the 7 day tests with 0.5 w/c-ratio can be seen on Figure 4.9.

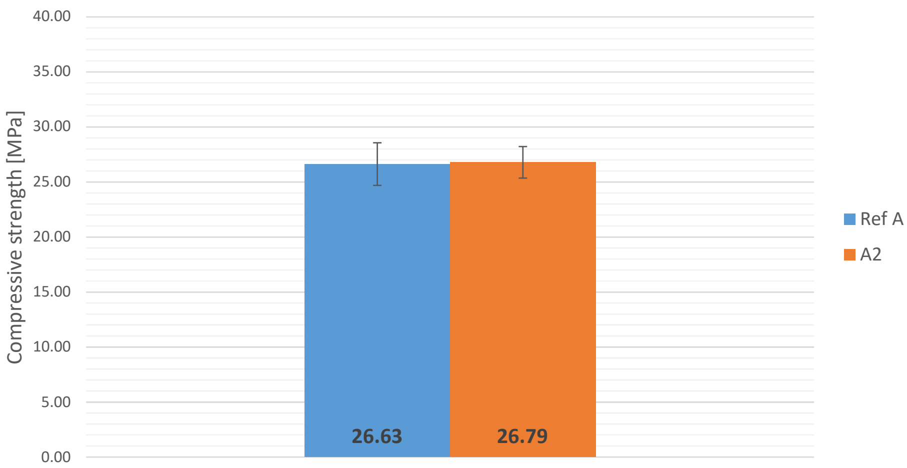

Figure 4.9: Compressive strength of specimens cured for 7 days with a water-cement ratio of 0.5.

As it can be seen on Figure 4.9, the compressive strength of Reference A is slightly lower than the A2 recipe, which is interesting since it contradicts the general view on the influence on compressive of RCA in new concrete. It should also be pointed out, that the standard deviation is 1.94 MPa for the reference specimen and 1.43 MPa for the A2-recipe, which is a fairly low standard deviation. But since it is only based on 4 specimens, further tests had to be made. It was decided to look at the compressive strength of the same recipe after 28 days of curing, since this is where the concrete should have reached it's maximum compressive strength. The results of the specimens after 28 days of curing can be seen on Figure 4.10.

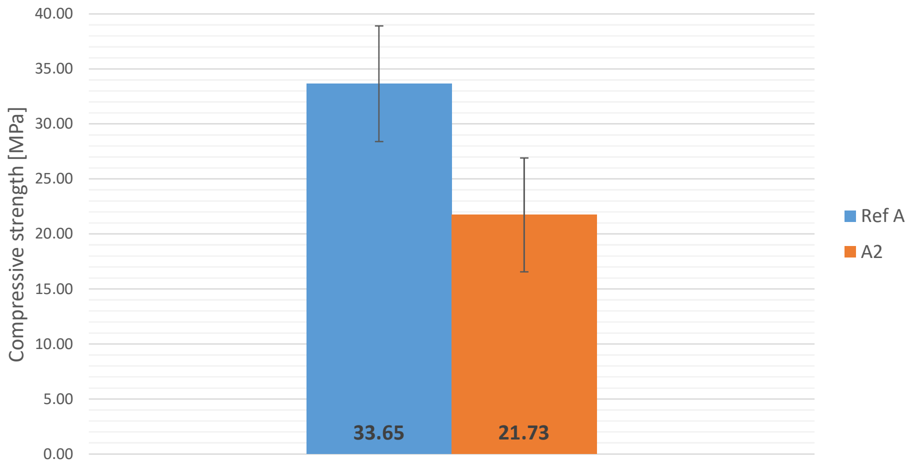

Figure 4.10: Compressive strength of specimens cured for 28 days with a water-cement ratio of 0.5

As it can be seen on Figure 4.10, the standard deviations are 5.26 MPa for Reference A and 5.17 MPa for A2, which is a really high standard deviation and the reliability of the tests has to be considered. It can also be seen that the compressive strength of the specimen with 50 % RCA is now considerably lower than the reference and lower than the corresponding test made for 7 days of curing, which doesn't make much sense. It should be noted that there were found a big piece of rubber in one of the A2 specimen, which resulted in the lowest compressive strength out of the four A2 specimens with a compressive strength 29 % lower than the average compressive strength for the whole sample.
The procedure for the specimens with a water-cement ratio of 0.5 was repeated for specimens with a water-cement ratio of 0.6. This lead to following results which can be seen on Figure 4.11.

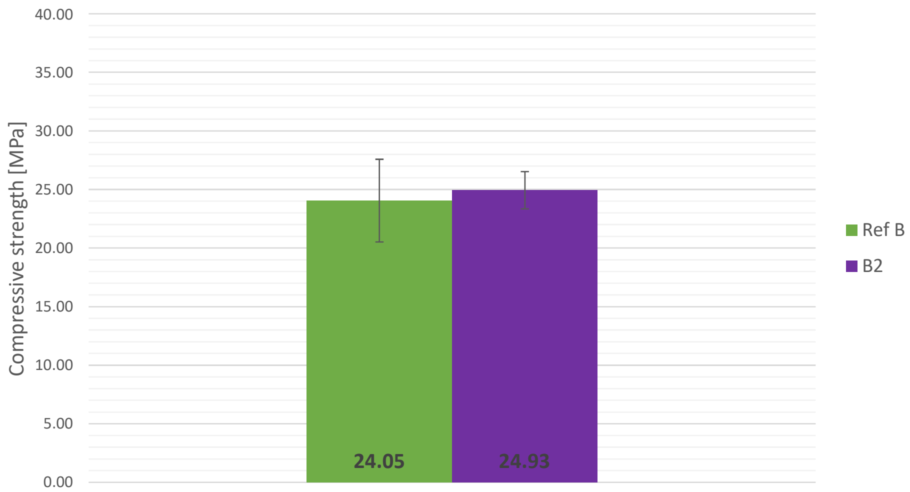

Figure 4.11: Compressive strength of specimens cured for 7 days with a water-cement ratio of 0.6

Similar to the first 7 day test, it was found that the compressive strength of the specimen with 50% RCA was slightly higher than for the reference. It can also be seen that the concrete with a water-cement ratio of 0.6 is lower than the concrete with a water-cement ratio which makes sense, since a lower water-cement ratio contributes to a higher compressive strength.

Similarly to before, there was made tests which were cured for 28 days. This resulted in a significantly lower compressive strength for the RAC specimen. This can be seen on Figure 4.12 below.

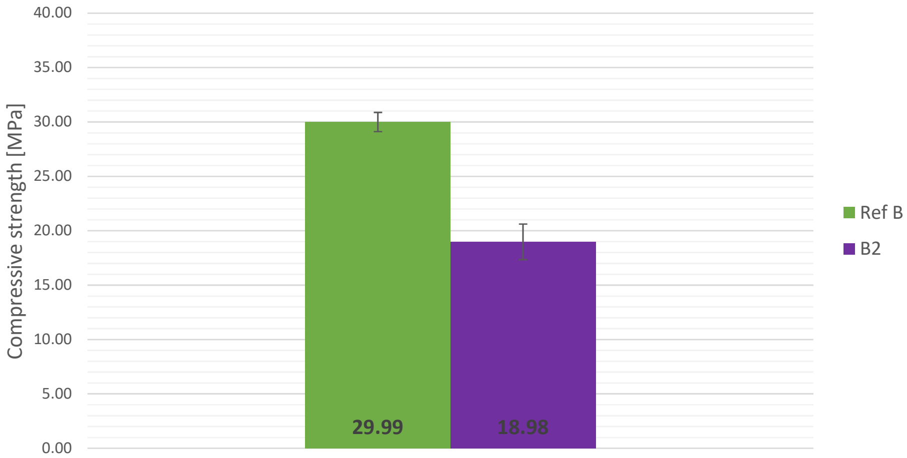

Figure 4.12: Compressive strength of specimens cured for 28 days with a water-cement ratio of 0.6

It has occurred both times that the compressive strength of the RAC sample was significantly lower than the reference after 28 days of curing. It was decided to test the next samples after 7 days, since these samples did make sense so far. But further 28 day samples will be made later in the project to try to make some sense of them.

During the mixing of the B2 recipe it was notably easier to handle the concrete compared to the A2 recipe with a lower water content. It was decided to further research recipes with a water-cement ratio of 0.6 due to the increased workability, which is an important factor when the concrete is used in practice.

To further analyse the impact RCA have on RAC, more compressive strength tests were made for specimens with a water-cement ratio of 0.6. A specimen with 100 % RCA was made with the B6 recipe. It was interesting to see what impact it would have if the RCA was saturated for 24 hours before casting. This was done with the B4 specimen, which have 50 % saturated RCA and with the B8 specimen, which have 100 % saturated RCA. To analyse whether treatment of the RCA was important, a specimen with non-treated RCA was made with the B10 recipe. The results of these specimens including the previous specimens with 0.6 water-cement ratio can be seen on Figure 4.13. rækkefølge

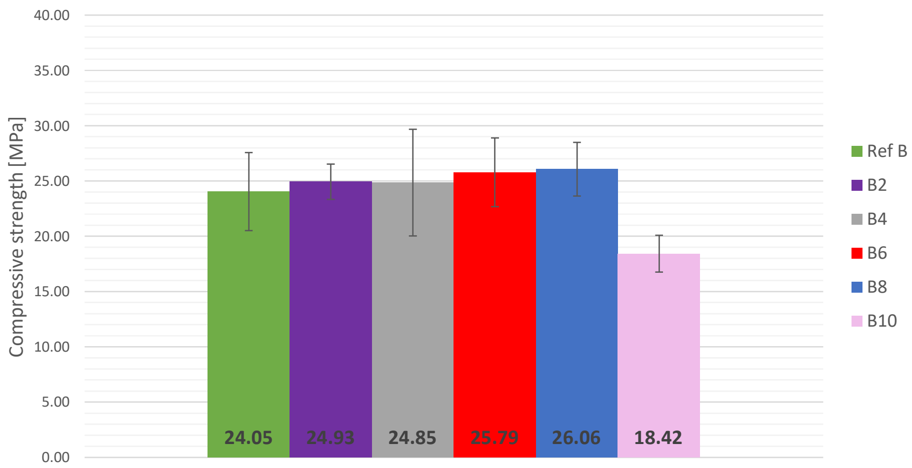

Figure 4.13: 6 different compressive strength tests, all with a water-cement ratio of 0.6.

As it can be seen on Figure 4.13, all the specimens have a higher compressive strength compared to the reference specimen, except for the non-treated specimen, B10. This implicates that the treatment used on the RCA have worked, and is important since the compressive strength achieved for the B10 specimen is significantly lower than the specimens with treated RCA. It should also be noted that the standard deviations of Ref B, B4 and B6 are respectively 3.53 MPa, 4.83 MPa and 3.10 MPa, which is relatively high.

Comparison with Bolomey's Formula

To get a better comprehension of the compressive strengths achieved so far they are compared to the theoretical compressive strengths predicted with Bolomey's formula. This formula can be applied to concrete with a water-cement ratio in the range 0.45-1.25. This formula is developed to find the characteristic compressive strengths for concrete, which is the lower 5 % quantile of the compressive strength. The K-value and α-value are based on the time the concrete has cured and on the type of cement used. These values can be seen in Table 4.7 and in Appendix Table C.6.

Table 4.7: K-values based on Table C.6 in Appendix C.

Curing [days]	K [MPa]	α
7	24	0.7
28	29	0.6

By using the K-values and α-values, the theoretical compressive strength predicted by Bolomey's formula (Equation 2.1) can be found. The theoretical compressive strength is compared with the measured compressive strength of the different specimens tested. This can be seen in Table 4.8.

Table 4.8: Comparison of the measured compressive strengths with the theoretical compressive strengths found with Bolomey's formula.

	Measured [MPa]		Theoretical [MPa]		Percentage	
	7 days	28 days	7 days	28 days	7 days	28 days
Ref A	26.63	33.65	31.20	40.60	85.35%	82.89%
A2	26.79	21.73	31.20	40.60	85.85%	53.51%
Ref B	24.05	29.99	23.20	30.93	103.65%	96.96%
B2	24.93	18.98	23.20	30.93	107.47%	61.37%
B4	24.85	-	23.20	30.93	107.11%	-
B6	25.79	-	23.20	30.93	111.14%	-
B8	26.06	-	23.20	30.93	112.34%	-
B10	18.42	-	23.20	30.93	79.42%	-

As seen in Table 4.8, all the 7 day specimens with a water-cement ratio of 0.6 and with treated RCA have a higher compressive strength compared to the theoretical compressive strength. The specimen with untreated RCA achieved a compressive strength lower than the corresponding theoretical compressive strength. The 7 day specimens with a water-cement ratio of 0.5 including the reference have achieved a lower compressive strength compared to the theoretical compressive strength. All the 28 day specimens have a lower compressive strength than Bolomey's formula predicted, with the two specimens with RCA being far below the theoretical compressive strength. In (ACPA 2009) it is reported that RAC with coarse aggregates substituted with coarse RCA have 0 % - 24 % less compressive strength. There are only two specimens that were found to have achieved more than 24 % reduction in compressive strength compared to the Bolomey's predicted compressive strength, which were the two 28 day specimens with RCA.

4.6.2 Further Compressive Strength Tests

The objective of the further compressive strength tests was to try to lower the standard deviations, or at least get a better understanding of these relatively high standard deviations by making additional specimens of the B2, B4, B6 and B8 recipes. An extra casting of the reference, Ref B, was also done to provide an extra 7 day compressive strength test. It was deemed unnecessary to cast an extra 28 day test for Ref B since it had an excellent standard deviation of 0.88 MPa. During the further compressive strength tests, each specimen were examined closely to try to determine whether there were fracture through the RCA aggregates, or if there were any other reasons for an eventual weak specimen. During the inspections of the specimens that had fractures through aggregates, the colour of the aggregates were examined since the RCA tends to have a lighter colour than the natural aggregates. In this section, the definitions for a satisfying standard deviation from (ACI-214R-02 2005) will be used. These definitions can be seen on Table 4.9 which applies to specimens designed to have a compressive strength below 34.5 MPa.

Table 4.9: The assessment of the standard deviations according to (ACI-214R-02 2005).

Overall variation					
Class of operation	Standard deviation for different control standards, MPa (psi)				
	Excellent	Very good	Good	Fair	Poor
General construction testing	Below 2.8 (below 400)	2.8 to 3.4 (400 to 500)	3.4 to 4.1 (500 to 600)	4.1 to 4.8 (600 to 700)	Above 4.8 (above 700)
Laboratory trial batches	Below 1.4 (below 200)	1.4 to 1.7 (200 to 250)	1.7 to 2.1 (250 to 300)	2.1 to 2.4 (300 to 350)	Above 2.4 (above 350)

It was chosen to repeat the casting of specimens with 50 % RCA with normally treated RCA and one with normally treated and saturated RCA - the B2 and B4 recipes. Specimens with 100 % RCA with normally treated RCA (B6) and one with normally treated and saturated RCA (B8) were also cast again. These four recipes were cast and cured for both 7 days and 28 days. This time the 7 day specimens and 28 day specimen were made from the same casting were the ingredients for the recipe were doubled to have enough concrete for twice the specimens.

