Recycle of Concrete Aggregates

Processing Procesures of Recycled Aggregates

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Preface

This thesis is made as the completion of the master education in Architectural Engineering at the department of Civil Engineering at the Technical University of Denmark. The project counts for 30 ECTS points and it has been made in the period from January 23th to June 23th 2017.

The thesis deals with recycling of concrete aggregates in fraction 4-8 mm as a replacement of natural aggregates in new concrete. The focus of the investigation is on the processing procedure of the aggregates. The thesis is written parallel with the thesis of Kristian Nyvang Jensen, a lot of the experiments have been made together with him and Mads Emil Herløv, and the results have been discussed between us.
In the execution of the project a special thanks goes to Prof. Lisbeth M. Ottosen, for providing valuable advise and great support throughout the whole period. In addition a special thanks goes to Assoc. Prof. Gunvor M. Kirkelund as co-supervisor for the extra support especially towards the end of project.

All tests have been conducted at BYG DTU. A thanks to laboratorian technicians Ebba C. Schnell and Malene Grønvold and assistant engineer John C. Troelsen for helping with the experiments regarding investigation of the materials.

Kongens Lyngby, July 5, 2017

Louise Green Pedersen, s112895

Abstract

Recycled concrete aggregates (RCA) can be used in new concrete as a partial replacement of the natural aggregates (NA).

An expanding building industry all over the world combined with an increasing interest and need for green solutions, led to the investigation of using RCA in new concrete. The use of RCA has been used successfully in two projects in Denmark. Other countries are further ahead with RCA in new concrete e.g. Holland and Japan. This thesis will investigate if RCA, in the fraction 4-8 mm of an unknown source, can be used in new concrete with success. This thesis investigates the practical possibilities and processes of replacing a partial amount of the NA with the RCA (4-8 mm). In this project the mix designs of the concrete was investigated without admixtures or increasing the amount of cement.

The RCA was obtained from the concrete waste of a construction site in Rødovre. Characteristics of the RCA show that the aggregates have a lower density than NA and higher water absorption. The RCA's high water absorption is encountered by saturating the aggregates, which ensures the amount of free water for the water/cement-ratio (w/c).
The proposed mix design methodology demonstrates that the deviation of the compressive strength and the workability of RAC can be met by RCA being saturated, in this thesis by pre-soaking.

Contents

CHAPTER 1

Introduction

Demolition of old structures and construction of new ones are frequent phenomena due to change of purpose, rearrangement of a city, expansion of traffic directions and structural deterioration. Each year about 900 million tons of construction and demolition waste are generated in the European Union, this represents 31% of the total waste generation. In Denmark the concrete waste produced is approximately 2 million tons per year, of which approximately half is registered. 95% of the concrete waste is derived from the demolition to fill, mainly road-fills or base layer (Miljøstyrelsen 2015). Figure 1.1 shows the possibilities of reuse and recycling of concrete.

Material and use	Example
Reuse of concrete construction and buildings.	Remodeling of old silos, factory buildings and recycling of concrete elements.
Recycled concrete aggregates in new concrete.	Concrete in exposure class X0, eg. foundations, floor slabs, dredged material, curbs.
Recycle debris and tiles.	Coastal protection and tiling.
Recycling of crushed concrete in surface coatings.	Eg. in cycle paths, temporary roadside roads. (Eg. mixed with crushed bricks and asphalt in coatings).
Fill	Eg. construction sites and road-fill.

Figure 1.1: Recycle of concrete.

Remodeling of old concrete constructions have the highest impact on lowering the CO_2 emission for a buildings at end of life. However, recycling of concrete as a base layer and road-fills does not help to reduce CO_2 emissions, as the need for extraction of natural resources for concrete production remains the same. RCA in new concrete could therefore up-cycle the concrete waste compared to the use for road-fill, this is illustrated in Figure 1.2.

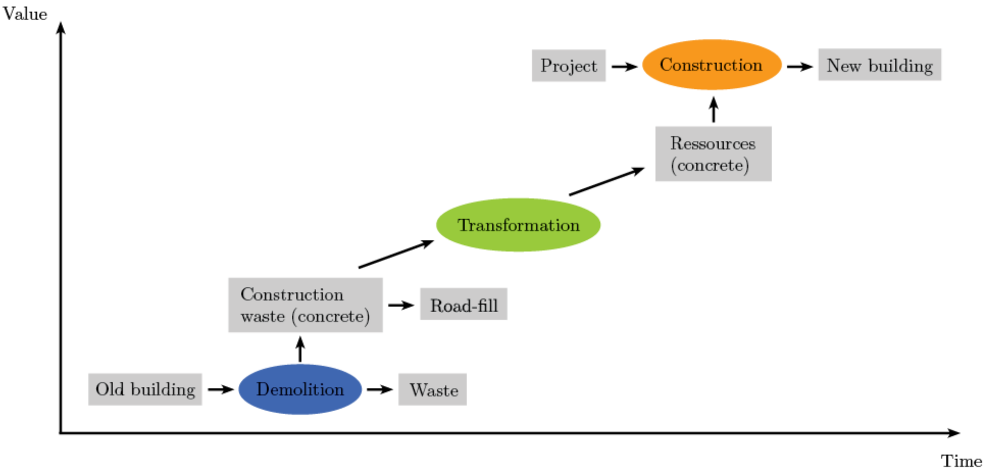


Figure 1.2: Value chain of RCA.

In Denmark there are produced about 9 million tons of concrete annually. All though raw materials for concrete (in principle) are available in most of the world, which means concrete could be produced locally by local materials, it is not always the case. Both technical requirements for the raw materials and the need to use land areas for other purposes put limits on the amounts that can be recovered into concrete and may also necessitate transporting materials long-range.

Denmark have access to good raw material deposits for the production of concrete, but the resource shortage around the big cities are beginning to show. It is therefore natural to look at the possibilities of recycling concrete waste for the production of new concrete. By adding RCA in new concrete the need of supply of NA will decrease. At the same time there is a possibility of getting a higher value for the concrete waste than for the use as road-fill or base layer. At the same time the need for paying for waste removal and delivery to receiving plant can be reduced.

The use of RCA for the production of new concrete are common in some other countries e.g. Japan and Holland, indicating that the use of RCA into new concrete has an unexploited potential.

Both the recovery of raw materials and the production of concrete requires a fair amount of energy consumption, it is important that the materials after end of life are utilized probably. This study therefore looks at the possibilities of RCA.

1.1 Objective

The purpose of this thesis is to investigate the possibilities of using RCA as a replacement of NA in concrete. The RCA investigated are in the fraction 4-8 mm of an unknown source.

The focus of the investigation is on the processing procedure of the aggregates. The processing procedures were examined based on various physical property tests of the aggregates and different mix design concretes examined for the compressive strength. The concrete is mix designed without admixtures.

1.2 Structure of Report

This thesis consists of six chapters and five appendices. Chapter 1 gives a motivation for this thesis with an introduction to concrete waste, reuse and the main objective. Chapter 2 describes the theory of concrete, recycled concrete aggregates and new concrete. Chapter 3 presents the material tested in this thesis. Chapter 4 describes the theory behind the tests and how they were conducted. Chapter 5 outlines the results and the discussion. Chapter 7, the final chapter, comes with a conclusion to the main objective presented here in Chapter 1. Appendix A, B and C elaborate Chapter 4 and 5. Appendix D, E, F and G presents a brief description of field trip to Holland, tables from standards of assessments, risk assessment and a poster from the midterm presentation.

CHAPTER 2

Theory

2.1 Concrete

Concrete is widely used all over the world either as prefabricated elements or in-situ, mainly due to its high versatility and relatively low cost. Concrete is in the simplest form composed of water, a binder and aggregates. The binder most commonly used is cement and the aggregates are a collective term of filler, mostly consisting of sand and stones. When mixing concrete one of the most important factors is the w/c-ratio since it is the cement combined with the water that creates the strength. The cement is called hydraulic when cement sets and hardens by a chemical reaction with water. A high w/c-ratio results in a concrete with lower strength but high permeability and a low w/c-ratio results in a concrete with high strength but low permeability. Cement is the most expensive part of the concrete, which is one of the reasons that aggregates are added (Geiker and Nielsen 2008).

Aggregates also contribute to the final properties of the concrete e.g. durability and final strength. The particle size distribution, particle shape, density and water absorption of the coarse aggregates affects the durability of the concrete. The aggregates density is necessary to determine the aggregates percentage of the concrete. The water absorbed in the aggregates is not included in the w/c-ratio and the water absorption of the aggregates therefore affects the strength of the concrete. NA is either from sea dredged gravel, gravel pits or crushed granite. Well graded coarse aggregates of rounded particles will pack better than evenly sized angled aggregates. This is one reason why sea dredged gravel are usually preferred as they are round.

2.2 Recycling Concrete Aggregates

It is always interesting with new sources of raw materials, especially when they are close by, which reduces the transportation costs and CO_2 emission. When looking at the possibilities of recycling concrete waste for the production of new concrete it is therefore interesting to look at the raw material extraction in the different areas of Denmark. Figure 2.1 illustrates the raw material recovery from the different regions of Denmark.

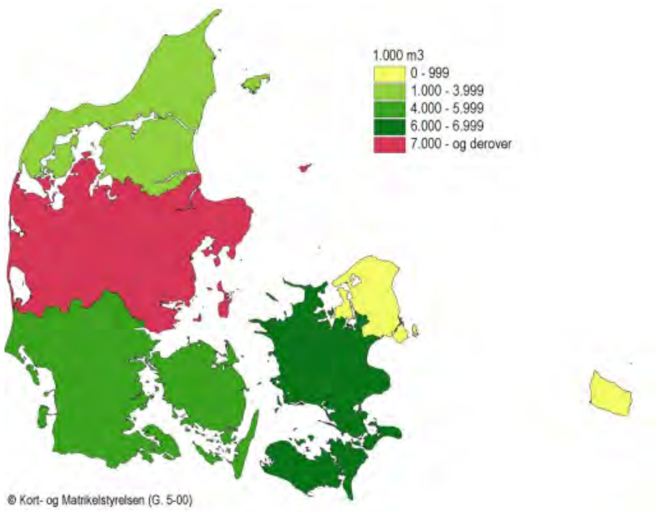


Figure 2.1: Raw material recovery in Denmark (Statistik 2012).