The first specimen analysed is the 50 % RCA with normally treated RCA and a water-cement ratio of 0.6 (B2). The result of the second casting of the B2 recipe is plotted alongside the first casting and a combined result of the two castings were the average compressive strength is found between the two castings and the overall standard deviation is plotted on top of the combined result. This can be seen in Figure 4.14.

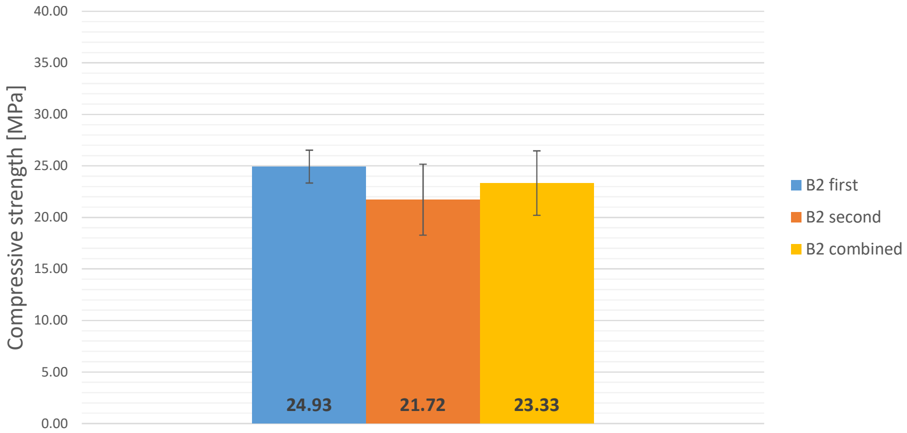

Figure 4.14: The compressive strength for the first, second and combined 50 % RCA 7 days specimen.

As it is seen on Figure 4.14 the second casting of the B2 recipe resulted in a compressive strength of 21.72 MPa, which is lower than the first casting that had a compressive strength of 24.93 MPa. The standard deviation of the second B2 casting was 3.44 MPa, which is higher than the standard deviation from the first casting on 1.59 MPa. The overall standard deviation was found to be 3.13 MPa which is a poor standard deviation according to (ACI-214R-02 2005), which categorizes standard deviations above 2.4 MPa for laboratory trial batches as poor. During the compressive strength test of the second B2 casting, it was noted that the fracture of the weakest specimen went through white aggregates, which indicates that the aggregates that fractured were RCA. In Figure 4.15 the fracture through aggregates can be seen, there is also a picture of another fracture that didn't go through aggregates.

The same procedure which were applied above will be repeated for the B4 recipe, which is specimens with 50 % saturated RCA. During the compressive strength test of the second casting of the B4 recipe one of the specimen were considered to have partially fractured through the aggregates. On Figure 4.16 it can be seen that the second casting of the B4 recipe resulted in a higher compressive strength of 26.40 MPa compared to the compressive strength of 24.85 MPa for the first casting. The standard deviation of the second casting was 1.86 MPa, which is a good standard deviation. The combined data results in a compressive strength of 25.63 MPa and a standard deviation of 2.72 MPa, which is categorized as a poor standard deviation according to (ACI-214R-02 2005).

(a) The specimen from the second B2 casting with the lowest compressive strength.

(b) A specimen from the second B2 casting with fracture through mortar and not through aggregates.

Figure 4.15: The difference between a fracture through aggregates and a fracture through mortar.

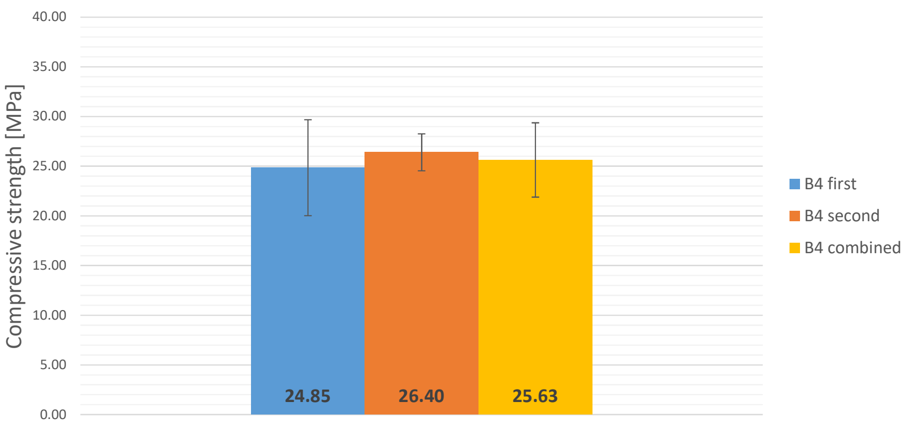

Figure 4.16: The compressive strength for the first, second and combined 50 % saturated RCA 7 days specimen.

The B6 recipe which is specimens with 100 % RCA was also cast again, which resulted in a lower compressive strength of 23.12 MPa compared to the first casting which had a compressive strength of 25.79 MPa. The standard deviation of the second casting were 2.76 MPa, which is a poor standard deviation. During the second casting of the B6 recipe 3 out of 4 specimens had fractures through aggregates, where all of these fractures were through the RCA, which is not a surprise since all coarse aggregates were RCA. The combined data results in a compressive strength of 24.30 MPa and a standard deviation of 3.34 MPa, which is a poor standard deviation according to (ACI-214R-02 2005). This can be seen on Figure 4.17.

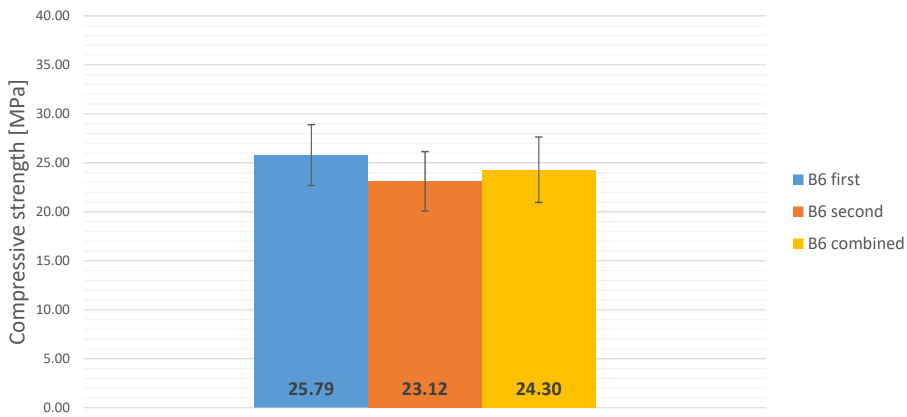

Figure 4.17: The compressive strength for the first, second and combined 100 % RCA 7 days specimen.

The results of the second casting of the B8 recipe which is 100 % saturated RCA, can be seen on Figure 4.18. This resulted in a compressive strength of 23.79 MPa, which is lower than the first casting that had a compressive strength of 26.06 MPa. The standard deviation was calculated to be 3.01 MPa, which is worse than the first casting, that had a standard deviation of 2.43 MPa. During the compressive strength testing of the second casting there were registered one case of fracture through aggregates, which also was the specimen with the lowest compressive strength - 18.6 % lower than the average compressive strength of the sample. The combined data results in a compressive strength of 24.93 MPa and a standard deviation of 2.96 MPa, which is considered a poor standard deviation according to (ACI-214R-02 2005).

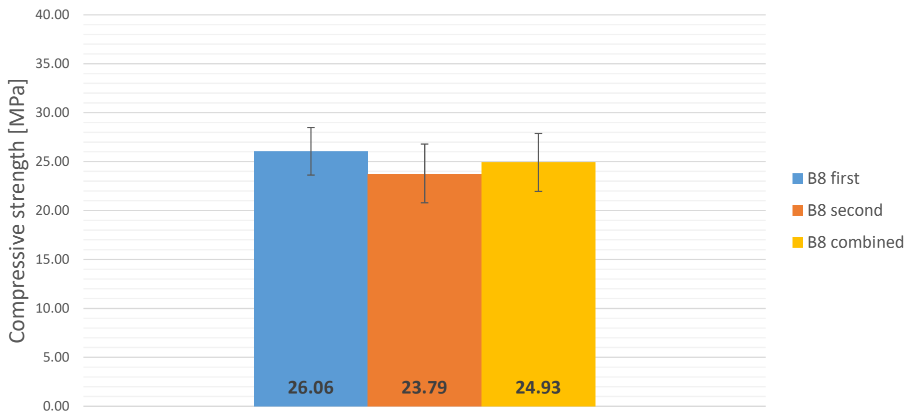

Figure 4.18: The compressive strength for the first, second and combined 100 % saturated RCA 7 days specimen.

During the first castings of specimens with saturated RCA it was discovered that some RCA was floating on top of the water during the saturation process. These black porous aggregates were also seen in most of the fractures, which lead to the conclusion that these aggregates had a negative impact on the compressive strength of the RAC. It was later discovered that these black porous aggregates were asphalt. It was decided to create a RAC where the asphalt was removed to see the impact on the compressive strength. This recipe was called B12, and it was discovered that removing all the asphalt from the RCA was a rather difficult task since there were a lot of them and not all of them were floating because they were trapped beneath heavier aggregates. The asphalt floating on top of the water and the asphalt removed from the bucket of saturated RCA can be seen on Figure 4.19. A total of 185 g of asphalt were removed, and the saturated RCA without asphalt was used to cast B12 specimens.

(a) The asphalt floating on top of the water. (b) The asphalt removed from the water and from the RCA.

Figure 4.19: The asphalt floating on top of the water and later removed from the water.

The result of the RAC with asphalt removed can be seen on Figure 4.20 along with all the results for 7 day specimens with a water-cement ratio of 0.6.

As it can be seen on Figure 4.20, the removal of the asphalt from the B12 recipe did not result in a high compressive strength. It did in fact result in a compressive strength of 18.69 MPa which is almost the same

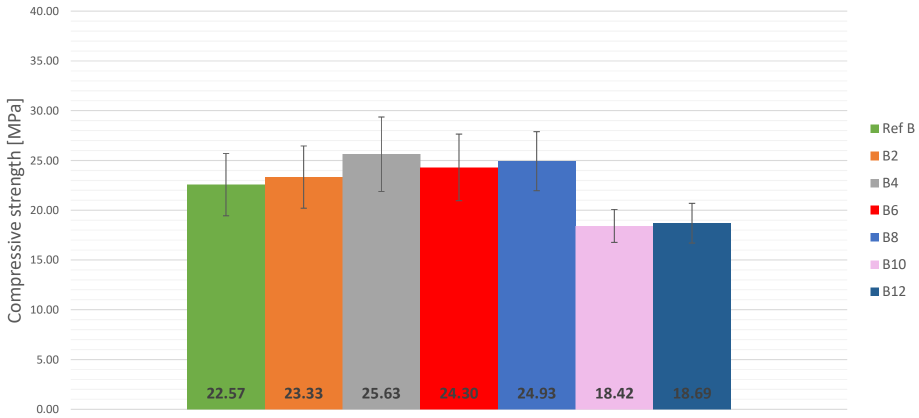

Figure 4.20: The compressive strength for all 0.6 w/c 7 days specimen.

compressive strength as the B10 recipe where untreated RCA were used. This low compressive strength could be the result of several factors. During the casting of the B12 recipe (only 10 kg RCA used, and the rest of the ingredients were scaled down), the measured extra water on the aggregates was only 80 gram, which seemed rather low compared to the other saturated castings, where around an extra amount of 400-800 gram water was measured. This could have caused an extra amount of water in the B12 casting, which would contribute to a higher water-cement ratio which means it would have a lower compressive strength. At the same time it should also be noted that the sand used for this casting was moist, whereas it normally feels dry, this would also contribute to a higher water-cement ratio. Another factor that could have contributed to the relatively low compressive strength of the B12 specimen was the removal of 185 gram asphalt without adding RCA the make up for the amount of RCA removed. The B12 specimens had a standard deviation of 2.00 MPa, which is considered a good standard deviation according to (ACI-214R-02 2005). The B10 specimens, which also had a relatively low compressive strength, had a standard deviation of 1.66 MPa, which is considered a very good standard deviation according to (ACI-214R-02 2005). The specimens Ref B, B2, B4, B6 and B8 all had poor standard deviations according to (ACI-214R-02 2005). From the figure it can also be seen that the specimen with the highest compressive strength was the B4 with 50 % saturated RCA that had a compressive strength of 25.63 MPa.

The casting of the five different 28 day specimens resulted in the following compressive strengths, which can be seen on Figure 4.21.

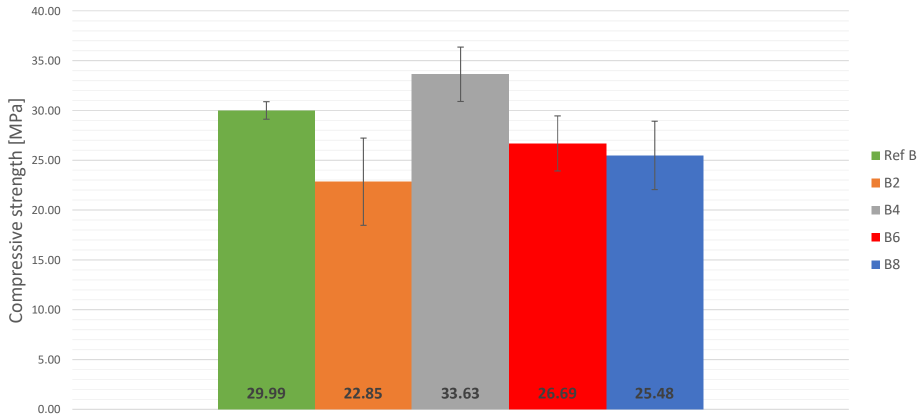

Figure 4.21: The compressive strength for all 0.6 w/c 28 days specimen.

As it can be seen on Figure 4.21, the compressive strength of the reference specimen, Ref B, was 29.99 MPa with a standard deviation of 0.88 MPa which is considered an excellent standard deviation according to (ACI-214R-02 2005). The 28 day specimen with 50 % RCA which was cast two times had a compressive strength of 22.85 MPa and a standard deviation of 4.38 MPa, which is considered a poor standard deviation according to (ACI-214R-02 2005). What can not be seen on Figure 4.21, is that the second casting of B2 resulted in a 28 day compressive strength of 26.72 MPa and a standard deviation of 2.39 MPa, which is considered a fair standard deviation according to (ACI-214R-02 2005). The 28 day specimen with 50 % saturated RCA resulted in a compressive strength of 33.63 MPa and a standard deviation of 2.72 MPa, which is considered a fair standard deviation according to (ACI-214R-02 2005). The 28 day specimen with 100 % RCA resulted in a compressive strength of 26.69 MPa and a standard deviation of 2.76 MPa, which is considered a fair standard deviation according to (ACI-214R-02 2005). The B8 recipe, which was a 28 day specimen with 100 % saturated RCA had a compressive strength of 25.48 MPa and a standard deviation of 3.43 MPa, which is considered a fair standard deviation according to (ACI-214R-02 2005). Like the 7 day specimens, the specimen with 50 % saturated RCA resulted in the highest compressive strength.

Comparison with Bolomey's Formula

The compressive strengths achieved in this section is compared to the corresponding theoretical compressive strengths calculated with Bolomey's formula, Equation 2.1. This can be seen in Table 4.10.