The Capital Region is the region with the lowest amount of raw material recovery and is in relation to the other four regions facing some challenges of raw material planning. The geographical distribution of the consumption of raw materials in the Capital Region are mainly related to expansion of Copenhagen. It is general near the capital that the majority of the raw materials are consumed and at the same time not possible to acquire raw materials immediately close by. This means that raw materials are transported over long distances which contributes to further CO_2 emission. Figure 2.2 illustrates the CO_2 emission for transportation of raw materials to Copenhagen from three gravel pits on Zealand by truck (Koncern-Miljø 2012).

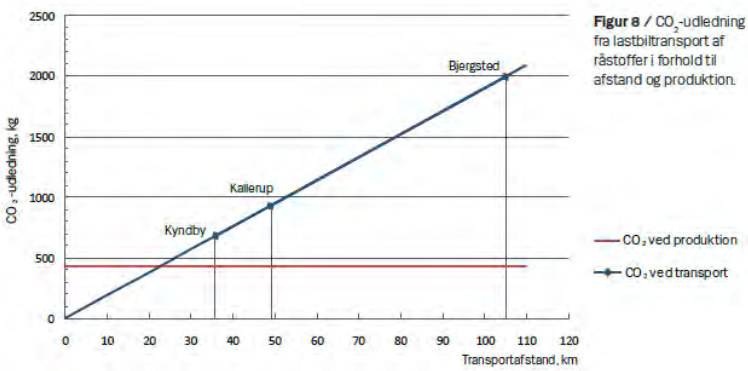


Figure 2.2: CO_2 emission for truck transportation of raw materials to Copenhagen (Koncern-Miljø 2012).

Recycling concrete waste for the production of new concrete does not only help the Capital Region's challenges with raw material planning and lowering the CO_2 emission from transportation. "In contrast to most other waste management contexts, transportation was shown to be important for the global warming impacts related to C&DW management: distances shorter than 40 km are recommended to ensure overall savings in case of utilization" (S. e. a. Butera 2015 p. 203).

Recycling of concrete aggregates can help the demolition projects saving money for waste removal and in connection with external recycling (delivery to receiving plant) and the construction projects save money on supply and delivery of materials.

The potential for companies in relation to increased recycling of concrete waste lies in lower prices for raw materials (demolished concrete waste) compared with the use of imported granite, and higher prices for residual materials (demolished concrete waste) when it is sold as a material for concrete and asphalt production rather than road-fill or base layer, as well as final savings in relation to the disposal of concrete waste.

The potential for recycling concrete waste for the production of new concrete is mainly in the use of construction concrete and concrete from bridges due their high and uniform quality in the concrete, for these the trace ability of the materials is satisfying. Trace ability of the materials increases possibilities of recycling concrete waste as aggregates, since the aggregates according to the standards require control of the documentation, selective demolition and certification.

In Denmark there have been very few test project of recycling concrete waste for the production of new concrete, in these cases has the crushing of the concrete happened on the construction site or on another site near by.

Another way to address the crushing of the concrete compared to doing it on the sites is to have concrete recycling plants. DAKOFA and Dansk Beton had arranged a field trip to Holland, to see how Theo Pouw and Rewinn work with recycling concrete aggregates, see Appendix D.

2.3 Characterization of Recycled Concrete Aggregates

RCA can be regarded as a two-phase composite made of NA and the adhering mortar, which consist of sand and fraction of un-hydrated cement, generally referred to as attached mortar (AM). Which means that aggregates from crushed concrete has properties from both coarse aggregates and mortar. Figure 2.3 shows a table from (al. 2013) which summarizes the basic physical properties of RCA from available literature.

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

Figure 2.3: Physical properties of NA and RCA (al. 2013).

The physical properties of RCA, which is described in this section, influences the mix proportion and properties of recycled aggregate concrete (RAC), this will also be referred to as new concrete through out the report.

2.3.1 Grading and Particle Shape

The RCA is generally very angular and rough due to the crushing and the attached mortar to the surface of the NA. Comparing the RCA to NA, it is similar to crushed granite in the particle shape. Beside the affect on the shape, the different equipment used for crushing the concrete influences the roughness and grading of RCA, Figure 2.4 shows the correlation between crusher settings and particle size distribution for natural rock. 15 % of the crusher product will be of a size above the settings of the crusher. Studies shows that the particle size distribution for RCA are in reasonable agreement with the prediction of Figure 2.4 (Hansen 1992).

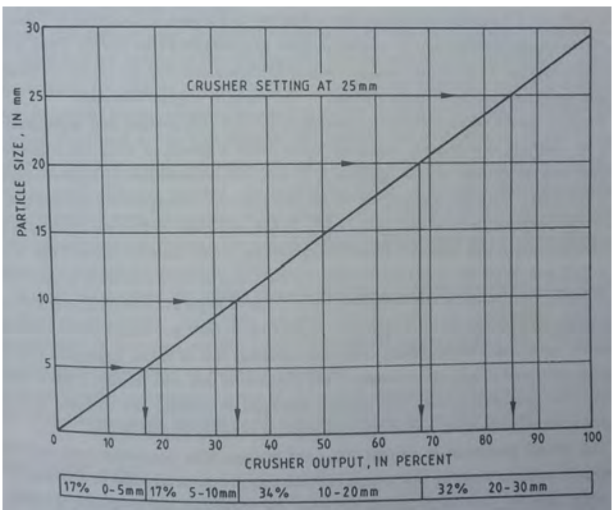


Figure 2.4: Correlation between crusher settings and particle size distribution of crushed product (Hansen 1992).

2.3.2 Los Angeles abrasion

The Los Angeles abrasion value measures the wear resistance of aggregates. A high L.A. abrasion value is obtained by the loss of the material due to a greater wear. The L.A. abrasion value of RCA are usually higher than for NA. RCA produced from all, but the poorest quality concrete, pass British standard requirements to the L.A. abrasion loss percentage (Hansen 1992). In Denmark there is no requirement for the L.A. abrasion value, as the danish gravel material often have a value (below 25%).

2.3.3 Attached Mortar

The RCA particles typically consist of 25-60% of AM, depending on the aggregate size (Hansen and Narud 1983). The AM is characterized by micro cracks and big open pores. Studies show that the volume percentage of AM is higher the smaller the fractions of the RCA. This is one of the reasons the fractions under 4 mm often are avoided, due to the AMs affect on the quality of the new concrete (Hansen 1992). Figure 2.5 illustrates RCA with AM and mortar fractions in new concrete.

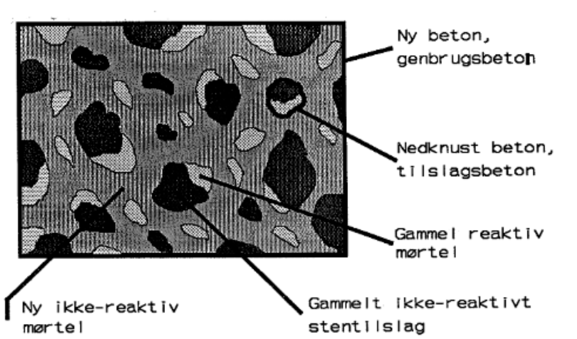
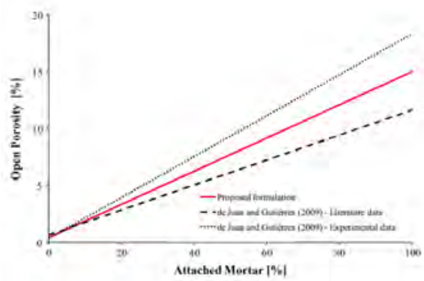
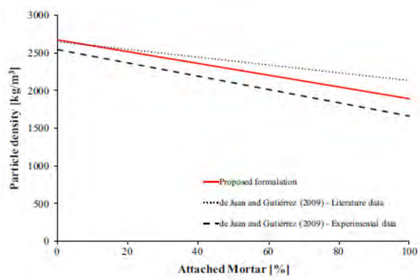


Figure 2.5: New concrete with recycled concrete aggregates and attached mortar.

AM is very porous comparing to NA, this affects the density and water absorption of the RCA, since it has a higher porosity compared to the NA. The AM affects the physical properties of the RCA so they have resemblance with the physical properties for lightweight aggregates. Studies highlight that RCA's are significant more porous than NA, this is due to AM (McNeil and Kang 2013, Behera 2014). (Pepe 2016) report the correlation between AM and physical properties open porosity and particle density, see Figure 2.6, in connection with their proposal of a conceptual formulation for predicting the compressive strength of RAC by only taking the water absorption into account.



(a) Correlation between AM and open porosity.



(b) Correlation between AM and particle density.

Figure 2.6: (Pepe 2016)

2.3.4 Water absorption

Following the AM and its high porosity, the RCA can absorb a larger amount of water than NA. The amount and the rate of the water absorption influences the casting of the concrete. Figure 2.7 illustrates water absorption under different circumstances.

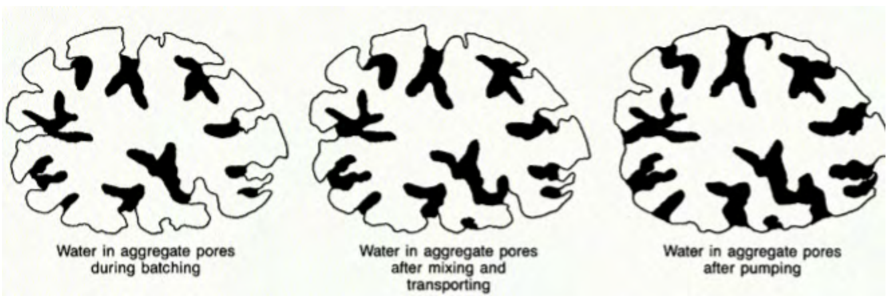


Figure 2.7: Water absorption (Goeb 1985).

In general a high porosity and high water absorption combined with a low density often results in weaker aggregates which can give a less durable concrete. The water absorption is the physical property where of RCA and NA differ the most. Due to the high water absorption it can be suggested to use pre-soaked aggregates when casting RAC, to maintain an uniform quality during production of the concrete. (Goeb 1985) discuss practical ways of pre-soaking lightweight aggregates e.g. by sprinkling, immerse the aggregates in water and vacuum to produce a degree of saturation. Figure 2.8 shows how the water absorption as a parabolic relation to the density of RCA (Hansen 1992).

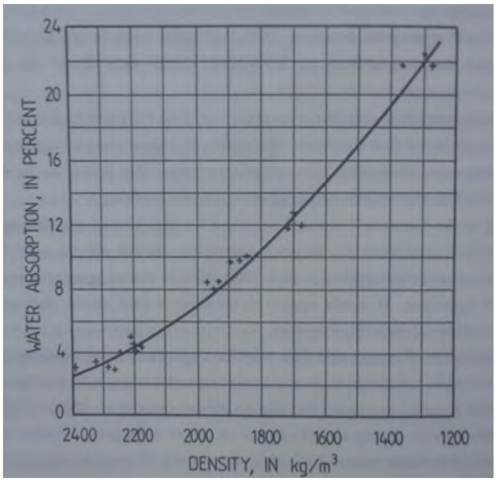


Figure 2.8: Water absorption as a function of density of recycled concrete aggregates (Hansen 1992).

2.3.5 Density

The density of RCA is usually lower than the density of NA, as shown in Figure 2.3. The density of RCA in saturated and surface dry (s.s.d.) condition for RCA (4-8 mm), were found to 2340 kg/m^3 and for RCA (8-16 mm)to 2450 kg/m^3 (Hansen and Narud 1983, Anderson 2009). The s.s.d. densities of NA range from 2500 to 2610 kg/m^3. This is due to the higher porosity of the AM to the coarse aggregates and the crushed concrete fractions (Anderson 2009). This is shown by (Pepe 2016), see Figure 2.9.

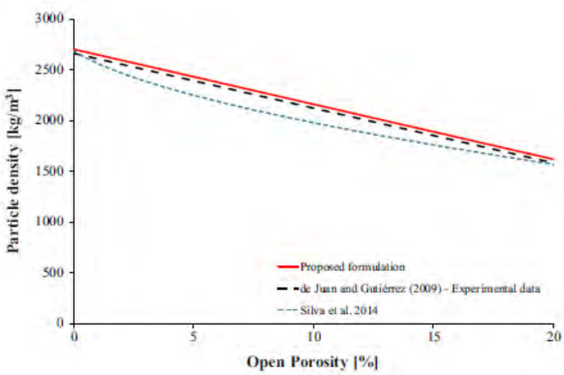


Figure 2.9: Proposed correlations for the physical properties of RCAs (Pepe 2016). Results of RCA (4-8 mm) are illustrated green.

Any variation in density of RCA during concrete production will increase variations in mix proportions and therefore concrete properties.

2.3.6 Recycled Aggregate Concrete

2.3.6.1 Workability

Concrete's workability depends on the consistency and the stability of the concrete mixture. The workability of freshly mixed concrete is determined of how easily it can be mixed, placed and compacted.
Consistency describes the ease of flow of the concrete mixture. RAC has a tendency to a low consistency which might result in difficulties with placement, compaction and segregation of the coarse aggregates during placement. This is due to the water content's direct relation to the consistency of the mixture and the RCA's high water absorption.

2.3.6.2 Mechanical Properties

The compressive strentgh of RAC depends on the strength of the original concrete and is mainly controlled by the w/c-ratio of the original concrete and the new concrete. The strentgh of the RAC can be as good as or higher than the original concrete, depending on the w/c-ratio (Hansen and Narud 1983). Due to the high water absorption of the RCA, the w/c-ratio can be difficult to maintain as a free constant. This can lead to larger standard deviation. Large standard deviations make it expensive in terms of cement consumption to meet requirements to characteristic strength in the codes and specifications (Hansen 1992).
Drying shrinkage and creep of RAC is approximately 50% higher than shrinkage for conventional concrete (Hansen 1992, Anderson 2009). Drying shrinkage increases with the amount of mortar in concrete, since RCA is a two-phase composite, it adds more mortar to the concrete thus increasing the drying shrinkage. The AM also influences the modulus of elasticity of the new concrete, where the AM has a relatively low modulus of elasticity. This leads to lower modulus of elasticity of new concrete than for conventional concrete.

2.3.6.3 Influence on the Strength of Concrete

The w/c-ratio has a great influence on the strength of the concrete, the strength gets higher when the w/c-ratio is decreased, this is described in the empirical Bolomey Formula:

$$f_c = K\left(\frac{1}{w/c} - 0.5\right) \tag{2.1}$$

where f_c [MPa] is the strength of the concrete, K [MPa]is a constant, which varies depending on the cement type, w/c is the w/c-ratio of the concrete and α is a constant which depend on the cement type and the days of curing.

2.3.7 Contaminants

Contaminants of concrete waste are divided into two categories; contaminants from demolition debris and contaminants of pollutants in the concrete.
Different levels of pollutants are found depending on the aging level and the material used. There are a number of potential harmful compounds in concrete waste, such as several inorganic elements and organic pollutants; polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs). The PAHs can come from additives in cement or concrete production e.g. coal fly ash (FA), or even be naturally present in their raw materials. Furthermore they can arise from tar-containing fractions during the demolition (e.g. asphalt). The PCBs can occur from contamination from PCBs-containing products, e.g. sealing materials and paint. The main environmental issue from pollutants in concrete waste is leaching of harmful inorganic compounds with potential contamination of the underlying soil and groundwater (S. Butera 2015). S. Butera has investigated 11 recycling facilities in Denmark for samples of construction and demolition waste, these were characterized in terms of total content and leaching of inorganic elements and presence of the persistent organic pollutants PCBs and PAHs.
Contaminants from demolition debris, can come into new concrete with the RCA. The contaminants can be soil, joint filler, gypsum, cords, bricks, organic materials, chemical admixtures, metals, wood, asphalt and glass. The contaminant materials which are weakened by water immersion affect the concrete's stability and can reduce the strength of the concrete. However by incorporating some simple precautions during the demolition process, the potential for recycling the concrete can be improved and the value of the debris increased. (Yanagi and Hisaka 1994) found the compressive strength of RAC is increased by washing the RCA compared to unwashed. The new concrete becomes stronger but more permeable.

2.4 Relevant Standards of Assessment of RCA

Different norms and standards in Europe have decided on requirements and recommendations for aggregates for concrete in general and for recycled concrete aggregates, in order to ensure the concrete's durability. Depending on which strength and where the concrete is used, there are different requirements to the materials durability. In this sections some requirements for RCA are mentioned.
According to concrete norm DS/EN1992-1-1, crushed concrete in new concrete must meet DS/EN206 and be divided in sandfraction (<4mm) and coarsefraction (4mm-32mm). The RCA have to fulfill the requirements for aggregates in table 2426-3, see Figure E.1. The coarse aggregate therefore also has to comply to DS/EN12620+A1.

Table E.2 — Maximum percentage of replacement of coarse aggregates (% by mass)

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.

NOTE For the risk of alkali-silica reaction with recycled aggregates, see EN 12620:2002+A1:2008, G.3.2.

Figure 2.10: DS/EN206 - Annex E.

Figure 2.10 shows table E.2 from DS/EN206 with the percentage of RCA (with $d \geq 4mm$) replacement of NA. Figure 2.10 divides the RCA into two types, an extended description of the constituents of RCA for the two types can be seen in Appendix E. If the source is known for the RCA (type A), the new concrete can be used in exposure class to which the original concrete was designed with a maximum replacement of 30 % RCA. Otherwise the new concrete has to be in exposure class X0 or XC1, which is a dry environment where corrosion can not occur. RAC can be used up to strength C30/37.

According to DS/EN12620+A1 the RCA need CE certification, table 20 specifies that only RCA from pure categories can be used, see Figure E.2.

Together DS/EN206 and DS/EN12620+A1 set the limits for the percentage of RCA that can be used, where DS/EN12620+A1 .

CHAPTER 3

Materials

This section contains a description of the material tested and the preparation process of the tested materials.

3.1 Crushed Concrete - Isslevgaard

Crushed concrete was collected from Islevgaard allé 5, 2610 Rødovre in aggreement with Cervo Gruppen. The concrete was collected over three times; the 10th of January, 24th of February and 3rd of May 2017. The material collected in January and May was after days with dry weather conditions, see Figure 3.1(a) and the material collected in February was during snow, see Figure 3.1(b). The concrete pile is approximately 8 m high. Each time the concrete was collected by digging at two spots in a few meter of each other. The 10th of January and the 3rd of March approximately 170 kg were collected per time and in February approximately the double was collected. The concrete is from the previous buildings on the construction site at Islevgaard allé. The demolished concrete consist of concrete from the five previous buildings on the site. Some of the beams compressive strength was traced to 34 MPa from the building permit. The compressive strengths for the concrete slab, walls, decks etc. are unknown.

(a) Dry weather conditions.

(b) Snow.

Figure 3.1

3.1.1 Preparation Process

The method used for preparing the sampled concrete prior to testing and casting is described in Figure 3.2.

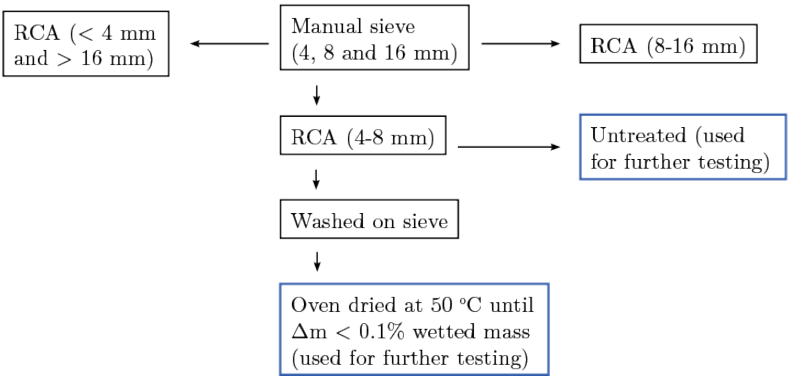
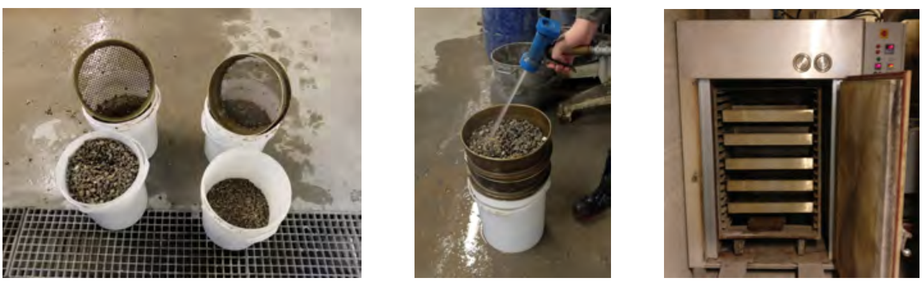


Figure 3.2: Preparation process.