Table 4.10: Comparison of the measured compressive strengths with the theoretical compressive strengths found with Bolomey's formula.

	Measured [MPa]		Theoretical [MPa]		Percentage	
	7 days	28 days	7 days	28 days	7 days	28 days
Ref B	22.57	29.99	23.20	30.93	97.29%	96.96%
B2	23.33	22.85	23.20	30.93	100.55%	73.87%
B4	25.63	33.63	23.20	30.93	110.45%	108.72%
B6	24.30	26.69	23.20	30.93	104.73%	86.28%
B8	24.93	25.48	23.20	30.93	107.44%	82.38%
B10	18.42	-	23.20	30.93	79.42%	-
B12	18.69	-	23.20	30.93	80.58%	-

As it can be seen on Table 4.10, all the 7 day specimens with treated RCA have a higher compressive strength compared to the theoretical compressive strength except for the B12 specimen. The reference specimen, Ref B, came close to the theoretical compressive strength with 97.29 % and 96.96 % of the theoretical compressive strength for the 7 day specimen and the 28 day specimen. The B4 recipe that had cured for 28 days exceeded the theoretical compressive strength with 8.72 percentage points. The 28 day specimens for B2, B6 and B8 achieved respectively 73.87 %, 86.28 % and 82.38 % of the theoretical compressive strength. All but the 28 day B2 specimen had a lower than 24 % reduction in compressive strength compared to the theoretical compressive strength, which is stated in (ACPA 2009). It should be noted that the second casting of the 28 day B2 specimen achieved a compressive strength of 26.72 MPa which is a reduction of 14 % compared to the theoretical compressive strength.

4.6.3 Compressive Strength Development

The development of compressive strength can be evaluated by analysing the compressive strength series of the second castings of B2, B4, B6 and B8, since the 7 day specimens and corresponding 28 day specimens came from the same castings. In Table 4.11, the percentage of the 28 day compressive strength that the 7 day specimen has developed can be seen.

Table 4.11: Compressive strength development

	7 day compressive strength [MPa]	28 day compressive strength [MPa]	Percentage [%]
B2	21.72	26.72	81.29%
B4	26.40	33.63	78.50%
B6	23.12	26.69	86.63%
B8	23.79	25.48	93.35%

As it can be seen in Table 4.11, the percentage of 28 day compressive strength developed for the B2 specimen is 81.29 %, for B4 it is 78.50 %, for B6 it is 86.63 % and for B8 specimen it is 93.35 %. This can be compared to (Portland 2007), where it is stated that a 7 day concrete specimen cast with Aalborg Portland Basis cement should have developed 86 % of the corresponding 28 day specimen's compressive strength. The figure this information is taken from, can be seen in Appendix C Figure C.1.

CHAPTER **5**

Conclusion

A various series of experiments have been conducted to characterize and determine the properties of the 8-16 mm fraction of an RCA material, collected at a construction site in Rødovre, to get a better understanding of the advantages and disadvantages this RCA provides.

The porosity of the RCA material was found with the means of a desiccator experiment, which showed that the average porosity of the RCA was 29.8 volume percent, which is approximately twice the porosity for RCA which is provided in the literature.

The density of the RCA was determined by two experiments - a desiccator experiment and a pycnometer experiment. The desiccator experiment resulted in a solid dry state density of 2482.79 kg/m^3, whereas the pycnometer experiment resulted in a solid dry state density of 2484.1 kg/m^3. These two results are close together and also are backed up by the literature, where one reference reports the solid dry state density of RCA of the fraction 8-16 mm with a water-cement ratio of 0.70 to be 2440 kg/m^3 and another reference reports the density of RCA to be in the range 2100-2500 kg/m^3.

The attached mortar was found to be 27.26 %. This was lower than the reported amount of attached mortar in the literature, where it was found to be 39 % for 8-16 mm RCA with a water-cement ratio of 0.70.

During the project, two Grain-size distribution curves were created to describe the distribution of the untreated aggregate sizes. The two grain-size distributions created had visible differences, so the mean of the two were used to describe the quality of the aggregate distribution by comparing the mean grain-size distribution curve with the requirements for a top quality RCA to be used as road fill. The grain-size distribution was sufficient in all aggregate sizes except the quantity of aggregates below 0.063 mm was too small.

The impact of the RCA implemented in RAC was analysed by testing various properties of the RAC. This was done by casting 24 samples where each sample consisted of 4 200x100 mm cylindrical concrete specimens. The 24 samples was divided into 9 different mix designs. The process started with testing the properties of RAC with 50 % RCA in the 8-16 mm fraction, which lead to further castings where up to 100 % of the natural aggregates in the 8-16 mm fraction were substituted with RCA.

The slump was tested for each casting, which showed that the RAC of all mix designs had a low slump, which also was noted during the casting since the low workability had a significant impact on the ease of manoeuvring the RAC. The slump tests showed that the highest slump found for an RAC was 5 cm, and the slump would typically be in the range of 1-2 cm. The RAC which were made with saturated RCA showed a great increase in workability, which was noticed during the castings, but this claim was not supported by the slump tests, which showed that the RAC made with saturated RCA had slumps in the range of 1-3 cm. The better workability of the RAC with saturated RCA shows that the high porosity of the RCA probably lead to a high water absorption of the non-saturated RCA, which causes less free water in the fresh concrete,

leading to a worse workability.
The air content was tested for each casting, and it showed that the air content for all mix designs were in the range of 1.1 - 2.2 %. The air content for fresh concrete is normally in the range 1.0-2.0 %.
The compressive strength of the 24 cylindrical concrete samples were tested, and it was seen that the compressive strength achieved was higher or close to the theoretical compressive strength predicted with Bolomey's formula. The compressive strength tests also provided support of the importance of treating the aggregates by washing them through sieves and drying them. From the compressive strength results it can be concluded that it is indeed feasible to substitute all the natural aggregates in the 8-16 mm fraction with RCA. It can also be concluded that the compressive strength development was sufficient.
The difference between a concrete specimen that fractured through the mortar and a concrete specimen that fractured through the aggregates was found to be important, and is an indicator that weak parts of the RCA should be removed if possible. RCA from a known source is preferred to RCA from an unknown source since knowing the source makes the possibility of contaminants or parts of low strength concrete being part of the RCA lower. The RCA used in this project came from an unknown source, the compressive strength tests showed that the standard deviations of the compressive strength of RAC was high.

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Appendices

APPENDIX **A**

Theory

A.1 Recycled Concrete Aggregates

Tabel 2426-3 – Tilslag – Generelle krav

		Miljøklasse			
Punkt i DS/EN 12620	**Egenskab**	**Passiv**	**Moderat**	**Aggressiv**	**Ekstra aggressiv**
4.3	Sorteringer af tilslag	Krav til kategori $G_c85/20$, $G_c90/15$, G_F85, G_NG90 eller G_A90 skal opfyldes			
4.3.2 - 6	Kornstørrelsesfordeling	Skal deklareres			
4.3.3	Fint tilslag: Variationsbånd	Krav i DS/EN 12620, anneks C, skal opfyldes			
4.7	Finstofkvalitet	Krav i 4.7 skal opfyldes[1)]			
5.5	Densitet og vandabsorption	Forventelig værdi skal deklareres			
5.7.2	Volumenstabilitet	–	For tilslag, der ikke tidligere er anvendt til den aktuelle miljøklasse: Krav i 5.7.2 skal opfyldes		
6.2	Chloridindhold og vandopløse-lige alkalier	Forventelig værdi skal deklareres[2)3)]			
6.3	Højovnsslagge	–	Højovnsslagge er ikke tilladt		
6.3.1	Syreopløseligt sulfat	–	For tilslag, der ikke tidligere er anvendt til beton i den aktuelle miljøklasse: Kategori skal deklareres		
6.3.2	Totalt svovlindhold	For tilslag, der ikke tidligere er anvendt til den aktuelle miljø-klasse: Krav i 6.3.2 skal opfyldes			
6.4.1	Organisk materiale	Krav i 6.4.1 skal opfyldes for fint tilslag			

1) I anneks D i DS/EN 12620 bør vurdering af finstof ske i henhold til punkt a), c) eller d). Ved prøvning i henhold til punkt c) bør resultatet være maks. 1,2 gram pr. 100 gram for tilslag til miljøklasse A og E.

2) Chloridindholdet kan bestemmes ved anvendelse af teststrips.

3) Indholdet af vandopløselige alkalier skal deklareres. Indholdet beregnet som Na_2O beregnes ud fra det målte indhold af chlorid multipliceret med en faktor på 0,87.

NOTE – Krav til modstandsdygtighed over for afskalning, slag, slid, polering eller overfladeslid, jf. DS/EN 12620, bør kun stilles i specielle tilfælde, hvor der er særlige behov for modstandsdygtighed.

Figure A.1: Table 2426-3 from (DS/EN-206-1 2011).

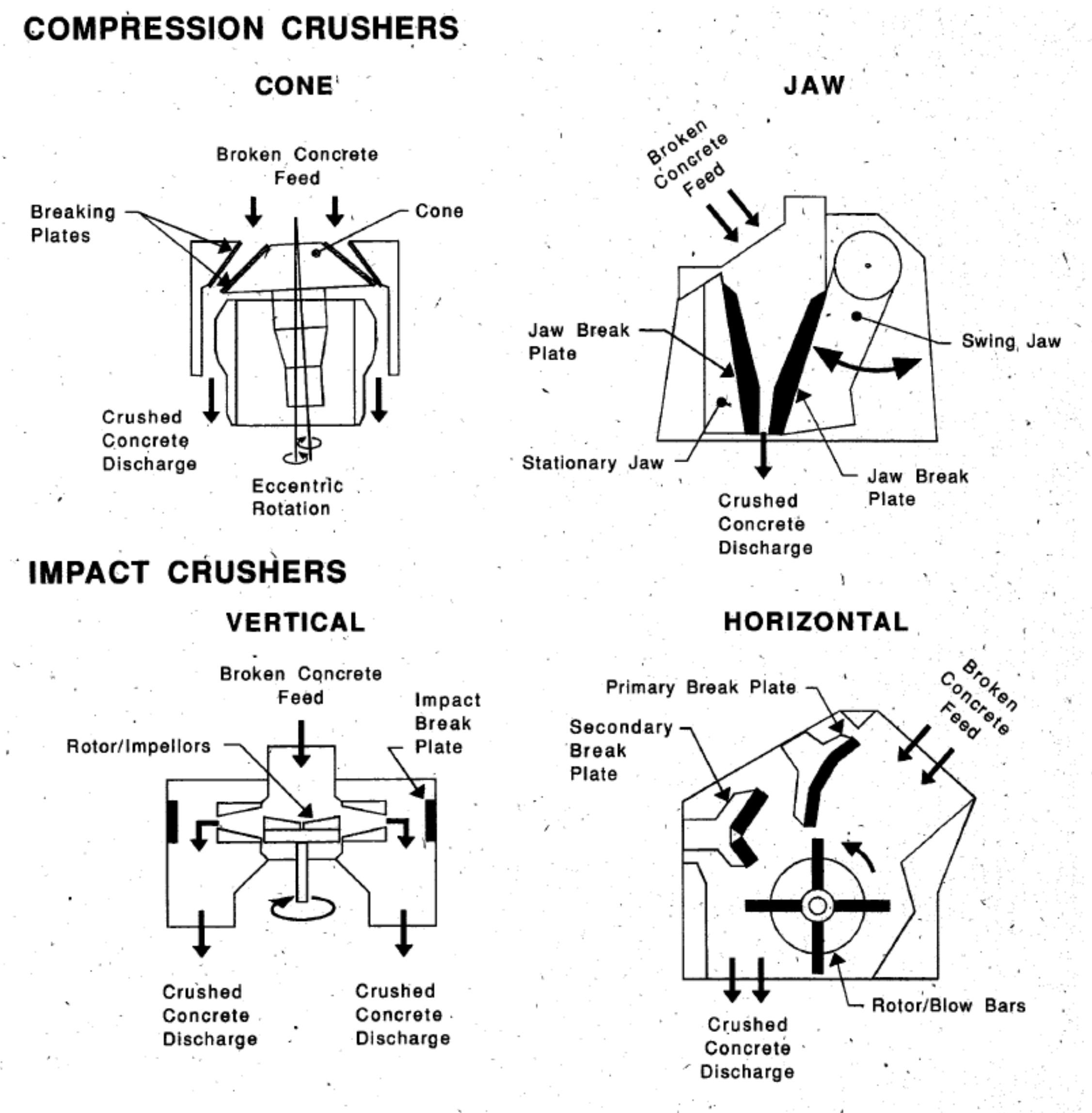


Figure A.2: Two types of crushers used to produce RCA.

APPENDIX B

Methods

B.1 Guideline to desiccator experiment

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)

B.2 Guideline to pycnometer experiment

B.3 Guideline to attached mortar experiment

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 C

Results

C.1 Pycnometer

Table C.1: Results from the pycnometer experiments. The experiment was done two times.

				1	2	3
Fra kalibrering af pyknometer						
Pyknometer nummer				40	40	
Pykn. + prop (tomt)		m_0	g	363.67	363.67	
Pykn. + prop (vandfyldt)	W_2	m_1	g	944.15	944.15	
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	466.87	463.8500	
Pykn.+ prop + jord + vand	W_1	m_3	g	1006.44	1003.55	
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	103.2	100.18	
Jord - volumen	V_s		cm^3	41.0002004	40.8699138	
Korndensitet	ρ_s	ρ_s	g/cm^3	2.51706087	2.45119186	
Resultat - middel	ρ_s	ρ_s	g/cm^3	**2.4841**		
Betegnelser fra	dgf15	DS				

C.2 Grain-Size Distribution Curve

Table C.2: An overview of the measurements from the sieve method for grain-size distribution curve 1

Fraction [mm]	Passing [g]	Passing [%]	Cumulative passing [%]
1	1525	17.75	17.75
2	687	7.99	25.74
4	1073	12.49	38.23
8	1533	17.84	56.07
16	2063	24.01	80.08
31.5	1712	19.92	100.00

Table C.3: Data from laser diffractometer used to create grain-size distribution curve 1