First the crushed concrete was sieved manual through 4 mm, 8 mm and 16 mm sieves, see Figure 3.3(a). Aggregates are typically produced in 4 fractions: 1 sand fraction (0-4 mm) and 3 stone fractions (4-8 mm), (8-16 mm) and (16-32 mm). In order to investigate recycled concrete coarse aggregates, the sand fraction was discarded, since the fractions of NA used for the concrete mixture design was in (4-8 mm) and (8-16 mm), fraction (16-32 mm) was also discarded. The fraction (8-16 mm) have been further investigated by KNJ.
The RCA (4-8 mm) was divided in to two parts. First part of the RCA (4-8 mm) was kept untreated. The second part was washed on sieves, see Figure 3.3(b) and dried in an oven at 50 ^{o}C, see Figure 3.3(c). It was kept in the oven until the mass change was less than 0.1%.



(a) 4 and 8 mm sieves. (b) Washing. (c) Oven.

Figure 3.3

CHAPTER 4

Method

This section starts with an overview of the laboratory tests. Hereafter each test is introduced with the test's method theory presented.
The crushed concrete aggregates studied in this report were exposed to seven different laboratory tests; six to characterize the aggregates by determining the physical properties and quality, as introduced in the previous sections, and one to determine the compressive strength for the different mix designs. An overview of the tests which were conducted is given in Table 4.1 including abbreviations and standards. The expressions used for calculations in relation to the tests are from the tests' respective standards. The methods and expressions used for calculating the mean and standard deviation for the results in Chapter 5, can be found in Appendix A. Appendix A also entails further elaboration of some of the test methods and Appendix B elaborate on the experimental procedures.

Test name	**Abbreviation**	**Standard**
Particle size distribution	PS	DS/EN933-1
Los Angeles abration	LA	DS/EN1097-2
Cement content	CC	TI-B 9 (85)
Porosity and Density	PD	LBM testmethod 2
Density and Water absorption	DW	DS/EN1097-6
Water content	WC	DS/EN1097-5
Compressive strength	CS	DS/EN12390-3

Table 4.1: Test performed in this report.

4.1 Particle Size Distribution

The particle size distribution test was conducted for the crushed concrete (0-32 mm) collected according to DS/EN933-1. In practice an aggregate quantity is a mixture of different size varieties. Aggregates therefore have a unique particle size distribution. To determine the particle size distribution a sieve analysis is performed, an aggregate is indicated by two screen sizes, between which most grains are with basic sieve sets - a series of 0, 1, 2, 4, 8, 16, and 31.5 mm sieves.
The size of test portions was determined based on the maximum diameter of the crushed concrete. The maximum diameter was 32 mm and the test portions therefore

10 kg. Two particle size distribution tests were conducted. The crushed concrete was prepared by drying in oven at 110 ± 5 ^oC until constant mass was reached, mass change less than 0.1%.

The dry material was poured directly into the sieving column and the sieving column was shaken manually. The material retained by each sieve was weighed on a scale with three decimal places. The sieving column together with the different fractions can be seen in Figure 4.1(a). The fraction with $d \leq 1mm$ was run through Mastersizer 2000 laser diffractor, see Figure 4.1(b).

(a) Sieving column $d \geq 1mm$.

(b) Laser diffraction $d \leq 1mm$.

Figure 4.1

4.2 RCA 4-8mm Characterization

The RCA (4-8 mm) has been characterized through observation during the castings of the concrete, by microscope and by the laboratory tests in this chapter.

4.2.1 Los Angeles Abrasion

The test of the LA abrasion value was conducted according to DS/EN1097-2. The test was conducted for the two fraction of 4-8 mm from the particle size distribution test. The test portion was tested in a Los Angeles abrasion machine, see Figure 4.2(a) with 8 spherical steel balls with a diameter of 46 mm, see Figure 4.2(b). The LA abrasion loss, LA [%], can be calculated by:

$$LA = \frac{m_0 - m_1}{m_0} \cdot 100 \quad (4.1)$$

where m_0 [g] is the mass of the test portion and m_1 [g] is the mass retained on 1.4 mm sieve. According to DS/EN1097-2 the sieve should be 1.7 mm, but this was not available at DTU BYG and a 1.4 mm sieve was used instead.

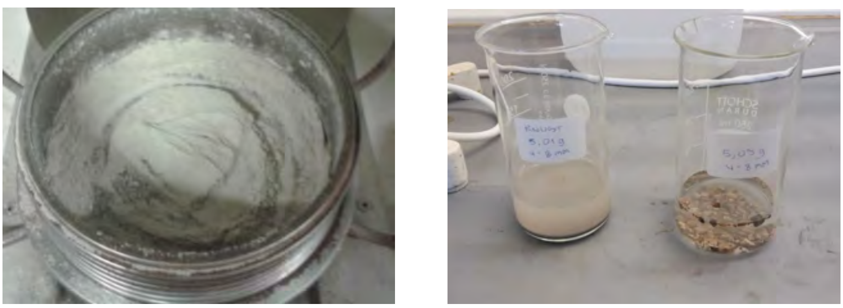
(a) Los Angeles abrasion machine.

(b) 46 mm steel balls.

Figure 4.2

4.2.2 Cement content

Test of the cement content was conducted according to the TI-B 9 (85) method, see Appendix A.3. The test was conducted for three test portions RCA (4-8 mm) and three test portions RCA (4-8 mm) crushed in vibratory disc mill for 20 sec., see Figure 4.3(a). Each portion was weighed on a scale with two decimal places and was approximately 20 g. The test portions were weighed before and after the extraction of the cement.



(a) RCA (4-8 mm) crushed in vibratory disc mill.

(b) RCA (4-8 mm) and crushed RCA (4-8 mm) in nitric acid.

Figure 4.3

4.2.3 Porosity and Density (LBM Test Method 2)

The porosity and density test was conducted according to the LBM (Laboratory for Building Materials) test method 2. Three test portions of the RCA (4-8 mm) were tested. Each test portion was approximately 100 g. As preparation the aggregates had been washed and dried to a constant mass. The aggregates were weighted in dried, cooled conditions including the net container, see Figure 4.4(b), and then kept in vacuum in an desiccator. Afterwards airless water was lead into the desiccator, covering 30 mm above the specimens, and left soaking overnight, see Figure 4.4(c). Next day the test specimens were weighted under 20 ^{o}C water, see Figure 4.4(a).

Based on the result the open porosity, P_o $[m^3/m^3]$, and the apparent density, ρ_d $[kg/m^3]$ can be calculated by:

$$P_o = \frac{V_{po}}{V} \tag{4.2}$$

$$\rho_d = \frac{m_d}{V} \tag{4.3}$$

where V_{po} $[m^3]$ is the test aggregate's open pore volume, V $[m^3]$ is the aggregate's volume, m_d [kg] is the mass before the test (dry).

In order to calculate (4.2) and (4.3) based on this test, following properties were necessary to be determined:

- Volume
- Pore volume
- Real density
- Vacuum saturated density
- Water/solid ratio

See Appendix A.2 for elaborated version of the method.

(a) Scale used to weigh test specimens under water.

(b) Test specimens in net container.

(c) Test specimens kept soaking in desiccator.

Figure 4.4

4.2.4 Density and Water Absorption (Pycnometer)

The density and water absorption of RCA(4-8 mm) were found according to DS/EN1097-6, by using pycnometers. Three test were conducted, each test portion was approximately 150 g. The aggregates were washed and then dried in an oven until constant mass was reached, mass change less than 0.1%, for preparation. The test specimens were immersed in distilled water in 500 mL pycnometer. They were weighed on a scale with two decimal places. The pycnometer was then kept in vacuum in an desiccator, see Figure 4.5(b), after 24 hours the pycnometer was overfilled with distilled and air free water, closed and dried on the outside before it was weighed, see Figure 4.5(a).

(a) Pycnometer, 500 mL.

(b) Pycnometer kept in vacuum in a desiccator.

Figure 4.5

When measurements were complete the aggregates were removed from the water and dried to a s.s.d. in order to calculate the s.s.d. density. The aggregates were dried using dry cloths and then weighed. Based on the results the particle of the aggregates saturated to constant mass, ρ_{cm} $[Mg/m^3]$, and the water absorption, WA_{cm} [%], can be calculated by:

$$\rho_{cm} = \frac{M_3 \cdot \rho_w}{M_1 - M_2} \tag{4.4}$$

$$WA_{cm} = \frac{M_1 - M_3}{M_3} \cdot 100 \tag{4.5}$$

where ρ_W $[Mg/m^3]$ is the density of water at the temperature recorded when M_2 was determined, M_1 [g] is the mass of s.s.d. test portion, M_2 [g] is the apparent mass in water of the saturated test portion and M_3 [g] is the mass of the oven-dried test portion.

4.2.5 Water Content

The water content of the RCA (4-8 mm) was investigated according to DS/EN1097-5. Three samples of 200 g each were weighed on a scale with three decimal places and dried in a ventilated oven at 105 ^{o}C for 24 h and then weighed again. The water content, w [%], can be calculated by:

$$w = \frac{M_1 - M_3}{M_3} \cdot 100 \tag{4.6}$$

where M_1 [g] is the mass of the test portion and M_3 [g] is the constant mass of the dried portion.

4.3 Recycled Aggregate Concrete Cylinders

The process of designing the RAC mix consisted of two phases. A total of 15 of RAC mixtures were made through out this process. Two of these mixtures were references, where each mixture was doubled in order for two to cure in 7 days and two in 28 days. The other 13 mixtures contained different mix design and processing of the RCA 4-8mm, 13 was mixed for curing in 7 days and six in 28 days. For each mixture tested four concrete cylinders were cast.

Different concrete mixtures were produced with the aim to understand the influence of the three following parameters on the compressive strength:

- (Nominal) value of w/c ratio:
  - 0.5
  - 0.6
- RCAs-to-NAs replacement ratio, relative to the total volume of 4-8 mm aggregates:
  - 0 (NA)
  - 30% (RAC30)
  - 50% (RAC50)
- Initial conditions of the RCA:
  - Untreated (U)
  - Oven-dried, obtained by washing and then heating the aggregates for 24h at a temperature of 50 ± 5 ^{o}C (DRY)
  - Saturated surface dry, obtained by soaking the aggregates in water for 24h:
    - Corrected for water obtained by aggregates during soaking (SATC)
    - Without correcting for water obtained by aggregates during soaking (SAT)

Figure 4.6 illustrates the different replacement ratio for RCA (4-8 mm). In all mixtures fine aggregates are 40% (in volume) of the total amount of aggregates. The remaining 60% is equally divided into two coarse fractions of (4-8 mm) and (8-16 mm), where the (8-16 mm) are NA.

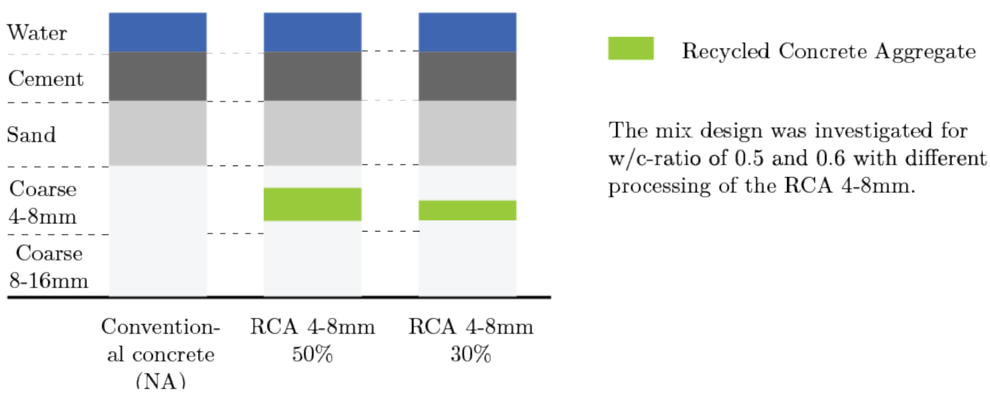


Figure 4.6: Mix designs investigated.

The compositions for the different RCAs to NAs replacement concrete mixtures, can be seen in Table 4.2. All mixtures feature Portland-limestone cement, CEM II/A-LL 52,5 N (LA), according to DS/EN197-1. The cement used is from Aalborg Portland (BASIS AALBORG Cement) and has following specification:

- CEM II/A-LL describes the cement as a limestone cement containing maximum 20 % limestone.
- 52.5N describes the minimum strength of the concrete to be at 20 MPa after 2 days of curing and 52.5 MPa after 28 days of curing.
- (LA) describes the alkali content to be approximate 0.6 %

The mix ratio for 1 m^3 was found from Pepe 2016. The test specimens was mixed and curing in water according to DS/EN12390-2 and DS/EN12390-3.

Mix designs	**w/c**	**CEM-II** $[kg/m^3]$	**Water** $[kg/m^3]$	**Sand** $[kg/m^3]$	**NA(4-8)** $[kg/m^3]$	**NA(8-16)** $[kg/m^3]$	**RCA(4-8)** $[kg/m^3]$
0.5NA	0.5	344	172	742	554	554	-
0.5RCA30	0.5	344	172	742	388	554	166
0.5RCA50	0.5	344	172	742	277	554	277
0.6NA	0.6	287	172	762	554	554	-
0.6RCA30	0.6	287	172	762	388	554	166
0.6RCA50	0.6	287	172	762	277	554	277

Table 4.2: Mix design for 1 m^3 concrete Pepe 2016.

4.3.1 Mixing RAC

The first phase included a screening of tests for different mix designs and gathering of information. Furthermore characteristics of the RCA (4-8 mm) were gathered by the performed tests mentioned in the section above. The process of investigating the mix design for RAC is illustrated in Figure 4.7.

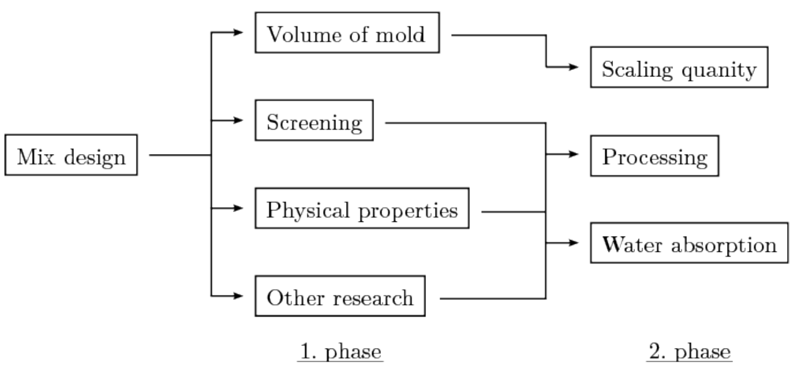


Figure 4.7: Process for designing RAC.

The second phase included redesigns of the mix designs based on gathered information from the screening from the first mix design tested and the characterization of the RCA (4-8 mm). The mix quantities were scaled from 1 m^3 to 20 l. Table 4.3 shows the composition for the different replacements of the RCA (4-8 mm).

Mix designs	**w/c**	**CEM-II** [kg]	**Water** [kg]	**Sand** [kg]	**NA(4-8)** [kg]	**NA(8-16)** [kg]	**RCA(4-8)** [kg]
0.5NA	0.5	6.88	3.44	14.84	11.08	11.08	-
0.5RCA30 DRY	0.5	6.88	3.44	14.84	7.756	11.08	3.324
0.5RCA30 SAT	0.5	6.88	3.44	14.84	7.756	11.08	3.324
0.5RCA30 SATC	0.5	6.88	3.06	14.84	7.756	11.08	3.324
0.5RCA30 U.SATC	0.5	6.88	3.29	14.84	7.756	11.08	3.324
0.5RCA50 DRY	0.5	6.88	3.44	14.84	5.54	11.08	5.54
0.5RCA50 U	0.5	6.88	3.44	14.84	5.54	11.08	5.54
0.6NA	0.6	5.74	3.44	15.24	11.08	11.08	-
0.6RCA30 DRY	0.6	5.74	3.44	15.24	7.756	11.08	3.324
0.6RCA30 SAT	0.6	5.74	3.44	15.24	7.756	11.08	3.324
0.6RCA30 SATC	0.6	5.74	3.00	15.24	7.756	11.08	3.324
0.6RCA30 U.SATC	0.6	5.74	3.25	15.24	7.756	11.08	3.324
0.6RCA50 DRY	0.6	5.74	3.44	15.24	5.54	11.08	5.54
0.6RCA50 U	0.6	5.74	3.44	15.24	5.54	11.08	5.54
0.6RCA50 SATC	0.6	5.74	3.00	15.24	5.54	11.08	5.54

Table 4.3: Mix design for concrete bathes.

The different processing abbreviations of the RCA (4-8 mm) are listed in Table 4.4.

Processing	**Abbreviation**
Untreated	U
Washed and oven dried	DRY
Saturated	SAT
Saturated and corrected for water adjustment	SATC

Table 4.4: Processing of RCA (4-8 mm).

All RAC batches were produced with the same mix proportions as the references. Ingredients were mixed according to standard DS/EN12390-3 in a standard concrete mixer, as shown in Figure 4.8.

Figure 4.8: Standard concrete mixer.

4.3.2 Slump

The slump value was measured according to DS/EN12350-2. However, the slump value was not adjusted according to DS/EN206, this was done in order to keep the amount of cement added equivalent to the references. Generally the different batches of had a low slump value, Fiugre 4.9(b) shows the slump value of the two references with w/c-ratio of 0.5 and 0.6 and the mix designed concrete with the lowest slump value.

(a) 0.5NA slump value 6 cm.

(b) 0.5RCA50 slump value 0 cm.

(c) 0.6NA slump value 13 cm.

Figure 4.9

4.3.3 Air Content

The air content of the concrete mixtures was measured according to DS/EN12350-7 with a pressure gauge method.

Figure 4.10: Pressure gauge.

4.3.4 Compressive Strength

The compressive strength tests were conducted on cylinders according to DS/EN12390-3. Compressive strength is defined as the ratio between the rupture load in axial compression and the cross-sectional area of the specimen.
Standard concrete will normally be tested for compression strength with a height/diameter-ratio of 2, according to DS/EN12390-1, cylinders with a height of 200 mm and a diameter of 100 mm were used. The H/D-ratio of 2 results in failure by cracking.
For each mixtures four compressive strength tests were conducted on the cylinder specimens after respectively 7 and 28 days of curing in a water bath at a temperature of 20 $\pm$ 2 ^{o}C, according to DS/EN12390-2. Before the specimens were tested, they were weighed and measured. The compression was applied as load per time: 4.71 kN/s, accorindg to DS/EN12390-3, see Appendix B for calculation.

Figure 4.11: Compression test, Toni Technik.

Fibreboards were used as equalizing layer between the platens of the testing machine and loadbearing surfaces of the specimen.

CHAPTER 5

Results and Discussion

The results obtained from the tests and processed by the methods described in Chapter 4 are presented in this chapter. The properties found through the tests are compared to relevant studies. Raw data can be found in Appendix B and additional results from the tests can be found in Appendix C.

5.1 Particle Size Distribution

The particle size distribution test was conducted according to DS/EN933-1. The result from the particle size distribution test is the mean based on two test portions of the crushed concrete. Figure 5.1 shows the distribution curves for the fraction < 1 mm combined with 1-31.5 mm and the mean. The results from the four test conducted are individually shown in Appendix C.