Laser diffractometer 1						
Raw data		Treated data				
[μm]	[mm]	Passing [%]	Cumul. passing [%]	Relative passing [%]	Relative cumul. passing [%]
1.659587	0.00166	0	0	0	0
1.905461	0.001905	0.022552	0.022552	0.0040023	0.0040023
2.187762	0.002188	0.046498	0.06905	0.008252	0.01225431
2.511886	0.002512	0.054734	0.123784	0.00971364	0.02196795
2.884031	0.002884	0.079926	0.20371	0.01418447	0.03615242
3.311311	0.003311	0.095818	0.299528	0.01700482	0.05315724
3.801894	0.003802	0.105932	0.40546	0.01879976	0.071957
4.365158	0.004365	0.11846	0.52392	0.0210231	0.0929801
5.011872	0.005012	0.130255	0.654175	0.02311636	0.11609646
5.754399	0.005754	0.142234	0.796409	0.02524227	0.14133873
6.606934	0.006607	0.154245	0.950654	0.02737387	0.1687126
7.585776	0.007586	0.166169	1.116823	0.02949002	0.19820262
8.709636	0.00871	0.178326	1.295149	0.03164752	0.22985014
10	0.01	0.190497	1.485646	0.03380751	0.26365765
11.48154	0.011482	0.203187	1.688833	0.0360596	0.29971725
13.18257	0.013183	0.216151	1.904984	0.03836033	0.33807757
15.13561	0.015136	0.229951	2.134935	0.04080941	0.37888699
17.37801	0.017378	0.244447	2.379382	0.04338202	0.422269
19.95262	0.019953	0.260414	2.639796	0.04621568	0.46848469
22.90868	0.022909	0.278373	2.918169	0.04940287	0.51788755
26.30268	0.026303	0.300124	3.218293	0.05326302	0.57115057
30.19952	0.0302	0.327472	3.545765	0.05811647	0.62926703
34.67369	0.034674	0.36315	3.908915	0.06444824	0.69371528
39.81072	0.039811	0.40925	4.318165	0.07262961	0.76634489
45.70882	0.045709	0.467938	4.786103	0.08304497	0.84938986
52.48075	0.052481	0.540715	5.326818	0.09596071	0.94535057
60.25596	0.060256	0.628629	5.955447	0.11156281	1.05691338
69.1831	0.069183	0.733648	6.689095	0.13020054	1.18711392
79.43282	0.079433	0.857468	7.546563	0.15217487	1.33928879
91.20108	0.091201	1.006511	8.553074	0.17862554	1.51791433
104.7129	0.104713	1.186596	9.73967	0.21058523	1.72849956
120.2264	0.120226	1.414083	11.153753	0.25095736	1.97945692
138.0384	0.138038	1.702404	12.856157	0.3021257	2.28158262
158.4893	0.158489	2.082315	14.938472	0.36954851	2.65113113
181.9701	0.18197	2.566036	17.504508	0.4553945	3.10652563
208.9296	0.20893	3.184601	20.689109	0.56517125	3.67169687
239.8833	0.239883	3.9185	24.607609	0.69541633	4.3671132
275.4229	0.275423	4.762717	29.370326	0.84523955	5.21235275
316.2278	0.316228	5.640117	35.010443	1.00095175	6.2133045
363.0781	0.363078	6.485966	41.496409	1.1510646	7.36436911
416.8694	0.416869	7.183188	48.679597	1.27480062	8.63916972
478.6301	0.47863	7.640761	56.320358	1.35600611	9.99517583
549.5409	0.549541	7.770526	64.090884	1.37903551	11.3742113
630.9573	0.630957	7.531783	71.622667	1.33666578	12.7108771
724.436	0.724436	6.936016	78.558683	1.23093499	13.9418121
831.7638	0.831764	6.0475	84.606183	1.07325003	15.0150622
954.9926	0.954993	4.974461	89.580644	0.88281776	15.8978799
1096.478	1.096478	3.85005	93.430694	0.6832685	16.5811484
1258.925	1.258925	2.788742	96.219436	0.49491814	17.0760666
1445.44	1.44544	1.886057	98.105493	0.3347186	17.4107852
1659.587	1.659587	1.174452	99.279945	0.20843004	17.6192152
1905.461	1.905461	0.589239	99.869184	0.10457227	17.7237875
2187.762	2.187762	0.130817	100.000001	0.0232161	17.7470036
2511.886	2.511886	0	100.000001	0	17.7470036

Table C.4: An overview of the measurements from the sieve method for grain-size distribution curve 2

Fraction [mm]	Passing [g]	Passing [%]	Cumulative passing [%]
1	1370	15.53	15.53
2	612	6.94	22.46
4	765	8.67	31.13
8	1016	11.52	42.65
16	1683	19.08	61.73
31.5	3377	38.27	100.00

Table C.5: Data from laser diffractometer used to create grain-size distribution curve 1

Laser diffractometer 2					
Raw data		Treated data			
[μm	[mm]	Passing [%]	Cumul. passing [%]	Relative passing [%]	Relative cumul. passing [%]
1.659587	0.00166	0	0	0	0
1.905461	0.001905	0	0	0	0
2.187762	0.002188	0.061173	0.061173	0.0094987	0.0094987
2.511886	0.002512	0.069693	0.130866	0.01082165	0.02032035
2.884031	0.002884	0.081457	0.212323	0.01264832	0.03296866
3.311311	0.003311	0.091868	0.304191	0.01426489	0.04723356
3.801894	0.003802	0.103595	0.407786	0.01608582	0.06331937
4.365158	0.004365	0.114675	0.522461	0.01780627	0.08112565
5.011872	0.005012	0.125963	0.648424	0.01955903	0.10068467
5.754399	0.005754	0.137021	0.785445	0.02127607	0.12196074
6.606934	0.006607	0.148146	0.933591	0.02300352	0.14496426
7.585776	0.007586	0.159164	1.092755	0.02471435	0.16967861
8.709636	0.00871	0.1705	1.263255	0.02647456	0.19615316
10	0.01	0.182079	1.445334	0.0282725	0.22442566
11.48154	0.011482	0.194565	1.639899	0.03021127	0.25463693
13.18257	0.013183	0.207917	1.847816	0.03228452	0.28692145
15.13561	0.015136	0.222881	2.070697	0.03460807	0.32152951
17.37801	0.017378	0.239312	2.310009	0.03715941	0.35868892
19.95262	0.019953	0.257727	2.567736	0.04001881	0.39870773
22.90868	0.022909	0.277791	2.845527	0.04313427	0.441842
26.30268	0.026303	0.299913	3.14544	0.04656929	0.48841129
30.19952	0.0302	0.324061	3.469501	0.05031889	0.53873018
34.67369	0.034674	0.351193	3.820694	0.05453184	0.59326202
39.81072	0.039811	0.382402	4.203096	0.05937785	0.65263986
45.70882	0.045709	0.419842	4.622938	0.06519138	0.71783124
52.48075	0.052481	0.466186	5.089124	0.07238749	0.79021873
60.25596	0.060256	0.524489	5.613613	0.08144055	0.87165928
69.1831	0.069183	0.598383	6.211996	0.09291451	0.96457379
79.43282	0.079433	0.69019	6.902186	0.10716993	1.07174372
91.20108	0.091201	0.803893	7.706079	0.12482528	1.19656899
104.7129	0.104713	0.941234	8.647313	0.14615103	1.34272003
120.2264	0.120226	1.110501	9.757814	0.17243413	1.51515416
138.0384	0.138038	1.317136	11.07495	0.20451959	1.71967375
158.4893	0.158489	1.580175	12.655125	0.24536323	1.96503698
181.9701	0.18197	1.909655	14.56478	0.29652356	2.26156053
208.9296	0.20893	2.335623	16.900403	0.36266616	2.62422669
239.8833	0.239883	2.862229	19.762632	0.44443542	3.06866211
275.4229	0.275423	3.513032	23.275664	0.5454895	3.61415161
316.2278	0.316228	4.26335	27.539014	0.66199586	4.27614748
363.0781	0.363078	5.098186	32.6372	0.79162584	5.06777332
416.8694	0.416869	5.9436	38.5808	0.92289833	5.99067165
478.6301	0.47863	6.728981	45.309781	1.04484914	7.03552079
549.5409	0.549541	7.344881	52.654662	1.14048362	8.17600441
630.9573	0.630957	7.699278	60.35394	1.19551296	9.37151738
724.436	0.724436	7.715628	68.069568	1.19805172	10.5695691
831.7638	0.831764	7.365644	75.435212	1.14370761	11.7132767
954.9926	0.954993	6.675813	82.111025	1.03659343	12.7498701
1096.478	1.096478	5.72937	87.840395	0.88963356	13.6395037
1258.925	1.258925	4.631198	92.471593	0.71911382	14.3586175
1445.44	1.44544	3.498882	95.970475	0.54329234	14.9019099
1659.587	1.659587	2.418107	98.388582	0.37547394	15.2773838
1905.461	1.905461	1.308372	99.696954	0.20315875	15.4805426
2187.762	2.187762	0.303046	100	0.04705577	15.5275983
2511.886	2.511886	0	100	0	15.5275983

Table C.6: The constants used in Bolomey's formula found in (Portland 2007).

Vejledende konstanter til Bolomeys formel

Cementtyper	Termin døgn	K	α
BASIS CEMENT	1 7 28	17 26 30	0,9 0,6 0,5
RAPID CEMENT	1 7 28	13 24 30	0,9 0,6 0,5
LAVALKALI SULFATBESTANDIG CEMENT	1 7 28	5 19 29	0,8 0,8 0,7
AALBORG WHITE	1 7 28	14 25 35	1,0 0,8 0,7
BASIS AALBORG CEMENT	1 7 28	13 24 29	1,0 0,7 0,6

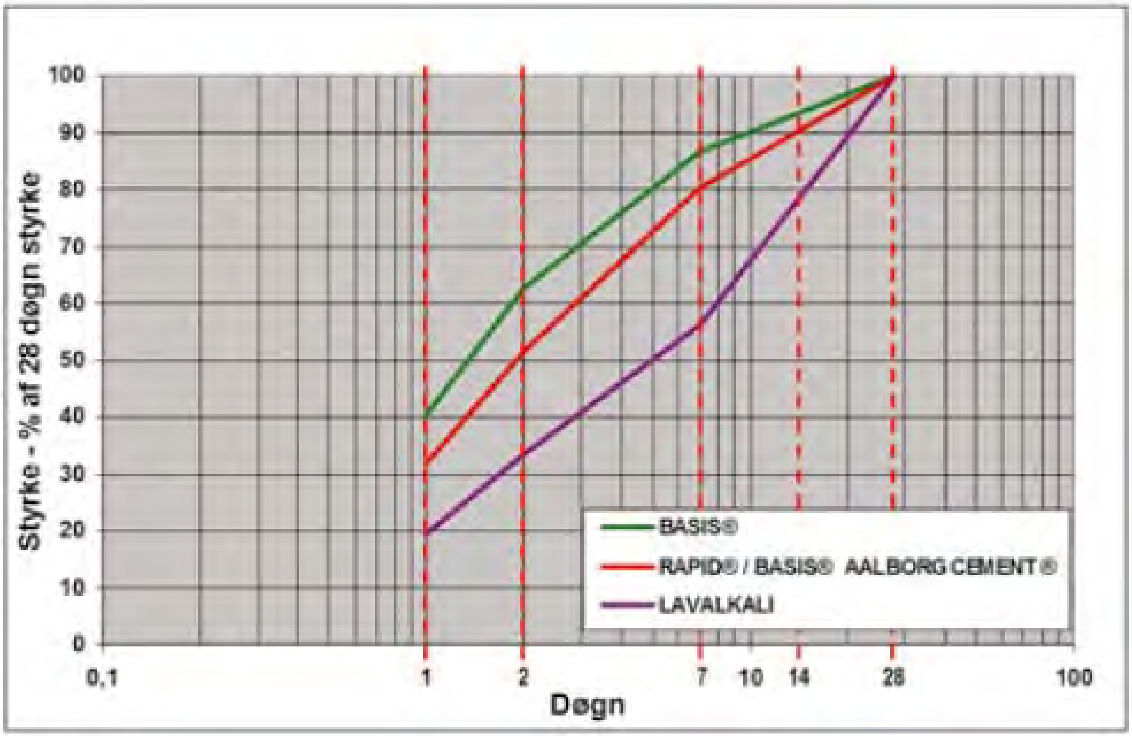


Figure C.1: The development of compressive strength according to (Portland 2007).

APPENDIX **D**

Compressive Strength Results

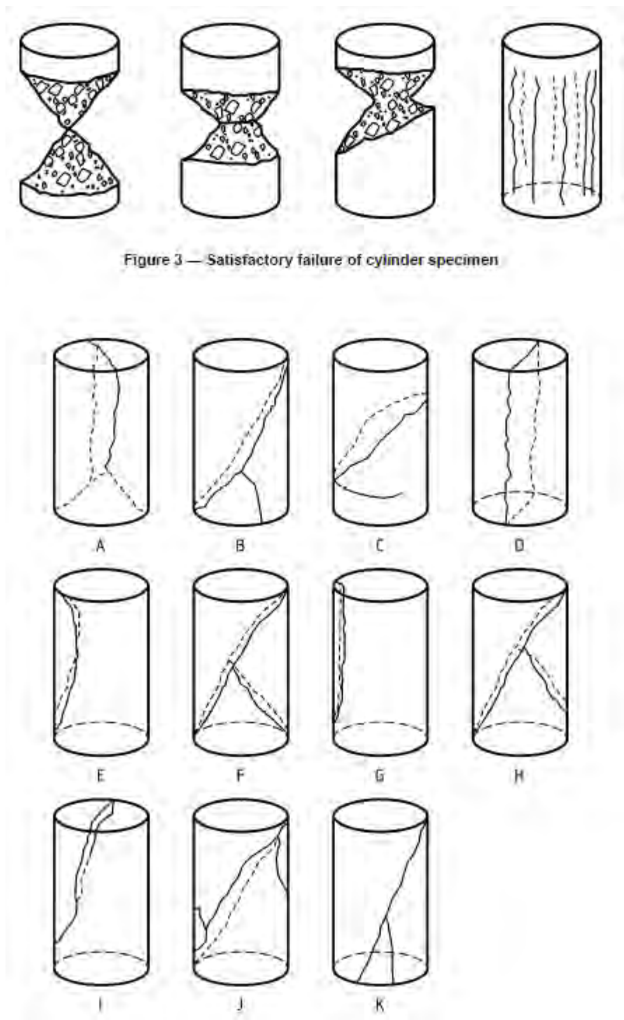


Figure D.1: The different types of failures for concrete specimen.