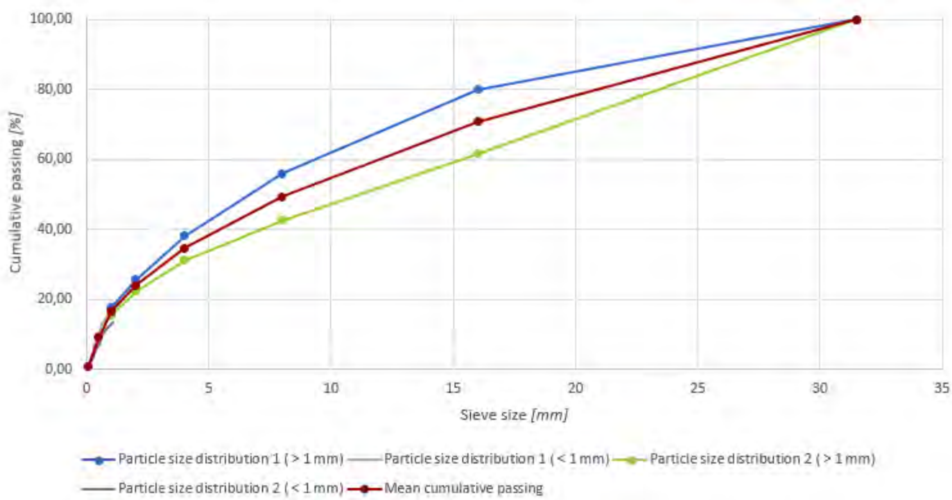


Figure 5.1: Particle size distribution. This figure will appear in the thesis of KNJ as well.

The distribution of the second test portion is generally lower than the distribution fr the first test portion, especially is the fraction (8-16 mm) lower than for the first test

portion. This shows that the second test portion has a much larger percentage of the biggest fraction (16-31.5 mm).
The results for the mean are also shown in Table 5.1.

Fraction [mm]	**Mean cumulative passing [%]**
16 - 31.5	100
8 - 16	70.90
4 - 8	49.36
2 - 4	34.68
1 - 2	24.10
0.5 - 1	16.64
0.063 - 0.5	9.15
0 - 0.063	0.96

Table 5.1: The mean cumulative passing percentage for the particle size distribution curve. This figure will appear in the thesis of KNJ as well.

From the particle size distribution test and from weighing the sieving of the material collected in January, the percentages of the fractions (4-8 mm) and (8-16 mm) of the crushed concrete collected are shown in Table 5.2.

Fraction [mm]	**PS test [%]**	**January collection [%]**
16 $<$	29.22	19,53
8 - 16	21.51	25.31
4 - 8	14.64	19.01
$<$ 4	34.63	29.83

Table 5.2: Percentages of the fractions (4-8 mm) and (8-16 mm).

The material collected in January was not sieved according to DS/EN933-1, the material was therefore dense and the some of the fraction ($<$ 4 mm) stuck the aggregates of the larger fractions. The fractions (4-8 mm) and (8-16 mm) make up 36.15-44.32 % of the crushed concrete (0-32 mm). The fraction ($>$ 16 mm) can also be used as coarse aggregates for production of new concrete, which give a percentage of 63.85-65.37 % of the crushed concrete that can be reused as RCA.

5.2 RCA 4-8mm characterization

The composition of the RCA (4-8 mm) was investigated through observations during the processes of the castings and with a microscope. Figure 5.2(a) shows the different states of the RCA (4-8 mm) and Figure 5.2(b) shows the contaminants floating during pre-soaking of the RCA (4-8 mm).

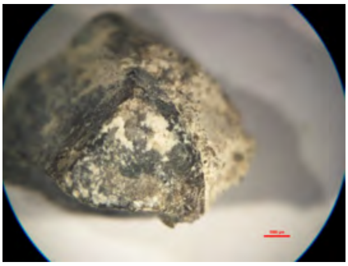
(a) Dried, saturated and untreated RCA (4-8 mm).

(b) Contaminants floating.

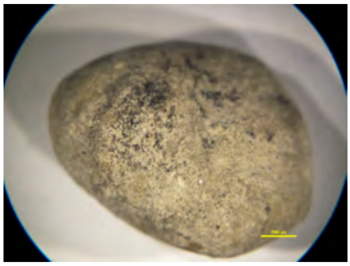
Figure 5.2: Aggregates and contaminants observed during casting.

The RCA (4-8 mm) is a mix of angular and round coarse aggregates, see Figure 5.3(a) - 5.3(c). Most of the RCA (4-8 mm) are angular with AM as Figure 5.3(a), the AM is the lighter coloured surface. The untreated RCA (4-8 mm)'s surface is covered in fine aggregates, Figure 5.3(c). Figure 5.3(d) shows a mortar fraction it is more porous than the raw material aggregates and the pores are much bigger and the open pores very visible, which is the main reason for the increased water absorption for RCA.

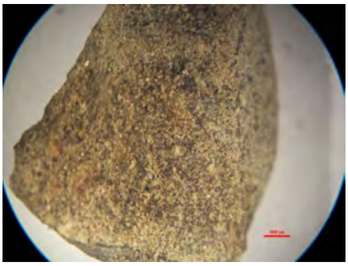
There are two types of contaminants observed in the RCA (4-8 mm) fraction. Figure 5.2(b) show the contaminants floating, when the RCA (4-8 mm) was pre-soaking for casting. The first type of contamination is shown in Figure 5.3(e) it is a dark, rounder, more porous material than the RCA (4-8 mm) and with bigger open pores, most likely asphalt. The other type of contamination, see Figure 5.3(f) has a rubbery feel and is most likely insulation or sealant The asphalt and the insulation/sealants are weaker materials than the crushed concrete and therefore weaken the strength of the new concrete.



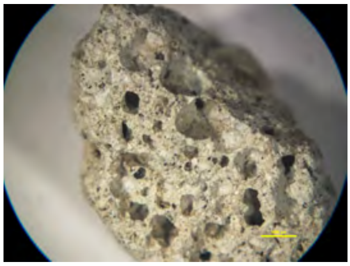
(a) Angular aggregate with AM.



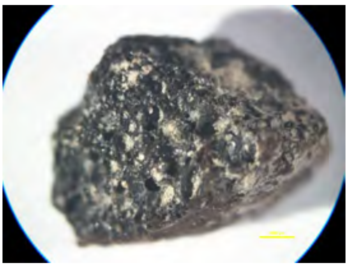
(b) Round aggregate.



(c) Untreated aggregate.



(d) Mortar fraction.



(e) Asphalt.

(f) Insulation or sealant.

Figure 5.3: RCA (4-8 mm) and contaminants, scale 1000 μ.

5.2.1 Los Angeles Abrasion

The LA abrasion test was conducted according to DS/EN1097-2. The mean result for the LA abrasion loss is based on two test portions. Table 5.3 shows the result for RCA (4-8 mm).

Property		**RCA (4-8 mm)**
LA abrasion loss	%	55.62

Table 5.3: LA abrasion loss for RCA (4-8 mm).

5.2.2 Cement Content

The cement content test was conducted according to TI-B 9 (85). The mean results for the cement content test are each based on three test portions. Table 5.4 shows the result for RCA (4-8 mm).

Property		RCA (4-8 mm)	Crushed RCA (4-8 mm)
Cement content	%	19.52	24.46

Table 5.4: Cement content for RCA (4-8 mm).

The cement content of the crushed RCA (4-8 mm) are higher than for RCA (4-8 mm), this was as expected, since the nitric acid having easier access to the cement. The results are illustrated in Figure 5.4, where the result for the crushed specimen is equivalent to the results from the studies of (Hansen 1992).

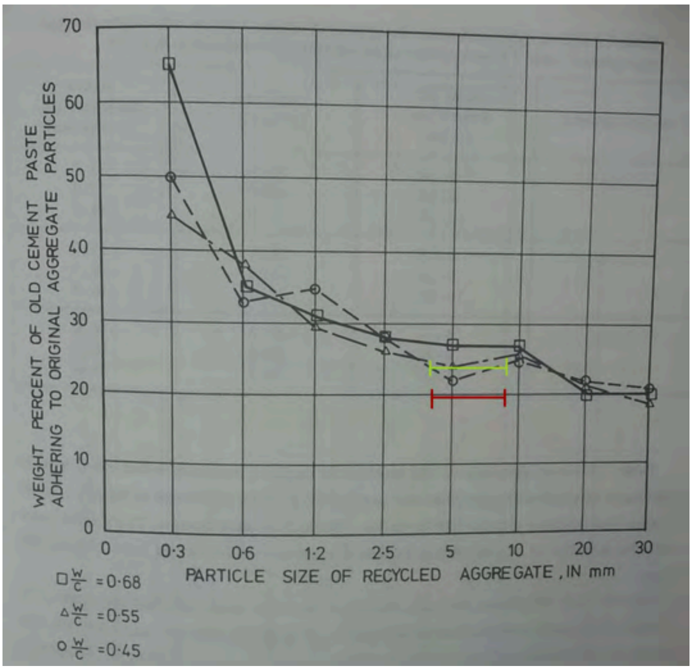


Figure 5.4: Cement content to aggregate size. Results of RCA (4-8 mm) are illustrated with red and crushed RCA (4-8 mm) with green (Hansen 1992).

5.2.3 Porosity and Density (LBM Test Method 2)

The porosity and density test was conducted according to the LBM test method 2. The mean values of the apparent density and the open porosity are shown in Table 5.6. The mean are based on three specimens.

Property		**RCA (4-8 mm)**
Open porosity P_o	m^3/m^3	0.1997
Apparent density ρ_d	kg/m^3	1980.32

Table 5.5: Open porosity and apparent density for RCA (4-8 mm).

Additional results for the RCA (4-8 mm)'s properties from the density and porosity test can be found in Appendix C.

5.2.4 Density and Water Absorption (Pycnometer)

The RCA absorb a lot of water and it is very important to control the water content during a mixing procedure to prevent the aggregates of stealing water that is assigned to cement. This is prevented by soaking the aggregates before mixing. The water used for soaking was ignored when calculating the w/c-ratio.

Property		**RCA (4-8 mm)**
Real particle density ρ_s	kg/m^3	2375.9
Water absorption WA	%	13.45

Table 5.6: Particle density and water absorption for RCA (4-8 mm).

Table 5.7 compares the real particle density from the pycnometer test to the real density from the LBM Method 2. The results from the two test are very similar with a percentage of 95.9.

Property		**RCA (4-8 mm)**
Real particle density ρ_s	kg/m^3	2375.9
Real density ρ_f	kg/m^3	2475.5
Percentage	%	95.9

Table 5.7: Real density of RCA (4-8 mm).

Figure 5.5 show the results for the water absorption as function of the density of recycled aggregates. The water absorption of RCA (4-8 mm) is much higher than the results illustrated in the figure. The reason for this can be the different ways of recycling concrete aggregates. In Denmark we use recycled concrete aggregates as all the crushed concrete in the respective fraction, where in Holland they mainly regenerate the aggregates from the concrete. The parabolic illustrated in Figure 5.5 is found by a German Kreijger, P.C., if Germany regenerates stones as Holland compared to crushed concrete, the water absorption of the aggregates will bi significant lower.

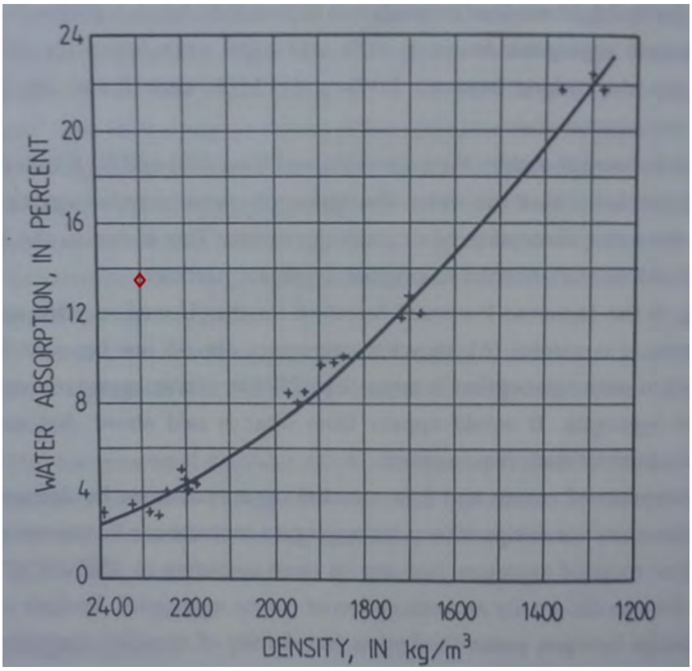


Figure 5.5: Water absorption as a function of the density. Results of RCA (4-8 mm) are illustrated with red (Hansen 1992).

5.2.5 Water Content

The water content test was conducted according to DS/EN1097-5. The mean result for the water content test is based on three test portions. Table C.4 shows the result for RCA (4-8 mm).

Property		**RCA (4-8 mm)**
Water content	%	12.5

Table 5.8: Water content for RCA (4-8 mm).

5.3 Recycled Aggregate Concrete

The following section will consider the workability of the concrete mixtures and two types of concrete cylinders: the reference cylinders which consist of 100 % NA (these are illustrated by the red bars) and the RAC cylinders which replace 30 and 50 % of the NA with RCA (4-8 mm). The results of the references will also appear in the thesis of KNJ and MEH.

5.3.1 Compressive Strength

The compressive strength test was performed according to DS/EN12390-3. The results for the compressive strength tests is the mean based on four specimens for each concrete mix design and the results can be seen in Appendix C and is illustrated in this section. The standard deviation is illustrated with error bars. The concrete cylinders ruptured due to cracks in the hardened cement paste. With some of the specimens the displacement fraction was set higher on the Toni Technik to see how the failure behaved around the RCA. Some of the RAC cylinders ruptured due to a slip at the AM.

5.3.1.1 First Phase

During the first phase of this project a screening was conducted. The screening consisted of reference specimens of 0.5 and 0.6 w/c-ratio curing in 7 and 28 days and mix designs with replacement of 30 and 50 % RCA (4-8 mm) in dry and saturated conditions and untreated for w/c-ratio 0.6. The results of the references will also appear in the thesis's of KNJ and MEH.

First the mix designs with replacement of 50% dry RCA (4-8 mm) was tested for 7 days curing. It was a bit lower than the reference for the w/c-ratio 0.6 and higher than the reference for 0.5 w/c-ratio, but with a higher standard deviation. Then the replacement of RCA was tested for 30 % according to the requirements for unknown sources DS/EN206. This was done for both dry and saturated conditions. Figure 5.6 and 5.7 both show that the compressive strength for the processed RCA (4-8 mm) is equal to the references and with standard deviation.

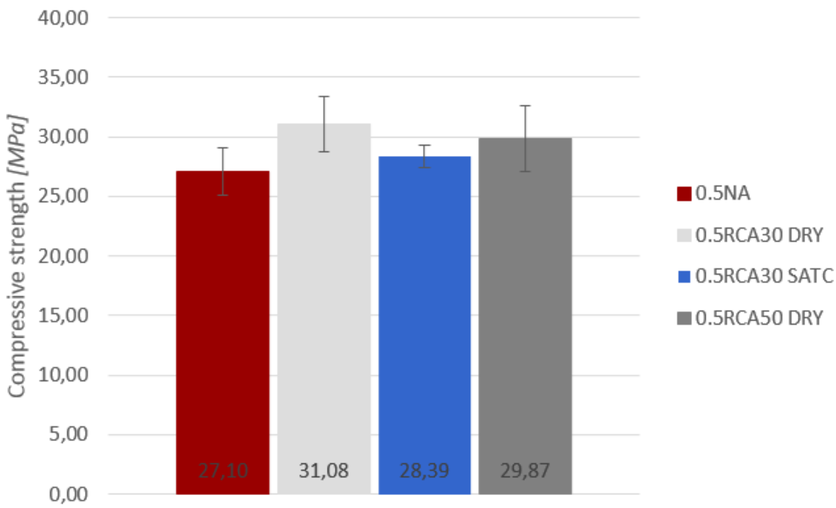


Figure 5.6: Compressive strength of specimens cured for 7 days with 0.5 w/c-ratio.

For the 0.6 w/c-ratio the mix designs of 50 % untreated RCA (4-8 mm) was also investigated, the compressive strength was much lower than the other tests.

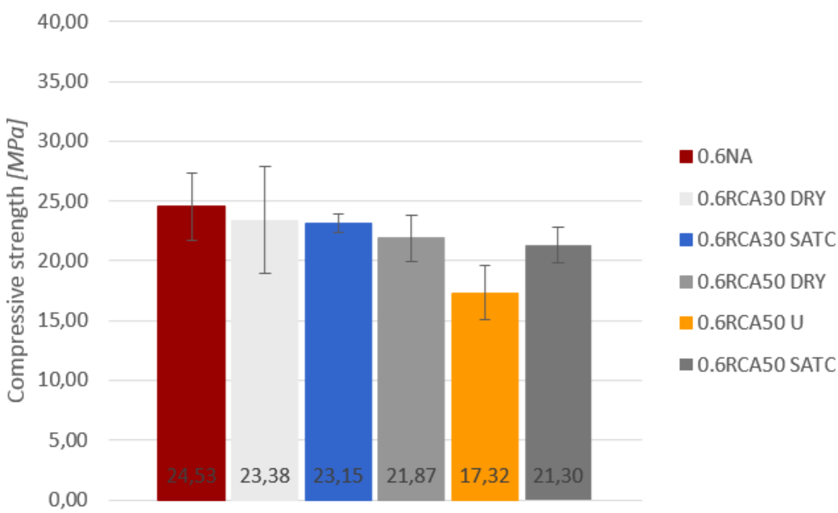


Figure 5.7: Compressive strength of specimens cured for 7 days with 0.6 w/c-ratio.

Figure 5.8 and 5.9 shows the screening for the specimens curing in 28 days. The figures show the 50 % relacement dry RCA (4-8 mm) equivalent to the references, but both with bigger standard deviation.

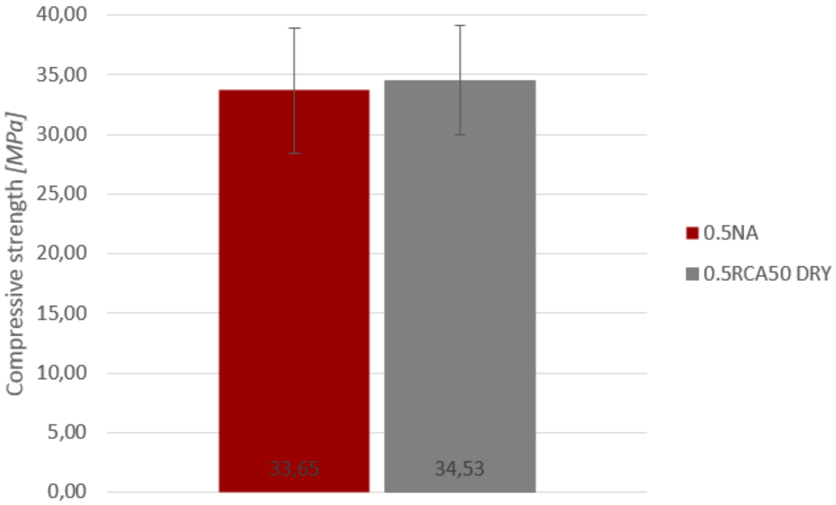


Figure 5.8: Compressive strength of specimens cured for 28 days with 0.5 w/c-ratio.

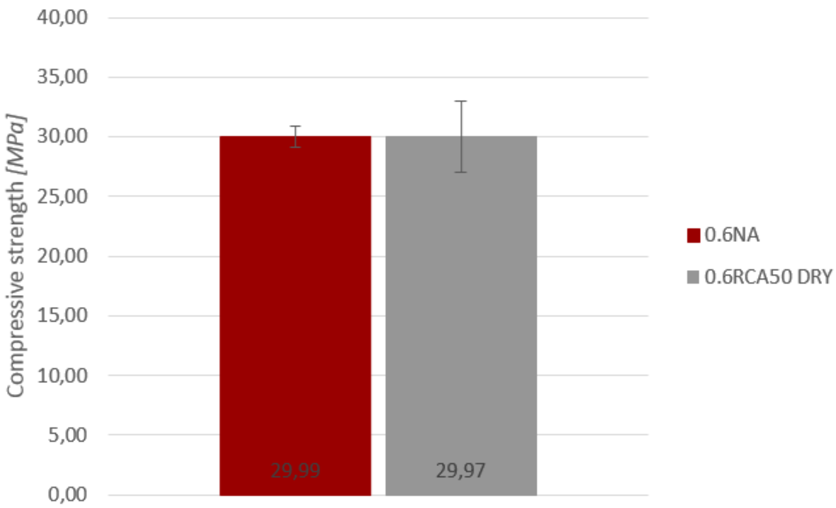


Figure 5.9: Compressive strength of specimens cured for 28 days with 0.6 w/c-ratio.