Specimen type	w/c	RCA	Date	Curing length [Days]	Comments	Slump [cm]	Air content [%]	Specimen	Diameter [mm]	Area [mm2	Height [mm	Weight [kg]	Force [kN]	Stress [MPa]	Mean stress [MPa]	Standard deviation	Displacement [mm]	Observation(s)	Extra remarks
Ref A	0.5	-	13-02-2017	28	Uneven in both ends	6	1.4	1	100.00	7850.00	200.00	3.762	278	35.41	33.65	5.26	1.6	3-4	
								2	100.00	7850.00	199.00	3.753	300	38.22			1.6	3-4	
								3	100.00	7850.00	200.00	3.722	194	24.71			2.2	D	
								4	99.00	7693.79	200.00	3.751	279	36.26			1.5	4	
			28-02-2017	7		4	1.5	1	101.00	8007.79	200.00	3.728	226	28.22	26.63	1.94		1	
								2	101.00	8007.79	199.00	3.706	231	28.85				3	
								3	101.00	8007.79	199.00	3.733	195	24.35				J	
								4	100.50	7928.70	198.00	3.681	199	25.10				4	
			11-04-2017	7		2	2.2	5	100.00	7850.00	200.00	3.746	238	30.32	29.30	1.42	1.8	I	
								6	99.00	7693.79	200.00	3.745	233	30.28			1.7	4	
								7	99.50	7771.70	200.00	3.744	231	29.72			1.5	E	
								8	100.00	7850.00	200.00	3.712	211	26.88			1.6	I	
			01-05-2017	28		6	1.5	5	100.00	7850.00	200.00	3.744	237	30.19	36.75	3.82	1.6	3	
								6	100.00	7850.00	199.50	3.740	301	38.34			1.6	I	
								7	100.00	7850.00	200.00	3.749	312	39.75			2.1	J	
								8	100.00	7850.00	200.00	3.754	304	38.73			1.7	4	
A2	0.5	8-16 mm, 50%	14-02-2017	28	Rubber in specimen	2	1.1	1	99.00	7693.79	200.00	3.685	229	29.76	21.73	5.17			
								2	100.00	7850.00	199.00	3.608	156	19.87					
								3	101.00	8007.79	199.00	3.552	124	15.48					
								4	100.00	7850.00	200.00	3.637	171	21.78					
			28-02-2017	7		2	2	1	101.00	8007.79	199.00	3.650	212	26.47	26.79	1.43		4	
								2	100.50	7928.70	199.50	3.630	198	24.97			3.1	I/J	
								3	101.00	8007.79	200.00	3.653	214	26.72				I/4	
								4	101.00	8007.79	198.50	3.639	232	28.97				4	
Ref B	0.6	-	13-02-2017	28		13	1.2	1	99.00	7693.79	200.00	3.717	237	30.80	29.99	0.88	1.6	4	
								2	100.00	7850.00	200.00	3.716	240	30.57			1.5	H	
								3	100.00	7850.00	199.00	3.702	236	30.06			1.6	4	
								4	100.00	7850.00	199.00	3.708	224	28.54			1.5	3-4	
			01-03-2017	7		3	1.7	1	105.00	8654.63	199.00	3.692	164	18.95	24.05	3.53	1.7	3	
								2	99.50	7771.70	199.50	3.712	181	23.29			2	I	
								3	100.00	7850.00	198.50	3.693	198	25.22			2.4	3	
								4	99.00	7693.79	200.00	3.667	221	28.72			2.4	4	
		-	11-04-2017	7		3	2.0	5	100.00	7850.00	200.00	3.733	165	21.02	21.09	1.67	1.3	E	
								6	98.50	7616.27	200.00	3.727	175	22.98			1.3	I	
								7	100.00	7850.00	200.00	3.732	145	18.47			1.3	E	
								8	100.00	7850.00	200.00	3.709	172	21.91			2.5	E	
B2	0.6	8-16 mm, 50%	15-02-2017	28		1	2.1	1	100.00	7850.00	197.00	3.595	164	20.89	18.98	1.64	4.1		
								2	100.00	7850.00	198.00	3.606	153	19.49			4.4		
								3	99.00	7693.79	200.00	3.612	126	16.38			2		
								4	99.50	7771.70	198.00	3.627	149	19.17			2.2		
			01-03-2017	7		2	1.8	1	100.00	7850.00	200.00	3.653	196	24.97	24.93	1.59	1.5	3	
								2	99.30	7740.48	199.50	3.629	198	25.58			1.5	4	
								3	100.30	7897.17	199.50	3.634	177	22.41			1.4	I	
								4	99.00	7693.79	200.00	3.631	206	26.77			1.5	4	
			07-05-2017	7	Used 2 times the normal volume to create the 7 day and 28 day specimens. In sample 7 there were glass in the bottom, and collections of sand in fracture	2	1.8	5	100.00	7850.00	200.00	3.656	201	25.61	21.72	3.44	1.4	3	
								6	100.00	7850.00	198.00	3.634	127	16.18			1	I	Fracture through aggregates
								7	100.00	7850.00	200.00	3.652	174	22.17			1.2	2	
								8	100.00	7850.00	200.00	3.667	180	22.93			1.3	2	
			07-05-2017	28				5	100.00	7850.00	200.00	3.639	216	27.52	26.72	2.39	1.5	2	
								6	100.00	7850.00	198.00	3.599	178	22.68			1.2	I	Fracture through aggregates
								7	100.00	7850.00	199.00	3.645	218	27.77			1.2	2	
								8	100.00	7850.00	199.00	3.660	227	28.92			1.4	3	
B4	0.6	8-16 mm, 50%	09-03-2017	7	Saturated, 3.01 kg water used	1	1.6	1	99.00	7693.79	199.00	3.629	143	18.59	24.85	4.83		3	
								2	100.00	7850.00	200.00	3.668	171	21.78				3	
								3	100.00	7850.00	199.00	3.655	226	28.79				4	
								4	99.50	7771.70	200.00	3.678	235	30.24			2.3	4	
			13-05-2017	7	Used 1.5 times the normal volume, and used it to 7 day and 28 day specimens. Saturated - used 4.735 kg water	3	1.9	5	100.00	7850.00	199.00	3.680	208	26.50	26.40	1.86	1.6	C	
								6	100.00	7850.00	200.00	3.694	184	23.44			1.3	2	
								7	100.00	7850.00	200.00	3.676	224	28.54			1.3	2	
								8	100.00	7850.00	200.00	3.660	213	27.13			1.2	2	
			13-05-2017	28				1	100.00	7850.00	199.00	3.682	277	35.29	33.63	2.72	1.3	2	
								2	100.00	7850.00	200.00	3.663	276	35.16			1.3	2	
								3	100.00	7850.00	199.50	3.650	227	28.92			1.1	I	Partial fracture through aggregates
								4	100.00	7850.00	199.00	3.670	276	35.16			1.3	3	
B6	0.6	8-16 mm, 100%	10-03-2017	7		1	1.7	1	100.00	7850.00	200.00	3.592	196	24.97	25.79	3.10	1.7	3	
								2	100.00	7850.00	201.00	3.616	229	29.17			1.8	I	
								3	100.00	7850.00	200.00	3.629	219	27.90			1.6	E	
								4	99.50	7771.70	200.00	3.619	164	21.10			1.8	I	
			09-05-2017	7		1	1.7	5	100.00	7850.00	199.00	3.604	155	19.75	23.12	3.03	1.5	3	Fracture through aggregates
								6	100.00	7850.00	199.00	3.584	177	22.55			1.5	3	Fracture through aggregates
								7	100.00	7850.00	200.00	3.615	220	28.03			1.5	4	
								8	100.00	7850.00	199.00	3.599	174	22.17			1.4	3	Fracture through aggregates
			09-05-2017	28				1	100.00	7850.00	199.00	3.601	181	23.06	26.69	2.76	1.4	I	Fracture through aggregates
								2	100.00	7850.00	199.00	3.601	241	30.70			1.4	B	
								3	100.00	7850.00	199.00	3.602	202	25.73			1.2	I	Partial fracture through aggregates
								4	100.00	7850.00	199.00	3.583	214	27.26			1.8	3	
B8	0.6	8-16 mm, 100%	14-03-2017	7	Saturated, 2.640 kg water used	1	1.2	1	100.00	7850.00	199.00	3.622	180	22.93	26.06	2.43	1.4	I	
								2	99.50	7771.70	200.00	3.638	226	29.08			1.6	3	
								3	99.50	7771.70	200.00	3.621	191	24.58			2.4	3	
								4	99.50	7771.70	199.00	3.653	215	27.66			1.4	I	
			13-05-2017	7	Used 1.5 times the normal volume, and used it to 7 day and 28 day specimens. Saturated - used 3.930 kg water	2	1.6	5	100.00	7850.00	200.00	3.608	217	27.64	23.79	3.01	1.4	3	
								6	100.00	7850.00	199.00	3.578	152	19.36			1.3	I	Fracture through aggregates
								7	100.00	7850.00	199.50	3.604	196	24.97			1.2	I	
								8	100.00	7850.00	200.00	3.580	182	23.18			1.4	2	
			13-05-2017	28				1	99.50	7771.70	199.00	3.609	218	28.05	25.48	3.43	1.2	2	
								2	100.00	7850.00	199.00	3.600	173	22.04			1.1	C	Fracture through aggregates
								3	100.00	7850.00	200.00	3.574	174	22.17			1.5	I	Fracture through aggregates
								4	100.00	7850.00	199.00	3.605	233	29.68			1.4	3	
B10	0.6	8-16 mm, 50%	13-03-2017	7	no washing or drying	4	1.4	1	100.00	7850.00	200.00	3.641	149	18.98	18.42	1.66	1.8	I	
								2	100.00	7850.00	200.00	3.630	152	19.36			3.4	3	
								3	99.00	7693.79	200.00	3.623	152	19.76			2.7	I/E	
								4	99.00	7693.79	199.00	3.613	120	15.60			3.8	I	
B12	0.6	8-16 mm, 100%	10-06-2017	7	Saturated, 3.015 water used + floating RCA removed	5	1.6	1	100.00	7850.00	199.50	3.597	157	20.00	18.69	2.00	1.4	E	Fracture through aggregates
								2	100.00	7850.00	200.00	3.585	141	17.96			1.3	2	Fracture through aggregates
								3	100.00	7850.00	199.00	3.578	124	15.80			2.9	2	Fracture through aggregates
								4	100.00	7850.00	199.50	3.598	165	21.02			1.2	3	

Specimen type	w/c	RCA	Date	Curing length [Days]	Comments	Slump [cm]	Air content [%]	Specimen	Diameter [mm]	Area [mm2	Height [mm]	Weight [kg]	Force [kN]	Stress [MPa]	Mean stress [MPa]	Standard deviation	Displacement [mm]	Observation(s)	Extra remarks	Drying shrinkage [microstrain]	Mean [microstrain]
Ref A	0.5	-	13-02-2017	28	Uneven in both ends	6	1.4	1	100.00	7850.00	200.00	3.762	278	35.41	35.20	4.85	1.6	3-4		0.00	-1250.00
								2	100.00	7850.00	199.00	3.753	300	38.22			1.6	3-4		-5000.00	
								3	100.00	7850.00	200.00	3.722	194	24.71			2.2	D		0.00	
								4	99.00	7693.79	200.00	3.751	279	36.26			1.5	4		0.00	
			01-05-2017	28		6	1.5	5	100.00	7850.00	200.00	3.744	237	30.19			1.6	3		0.00	-625.00
								6	100.00	7850.00	199.50	3.740	301	38.34			1.6	I		-2500.00	
								7	100.00	7850.00	200.00	3.749	312	39.75			2.1	J		0.00	
								8	100.00	7850.00	200.00	3.754	304	38.73			1.7	4		0.00	
			28-02-2017	7		4	1.5	1	101.00	8007.79	200.00	3.728	226	28.22	27.97	2.16		1		0.00	-5000.00
								2	101.00	8007.79	199.00	3.706	231	28.85				3		-5000.00	
								3	101.00	8007.79	199.00	3.733	195	24.35				J		-5000.00	
								4	100.50	7928.70	198.00	3.681	199	25.10				4		-10000.00	
			11-04-2017	7		2	2.2	5	100.00	7850.00	200.00	3.746	238	30.32			1.8	I		0.00	0.00
								6	99.00	7693.79	200.00	3.745	233	30.28			1.7	4		0.00	
								7	99.50	7771.70	200.00	3.744	231	29.72			1.5	E		0.00	
								8	100.00	7850.00	200.00	3.712	211	26.88			1.6	I		0.00	
A2	0.5	8-16 mm, 50%	14-02-2017	28	Rubber in specimen	2	1.1	1	99.00	7693.79	200.00	3.685	229	29.76	21.73	5.17				0.00	-2500.00
								2	100.00	7850.00	199.00	3.608	156	19.87						-5000.00	
								3	101.00	8007.79	199.00	3.552	124	15.48						-5000.00	
								4	100.00	7850.00	200.00	3.637	171	21.78						0.00	
			28-02-2017	7		2	2	1	101.00	8007.79	199.00	3.650	212	26.47	26.79	1.43	3.1	4		-5000.00	-3750.00
								2	100.50	7928.70	199.50	3.630	198	24.97				I/J		-2500.00	
								3	101.00	8007.79	200.00	3.653	214	26.72				I/4		0.00	
								4	101.00	8007.79	198.50	3.639	232	28.97				4		-7500.00	
Ref B	0.6	-	13-02-2017	28		13	1.2	1	99.00	7693.79	200.00	3.717	237	30.80	29.99	0.88	1.6	4		0.00	-2500.00
								2	100.00	7850.00	200.00	3.716	240	30.57			1.5	H		0.00	
								3	100.00	7850.00	199.00	3.702	236	30.06			1.6	4		-5000.00	
								4	100.00	7850.00	199.00	3.708	224	28.54			1.5	3-4		-5000.00	
			01-03-2017	7		3	1.7	1	105.00	8654.63	199.00	3.692	164	18.95	22.57	3.13	1.7	3		-5000.00	-3750.00
								2	99.50	7771.70	199.50	3.712	181	23.29			2	I		-2500.00	
								3	100.00	7850.00	198.50	3.693	198	25.22			2.4	3		-7500.00	
								4	99.00	7693.79	200.00	3.667	221	28.72			2.4	4		0.00	
		-	11-04-2017	7		3	2.0	5	100.00	7850.00	200.00	3.733	165	21.02			1.3	E		0.00	0.00
								6	98.50	7616.27	200.00	3.727	175	22.98			1.3	I		0.00	
								7	100.00	7850.00	200.00	3.732	145	18.47			1.3	E		0.00	
								8	100.00	7850.00	200.00	3.709	172	21.91			2.5	E		0.00	
B2	0.6	8-16 mm, 50%	15-02-2017	28		1	2.1	1	100.00	7850.00	197.00	3.595	164	20.89	22.85	4.38	4.1			-15000.00	-8750.00
								2	100.00	7850.00	198.00	3.606	153	19.49			4.4			-10000.00	
								3	99.00	7693.79	200.00	3.612	126	16.38			2			0.00	
								4	99.50	7771.70	198.00	3.627	149	19.17			2.2			-10000.00	
			07-05-2017	28	Used 2 times the normal volume to create the 7 day and 28 day specimens.	2	1.8	5	100.00	7850.00	200.00	3.639	216	27.52			1.5	2		0.00	-5000.00
								6	100.00	7850.00	198.00	3.599	178	22.68			1.2	I	Fracture through aggregates	-10000.00	
								7	100.00	7850.00	199.00	3.645	218	27.77			1.2	2		-5000.00	
								8	100.00	7850.00	199.00	3.660	227	28.92			1.4	3		-5000.00	
			01-03-2017	7		2	1.8	1	100.00	7850.00	200.00	3.653	196	24.97	23.33	3.13	1.5	3		0.00	-1250.00
								2	99.30	7740.48	199.50	3.629	198	25.58			1.5	4		-2500.00	
								3	100.30	7897.17	199.50	3.634	177	22.41			1.4	I		-2500.00	
								4	99.00	7693.79	200.00	3.631	206	26.77			1.5	4		0.00	
			07-05-2017	7	Used 2 times the normal volume to create the 7 day and 28 day specimens. In sample 7 there were glass in the bottom, and collections of sand in fracture	2	1.8	5	100.00	7850.00	200.00	3.656	201	25.61			1.4	3		0.00	-2500.00
								6	100.00	7850.00	198.00	3.634	127	16.18			1	I	Fracture through aggregates	-10000.00	
								7	100.00	7850.00	200.00	3.652	174	22.17			1.2	2		0.00	
								8	100.00	7850.00	200.00	3.667	180	22.93			1.3	2		0.00	
B4	0.6	8-16 mm, 50%	09-03-2017	7	Saturated, 3.01 kg water used	1	1.6	1	99.00	7693.79	199.00	3.629	143	18.59	25.63	3.74		3		-5000.00	-2500.00
								2	100.00	7850.00	200.00	3.668	171	21.78				3		0.00	
								3	100.00	7850.00	199.00	3.655	226	28.79				4		-5000.00	
								4	99.50	7771.70	200.00	3.678	235	30.24			2.3	4		0.00	
			13-05-2017	7	Used 1.5 times the normal volume, and used it to 7 day and 28 day specimens. Saturated - used 4.735 kg water	3	1.9	5	100.00	7850.00	199.00	3.680	208	26.50			1.6	C		-5000.00	-1250.00
								6	100.00	7850.00	200.00	3.694	184	23.44			1.3	2		0.00	
								7	100.00	7850.00	200.00	3.676	224	28.54			1.3	2		0.00	
								8	100.00	7850.00	200.00	3.660	213	27.13			1.2	2		0.00	
			13-05-2017	28				1	100.00	7850.00	199.00	3.682	277	35.29	33.63	2.72	1.3	2		-5000.00	-3125.00
								2	100.00	7850.00	200.00	3.663	276	35.16			1.3	2		0.00	
								3	100.00	7850.00	199.50	3.650	227	28.92			1.1	I	Partial fracture through aggregates	-2500.00	
								4	100.00	7850.00	199.00	3.670	276	35.16			1.3	3		-5000.00	
B6	0.6	8-16 mm, 100%	10-03-2017	7		1	1.7	1	100.00	7850.00	200.00	3.592	196	24.97	24.30	3.34	1.7	3		0.00	1250.00
								2	100.00	7850.00	201.00	3.616	229	29.17			1.8	I		5000.00	
								3	100.00	7850.00	200.00	3.629	219	27.90			1.6	E		0.00	
								4	99.50	7771.70	200.00	3.619	164	21.10			1.8	I		0.00	
			09-05-2017	7		1	1.7	5	100.00	7850.00	199.00	3.604	155	19.75			1.5	3	Fracture through aggregates	-5000.00	-3750.00
								6	100.00	7850.00	199.00	3.584	177	22.55			1.5	3	Fracture through aggregates	-5000.00	
								7	100.00	7850.00	200.00	3.615	220	28.03			1.5	4		0.00	
								8	100.00	7850.00	199.00	3.599	174	22.17			1.4	3	Fracture through aggregates	-5000.00	
			09-05-2017	28				1	100.00	7850.00	199.00	3.601	181	23.06	26.69	2.76	1.4	I	Fracture through aggregates	-5000.00	-5000.00
								2	100.00	7850.00	199.00	3.601	241	30.70			1.4	B		-5000.00	
								3	100.00	7850.00	199.00	3.602	202	25.73			1.2	I	Partial fracture through aggregates	-5000.00	
								4	100.00	7850.00	199.00	3.583	214	27.26			1.8	3		-5000.00	
B8	0.6	8-16 mm, 100%	14-03-2017	7	Saturated, 2.640 kg water used	1	1.2	1	100.00	7850.00	199.00	3.622	180	22.93	24.93	2.96	1.4	I		-5000.00	-2500.00
								2	99.50	7771.70	200.00	3.638	226	29.08			1.6	3		0.00	
								3	99.50	7771.70	200.00	3.621	191	24.58			2.4	3		0.00	
								4	99.50	7771.70	199.00	3.653	215	27.66			1.4	I		-5000.00	
			13-05-2017	7	Used 1.5 times the normal volume, and used it to 7 day and 28 day specimens. Saturated - used 3.930 kg water	2	1.6	5	100.00	7850.00	200.00	3.608	217	27.64			1.4	3		0.00	-1875.00
								6	100.00	7850.00	199.00	3.578	152	19.36			1.3	I	Fracture through aggregates	-5000.00	
								7	100.00	7850.00	199.50	3.604	196	24.97			1.2	I		-2500.00	
								8	100.00	7850.00	200.00	3.580	182	23.18			1.4	2		0.00	
			13-05-2017	28				1	99.50	7771.70	199.00	3.609	218	28.05	25.48	3.43	1.2	2		-5000.00	-3750.00
								2	100.00	7850.00	199.00	3.600	173	22.04			1.1	C	Fracture through aggregates	-5000.00	
								3	100.00	7850.00	200.00	3.574	174	22.17			1.5	I	Fracture through aggregates	0.00	
								4	100.00	7850.00	199.00	3.605	233	29.68			1.4	3		-5000.00	
B10	0.6	8-16 mm, 50%	13-03-2017	7	no washing or drying	4	1.4	1	100.00	7850.00	200.00	3.641	149	18.98	18.42	1.66	1.8	I		0.00	-1250.00
								2	100.00	7850.00	200.00	3.630	152	19.36			3.4	3		0.00	
								3	99.00	7693.79	200.00	3.623	152	19.76			2.7	I/E		0.00	
								4	99.00	7693.79	199.00	3.613	120	15.60			3.8	I		-5000.00	
B12	0.6	8-16 mm, 100%	10-06-2017	7	Saturated, 3.015 water used + floating RCA removed	5	1.6	1	100.00	7850.00	199.50	3.597	157	20.00	18.69	2.00	1.4	E	Fracture through aggregates	-2500.00	-2500.00
								2	100.00	7850.00	200.00	3.585	141	17.96			1.3	2	Fracture through aggregates	0.00	
								3	100.00	7850.00	199.00	3.578	124	15.80			2.9	2	Fracture through aggregates	-5000.00	
								4	100.00	7850.00	199.50	3.598	165	21.02			1.2	3		-2500.00	

Appendix E

Posters

Properties of recycled aggregate concrete

Kristian Nyvang Jensen

Introduction

In this project the properties of recycled aggregate concrete with recycled concrete aggregates in the fraction 8-16 mm have been investigated. These recycled concrete aggregates will be refered to as RCA while a cast concrete sample with recycled concrete aggregate is called recycled aggregate concrete (RAC).

The properties investigated is the porosity and the cement content of the RCA while the compressive strength of the RAC have been investigated.

The purpose of these investigations is to try and make the huge worldwide production of concrete more environmentally friendly by reusing crushed concrete as a replacement for some or all of the aggregates, and thereby reducing the production of these aggregates.

The recycled aggregate concrete samples after curing and before testing.

A recycled aggregate concrete sample after it has been tested.

Method

The recycled concrete aggregates were acquired at a construction site in Rødovre. The acquired recycled concrete were divided into two batches by sieving it through 4, 8 and 16 mm sieves. Hereafter the recycled concrete were washed through the sieves one more time to get rid of the small particles. The washed recycled concrete were then dried at 50ºC in an oven. After the drying, the recycled concrete aggregates were ready to be used in new concrete.

The recycled concrete aggregates before drying The recycled concrete aggregates after drying.

Below is a table where the different mix designs, that has been cast, can be seen. The reference mixtures have been made with the mix design designs used in the article ”A novel mix design methodology for Recycled Aggregate Concrete” by Marco Pepe et al.

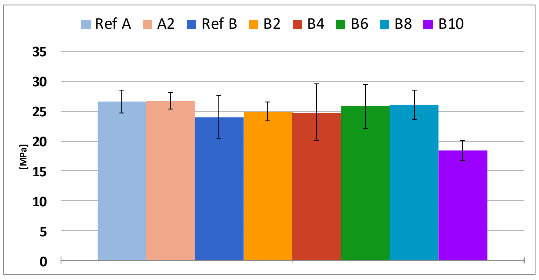
The different treatments listed are standard, saturated and no treatment. The standard treatment is the on listed above, whereas the saturated treatment is the standard treatment followed by saturating the recycled concrete aggregates 24 hours in water. The no treatment is done by only sieving the recycled concrete aggregates.

Name	v/c	Percentage 8-16 mm aggregates replaced with RCA	Treatment
Reference A	0,5	-	-
A2	0,5	50%	Standard
Reference B	0,6	-	-
B2	0,6	50%	Standard
B4	0,6	50%	Saturated
B6	0,6	100%	Standard
B8	0,6	100%	Saturated
B10	0,6	50%	No treatment

Some of the samples have cured for 7 days while some have cured for 28 days. Since all of the samples have cured for 7 days, these will be reviewed under the Result section. On the picture below some of the RAC samples can be seen before and after the compressive strength test.

Results

The RAC samples' compressive strength were tested, and is was found that the samples with a v/c relation of 0.5 had the highest compressive strength, which also was expected, since lower v/c in generel leads to a higher strength. Furthermore, it can be seen that the A2-sample had a slightly higher compressive strength than the corresponding reference sample, Reference A. The samples with a v/c relation of 0.6 followed the same pattern, were they in generel where slightly stronger than the corresponding Reference B. The only exception is B10, which were the sample with no treatment.



Furtermore, there have been made an experiment to calculate the porosity of the recycled concrete aggregates. The porosity was found to be 0.256.

Conclusion

In generel the compressive strength of the RAC samples were slightly higher than their corresponding references except for the sample that wasn't issued to any treatment. This means that there definitely is a case to be made about using treated recycled concrete aggregates as a replacement for some or all of the aggregates. The challenge with these RAC samples are that they are not as workable as the references since they tend to be a lot more dry and have a lower slump.

Another thing that has to be noted is the standard deviation which tends to be too high for the samples to be reliable. This has to be further examined in the last part of the project.

Figure E.1: Poster for midway presentation.

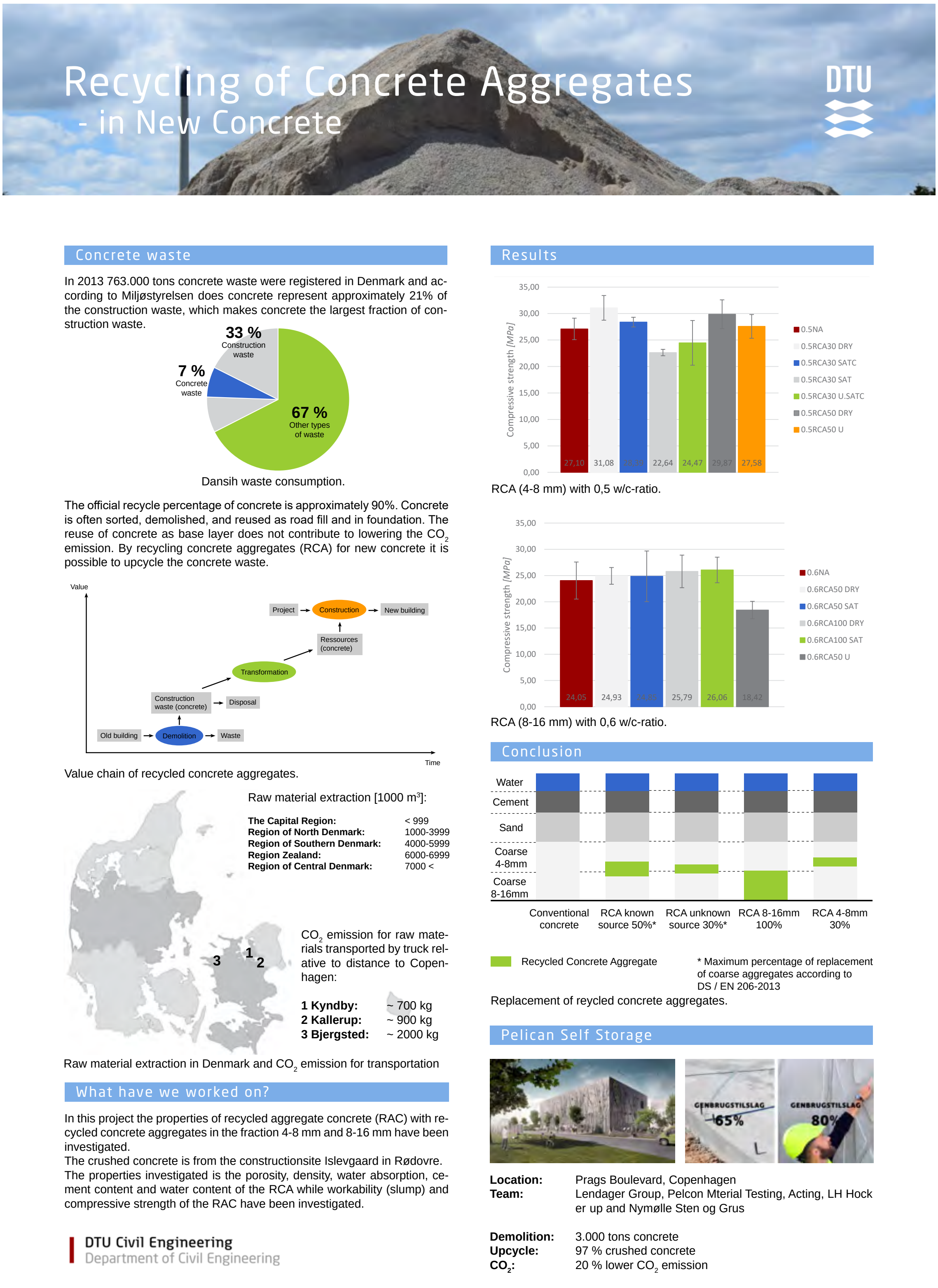


Figure E.2: Poster for Grøn Dyst.

Appendix F

Risk Assessment

Risikovurdering

Beskrivelse af det arbejdsområde risikovurderingen dækker – fx feltarbejde, støbning af beton, øvelseskursus nr. xxxx, navn på proces, kursus, etc.

THESIS - RECYCLE CONCRETE

Dato: 2/2-17

Udfærdiget af:

Navn/nr: LOUISE GREEN PEDERSEN, s112895

Navn/nr: Kristian Nyvang Jensen, s113804

Godkendt af ansvarlig vejleder (dato/underskrift): 07 02 17

BESKRIVELSE AF ARBEJDSPROCESSEN

Beskrivelsen kan evt. laves som et flowdiagram over processen – altså opdeling i logiske delprocesser.

VÆSENTLIGE FARER FRA ARBEJDSPROCESSEN

fx laser, vakuum, støvpåvirkning, udstyr

støvpåvirkning

arbejde med cement

trykstyrke test

RISIKO FOR PÅVIRKNING

Vurdér reel risiko ifht. arbejdsproces. Overvej hvor i arbejdsprocessen den pågældende risiko er til stede – er det under hele arbejdsprocessen eller kun i en enkelt delproces.

støvpåvirkning og arbejde med cement er tilstede under proces 1 og 2 (se diagram)

trykstyrke test er under proces 3.

NØDVENDIGE SIKKERHEDSFORANSTALTNINGER	
Ventilation	Stinkskab: - Punktsug: over materialer ved blanding Andet: Er det angivne nødvendigt i hele arbejdsprocessen, eller kun i dele, beskriv: ved blanding.
Handsker	Hvilken type: ja Er de angivne handsker nødvendige i hele arbejdsprocessen, eller kun i dele, beskriv: nødvendige i støbeproces.
Andre personlige værnemidler	Kittel/beskyttende tøj: ja Sikkerhedsbriller: ja Åndedrætsværn (angiv filter): ja Særligt fodtøj (angiv hvilket): ja Overlevelsesdragt: nej Vaccination: nej Andet udstyr: Er det angivne nødvendigt i hele arbejdsprocessen, eller kun i dele, beskriv: hele processen.
Sikkerhedsforanstaltninger i øvrigt	Særlig varmekilde v. brandfare: nej Fastsurring af udstyr under transport: nej Gravekasse ved gravearbejde: nej Andet:
Særligt nødhjælpsudstyr:	Særligt brandslukningsmiddel: nej Nødtelefon(satellit-telefon på øde sted): Øjenskylleflaske: ja Andet:
Særlig uddannelse eller instruktion:	Lovpligtig uddannelse, hvilken: nej Instruktion i brug af særligt farligt udstyr, hvilket: Bygs sikkerheds-video Andet:

Skemaet udfyldes ud fra kendskab, dels til arbejdsprocessen eller arbejdsopgaven Side 3 af 4

HVAD SKAL GØRES VED UHELD?

Her kan beskrives handling ved ***relevante*** *uheld og procedurer for information ved uheld osv.*

cement i øjne skylles

AFFALD

Bortskaffelse af affald eller lignende

Vådt beton skal i tilhørende containe, ligeledes med hærdet prøve legemer efter forsøg

GRAVIDE OG AMMENDE

Er arbejdsprocessen/området sikkert for gravide og ammende??

Ja - begrundelse ikke relevant.

Nej - begrundelse:

FORSLAG TIL FORBEDRINGER AF SIKKERHEDEN:

Dette punkt er tænkt som input til en samlet APV for instituttet/sektionen.

Godkendelse:

1. Vejleder skal godkende og underskrive dokumentet
2. Dokumentet skal laves til pdf
3. Dokumentet skal sendes til: **risk@byg.dtu.dk**
4. Dokumentet skal medbringes i laboratorie/værksted/forsøgshal/felten

Appendix G

The source of the RCA

259

Hr. rådgivende civilingeniør P. E. Malmstrøm,
Jagtvej 223,
Ø.

PR/GS B. 14.234

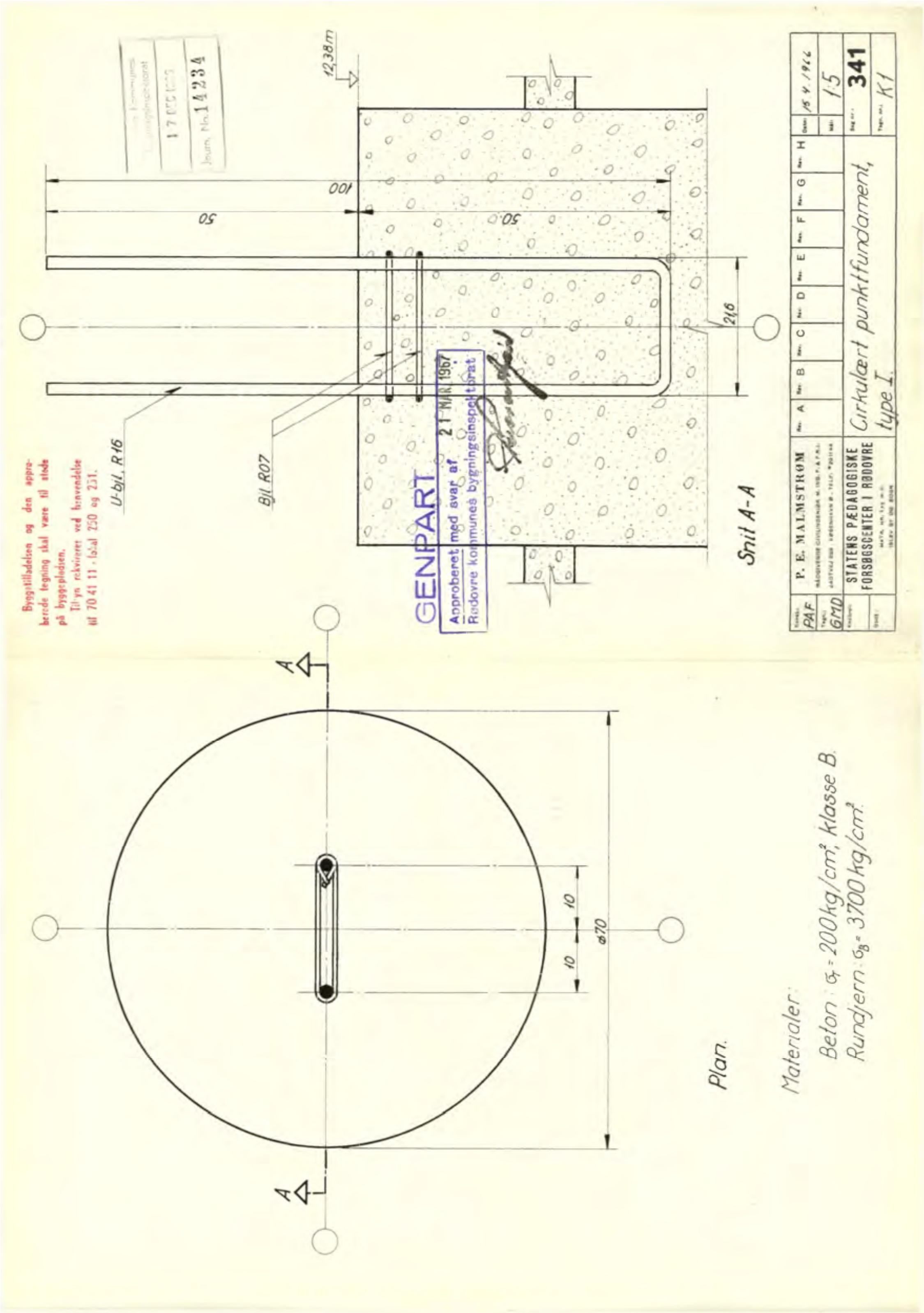
21 MAR. 1967

Under henvisning til Deres tegninger med tilhørende andragende om tilladelse til at udføre bærende konstruktioner ved opførelse af en skolebygning, 1.etape af Statens pædagogiske forsøgscenter på matr.nr. 1^{aq} af Islev, Islevgård Alle 5, meddeles herved approbation på betingelse af:

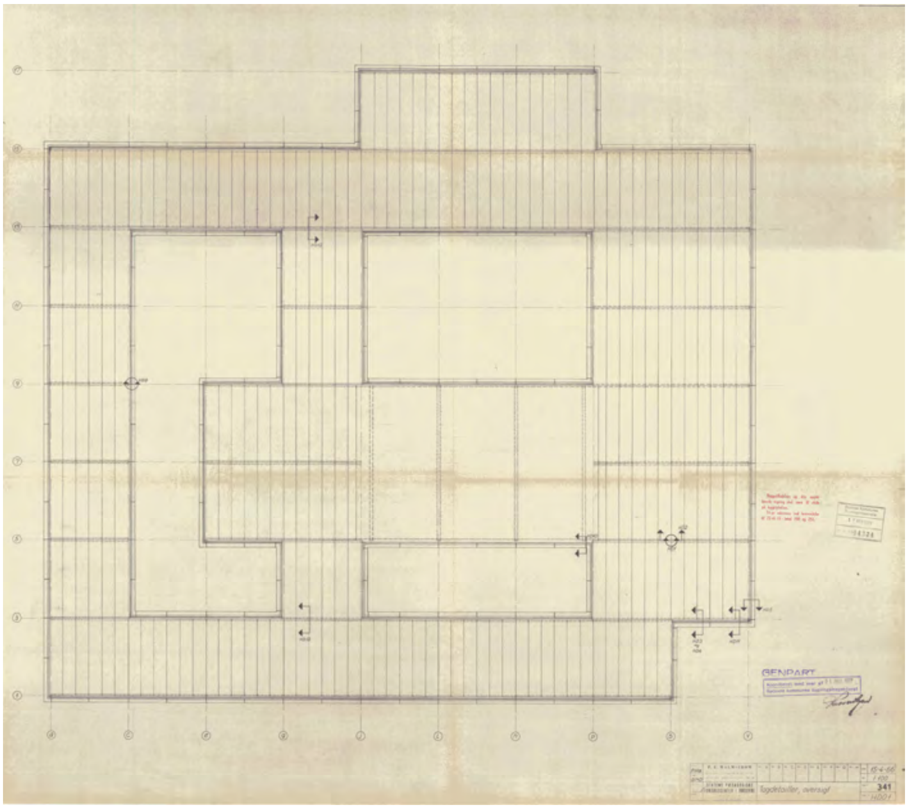
at alt jern synes og godkendes herfra, inden det inddækkes samt,

at bygningsreglementets bestemmelser i øvrigt nøje overholdes.

Børge T. Lorentzen



Byggetilladelsen og den approberede tegning skal være til stede på byggepladsen.
Tilsyn rekvireres ved henvendelse til 70 41 11 - lokal 250 og 231.
Journ. Nr. 14234
12,38 m
100
50
50
U-bjl. R16
Bjl R07
246
GENPART
Approberet med svar af 21 MAR 1967
Rødovre kommunes bygningsinspektorat
Snit A-A
A
A
10
10
ø70
Plan.
Materialer:
Beton: σ_r = 200 kg/cm², klasse B.
Rundjern: σ_B = 3700 kg/cm².
P. E. MALMSTRØM
STATENS PÆDAGOGISKE FORSØGSCENTER I RØDOVRE
PAF
GMD
Cirkulært punktfundament, type I.
15.4.1966
1:5
341
K1


GENPART
15-6-66
1:100
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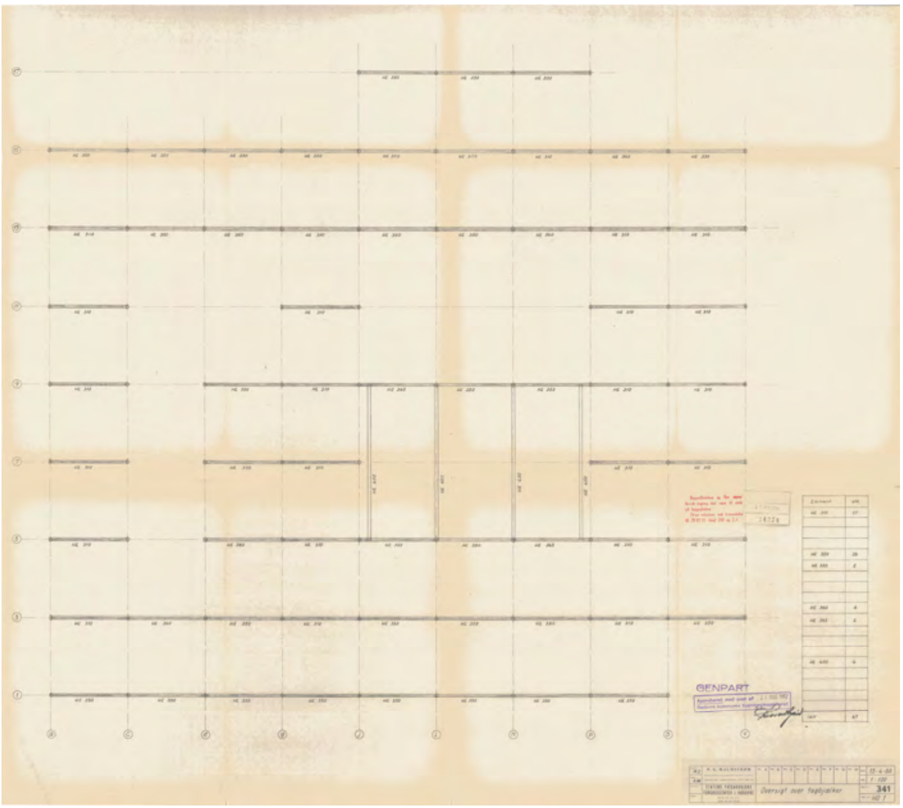
H001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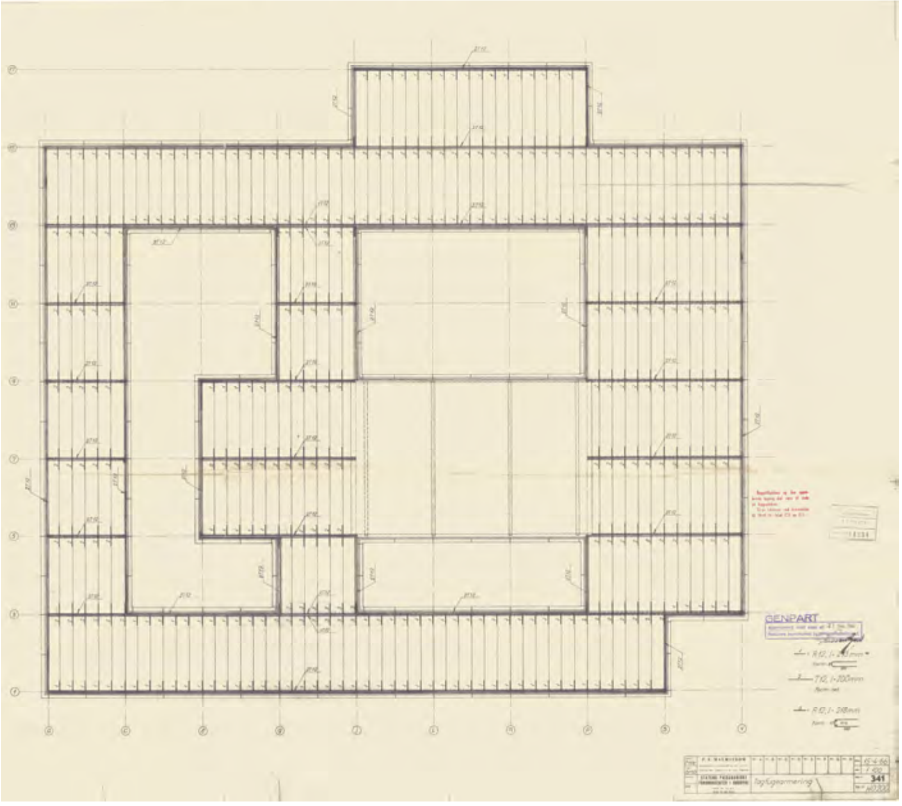
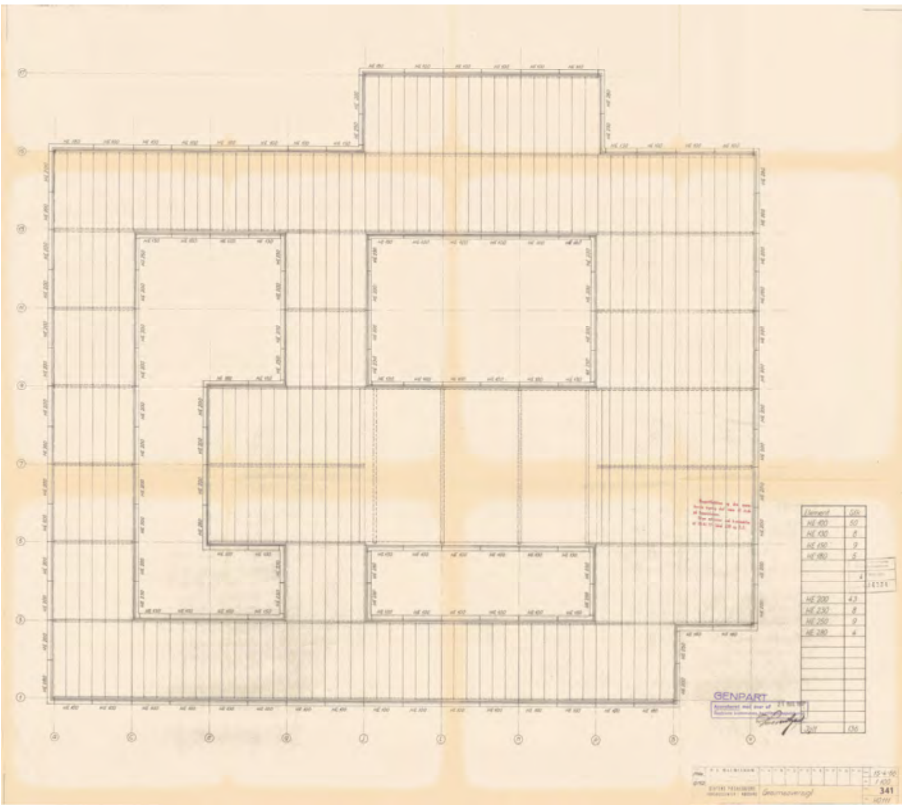
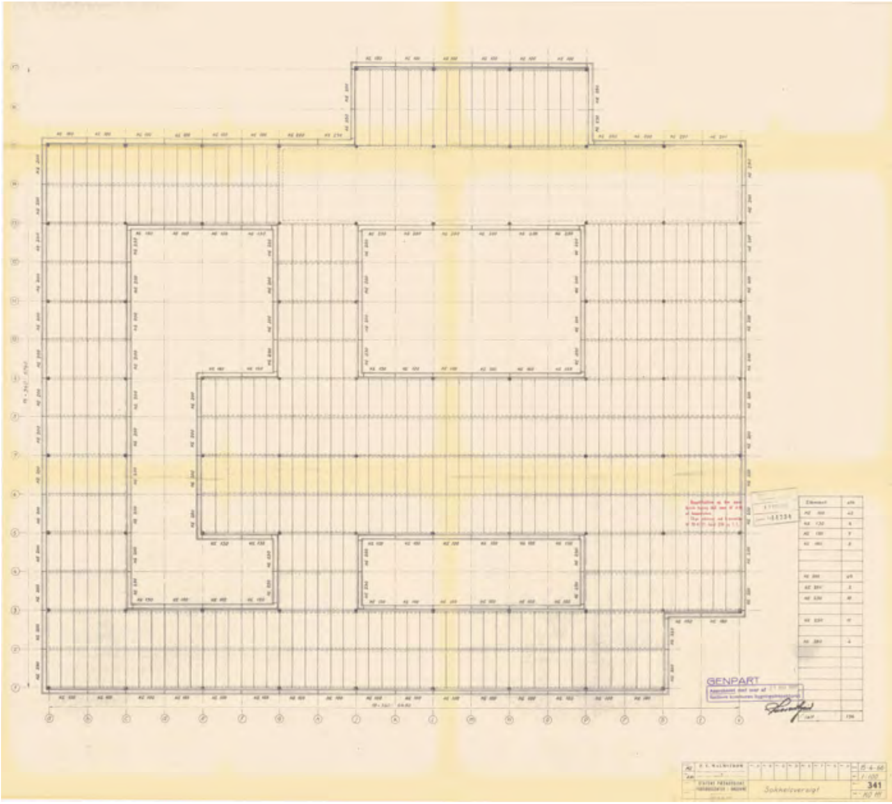

GENPART
T12, l=200mm
Tagfugearmering
341
15-4-66


GENPART
Element
HE 100 50
HE 130 8
HE 150 9
HE 180 5
HE 200 43
HE 230 8
HE 250 9
HE 280 4
341
1:100


GENPART
Sokkeloversigt
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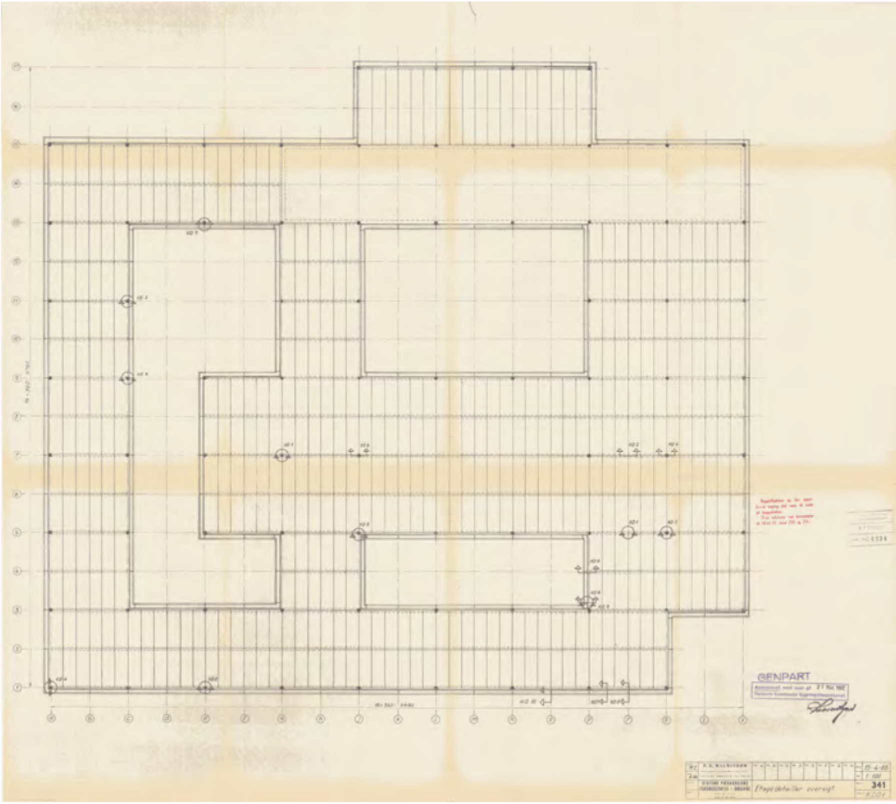
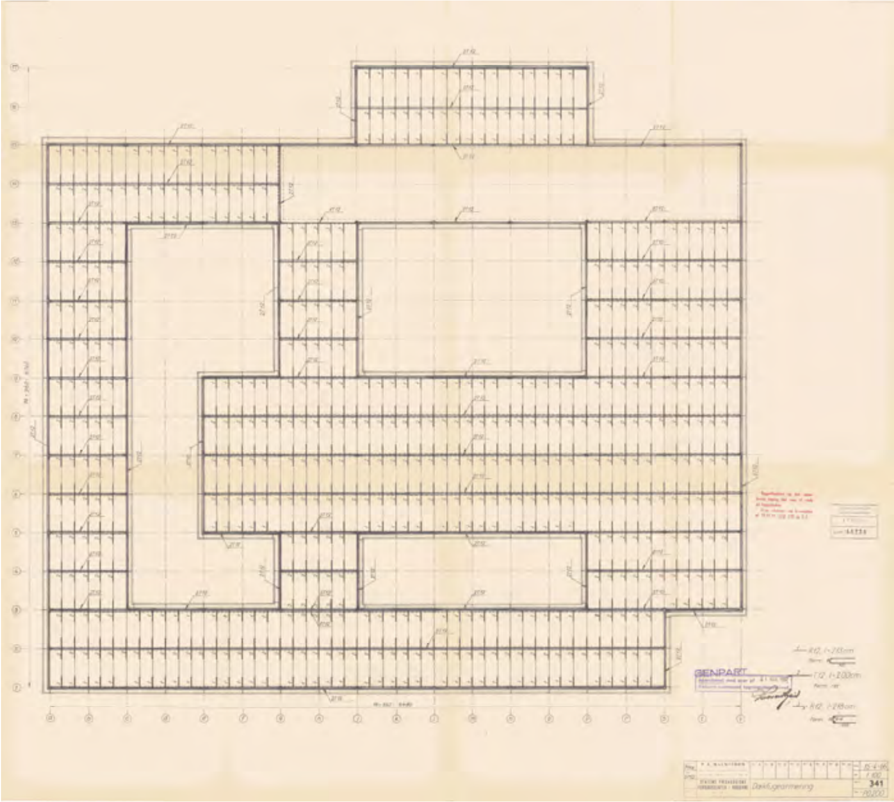
1:100


GENPART
15-4-66
1:100
341
Etagedetailler oversigt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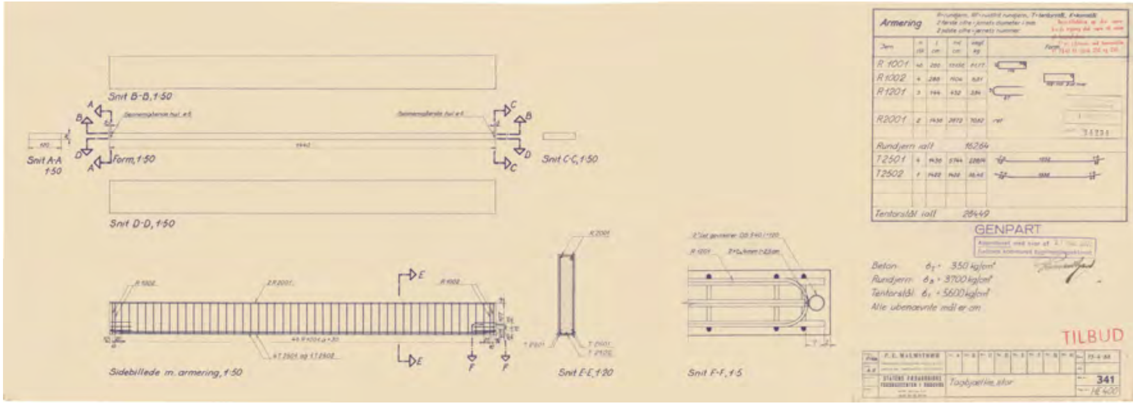
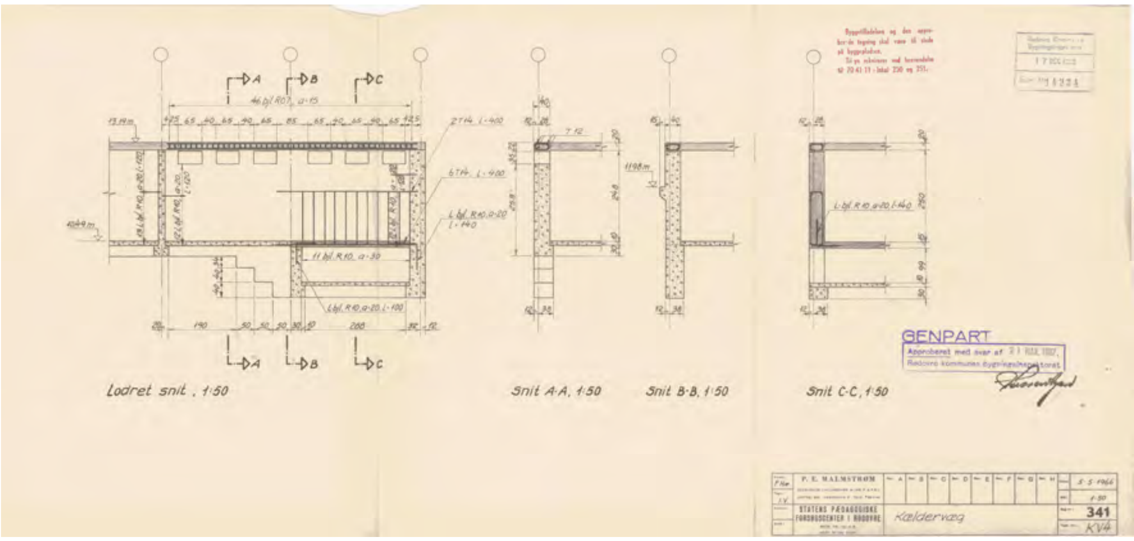
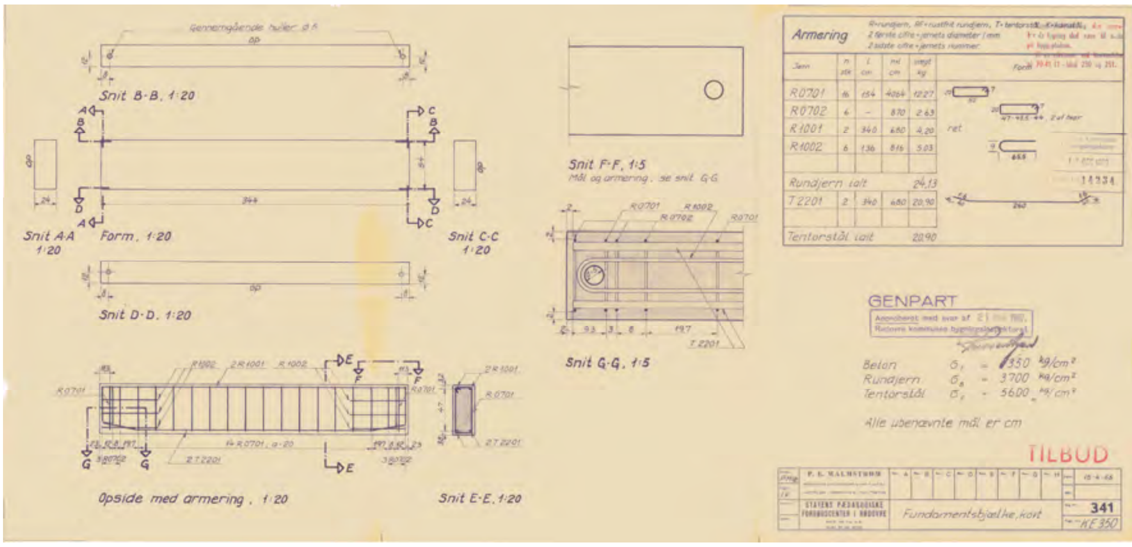

Snit B-B, 1:50
Snit A-A 1:50
Form, 1:50
Snit C-C, 1:50
Snit D-D, 1:50
Sidebillede m. armering, 1:50
Snit E-E, 1:20
Snit F-F, 1:5
Armering
Rundjern ialt 16264
Tentorstål ialt 28449
GENPART
Beton
Rundjern
Tentorstål
Alle ubenævnte mål er cm
TILBUD
Tagbjælke, stor
341
HE 400


Lodret snit , 1:50
Snit A-A, 1:50
Snit B-B, 1:50
Snit C-C, 1:50
GENPART
P. E. MALMSTRØM
STATENS PÆDAGOGISKE FORSØGSCENTER I RØDOVRE
Kælderværg
5-5-1966
1:50
341
KV4


Gennemgående huller Ø 5
Snit B-B. 1:20
Snit A-A 1:20
Form. 1:20
Snit C-C 1:20
Snit D-D. 1:20
Opside med armering. 1:20
Snit E-E. 1:20
Snit F-F. 1:5
Mål og armering, se snit G-G
Snit G-G. 1:5
Armering
R=rundjern, RF=rustfrit rundjern, T=tentorstål
2 første cifre = jernets diameter i mm
2 sidste cifre = jernets nummer
Jern
n stk
l cm
nl cm
vægt kg
Form
R0701 16 154 4064 12.27
R0702 6 – 870 2.63
R1001 2 340 680 4.20 ret
R1002 6 136 816 5.03
Rundjern ialt 24.13
T2201 2 340 680 20.90
Tentorstål ialt 20.90
GENPART
Beton σ = 350 kg/cm²
Rundjern σ = 3700 kg/cm²
Tentorstål σ = 5600 kg/cm²
Alle ubenævnte mål er cm
TILBUD
P. E. MALMSTRØM
STATENS PÆDAGOGISKE FORSØGSCENTER I RØDOVRE
Fundamentsbjælke, kort
15-4-68
341
KE 350