Phase 2 Based on the results from the mix designs of first phase redesigns of the mix design were investigated. Due to the low slump value and the deviation of the results, the focus for the second phase was on the processing procedure of the RCA (4-8 mm). From the first phase the aggregates was added to the mix either dried or as s.s.d. where there was corrected for the amount of water in relation to the water obtained during pre-soaking. To ease the process of production the processes of the RCA (4-8 mm) s.s.d. without correction for the water was tested. Due to the difficulties of getting a s.s.d. state for the RCA (4-8 mm) the mixture got very wet. As the water used for soaking has been ignored when calculating the w/c-ratio, the w/c-ratio increased and the strength of the mixture for both 0.5 and 0.6 w/c-ratio were significantly lower than the rest of the test.

In continuous to ease the processing procedure the s.s.d. where there was corrected for the amount of water was tested for untreated RCA (4-8 mm). Both for 0.5 and 0.6 w/c-ratio the strength was not much higher than for the s.s.d. without correction.

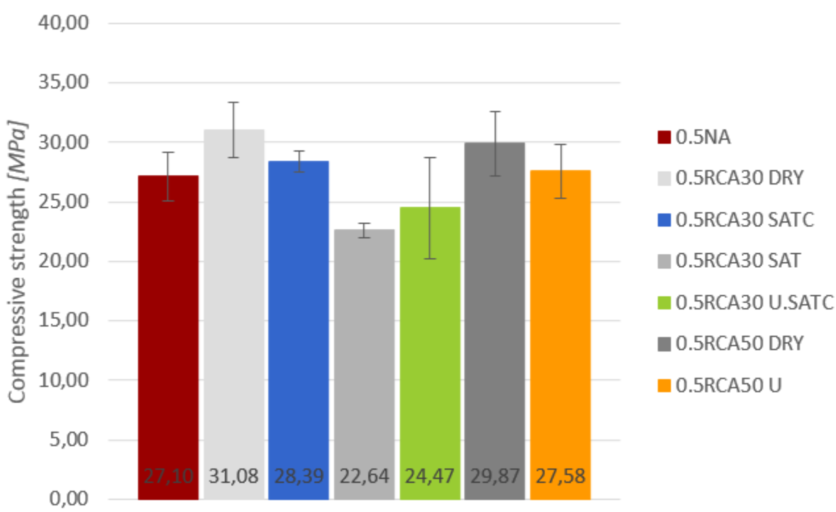


Figure 5.10: Compressive strength of specimens cured for 7 days with 0.5 w/c-ratio.

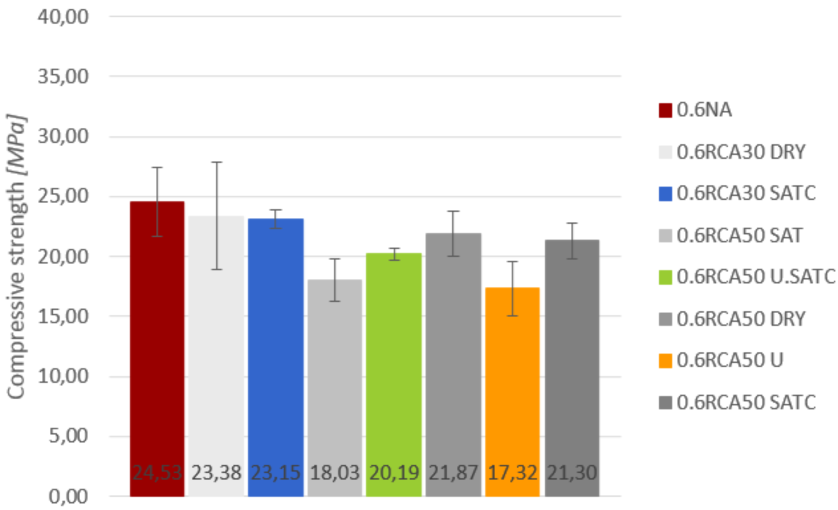


Figure 5.11: Compressive strength of specimens cured for 7 days with 0.6 w/c-ratio.

The 30 % replacement in dry and s.s.d. corrected for the water amount obtained during pre-soaking for both 0.5 and 0.6 w/c-ratio form the first phase were cast again for 28 days of curing. All except one (0.5RCA30DRY) corresponded to the references.

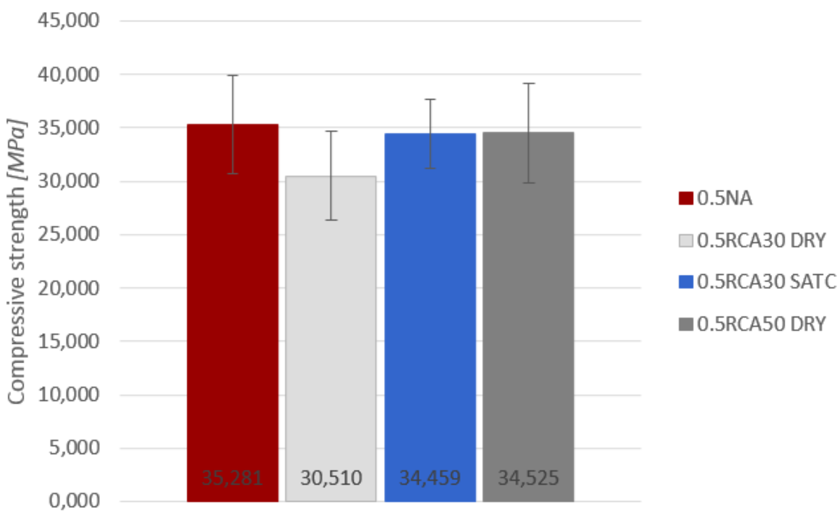


Figure 5.12: Compressive strength of specimens cured for 28 days with 0.5 w/c-ratio.

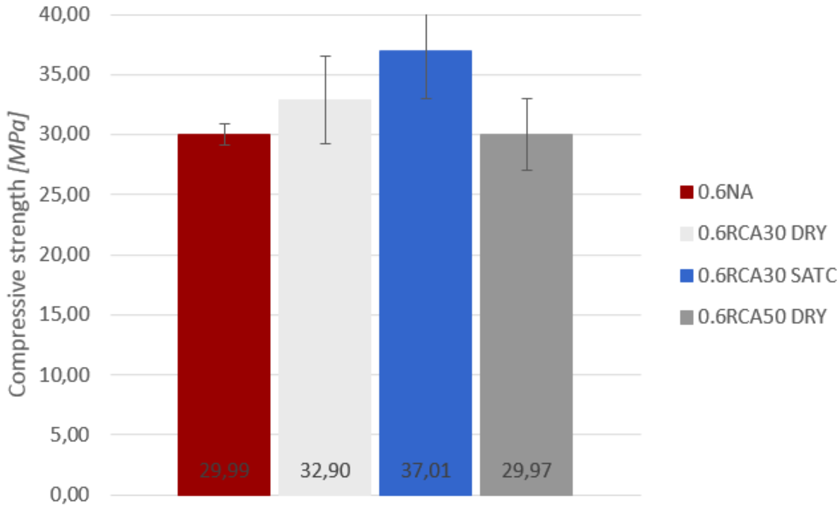


Figure 5.13: Compressive strength of specimens cured for 28 days with 0.6 w/c-ratio.

Saturating the RCA (4-8 mm) by pre-soaking affects the workability and gives a higher consistency which makes it easier with the placement and the compaction of the concrete mixture. Due to the RCA high water absorption, saturating the RCA (4-8 mm) make it easier to control the water absorption during mixing and therefore also the free water content, which prevent the RCA of stealing the water that is assigned for the cement. When taking the water used for pre-soaking into account for calculating the w/c-ratio, Figure 5.10 and 5.11 shows that deviation gets lot smaller .

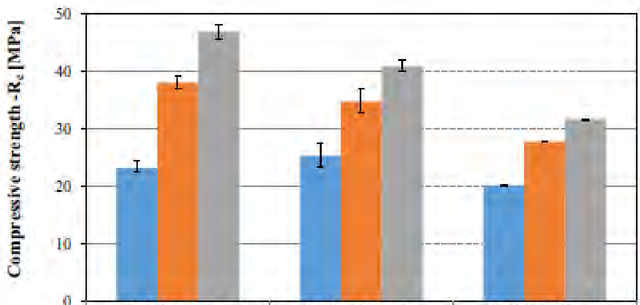
Comparing the compressive strength of the different mix designs to Bolomey formula only three of the mix designs with RCA (4-8 mm) exceed the calculated strength of the concrete, these are underlined in Table 5.9. Two others are less than 1 % from and and 9 of the mix designs are more than 10 % from.

Mix designs	**w/c**	**Curring** [d]	**Mean** $[MPa]$	f_c $[MPa]$	Percentage [%]
0.5NA	0.5	28	34.78	40.6	86.9
0.5NA	0.5	7	27.11	31.2	86.8
0.5RCA30 DRY	0.5	7	31.08	31.2	99.6
0.5RCA30 SATC	0.5	7	28.39	31.2	91
0.5RCA50 DRY	0.5	28	34.53	40.6	85.03
0.5RCA50 DRY	0.5	7	29.87	31.2	95.7
0.5RCA30 DRY	0.5	28	30.51	40.6	75.1
0.5RCA30 SAT	0.5	7	22.64	31.2	72.6
0.5RCA30 SATC	0.5	28	34.46	40.6	84.9
0.5RCA30 U.SATC	0.5	7	24.47	31.2	78.4
0.5RCA50 U	0.5	7	27.58	31.2	88.4
0.6NA	0.6	28	29.99	30.9	97.1
0.6NA	0.6	7	24.53	23.2	105.7
0.6RCA30 DRY	0.6	7	23.38	23.2	100.8
0.6RCA30 SATC	0.6	7	23.15	23.2	99.8
0.6RCA50 DRY	0.6	28	29.97	30.9	97
0.6RCA50 DRY	0.6	7	21.87	23.2	94.3
0.6RCA50 U	0.6	7	17.32	23.2	74.7
0.6RCA50 SATC	0.6	7	21.3	23.2	91.8
0.6RCA30 DRY	0.6	28	32.9	30.9	106.5
0.6RCA30 SAT	0.6	7	18.03	23.2	77.7
0.6RCA30 SATC	0.6	28	37.01	30.9	119.8
0.6RCA30 U.SATC	0.6	7	20.19	23.2	87

Table 5.9: Compressive strength for mix designs compared to Bolomey formula.

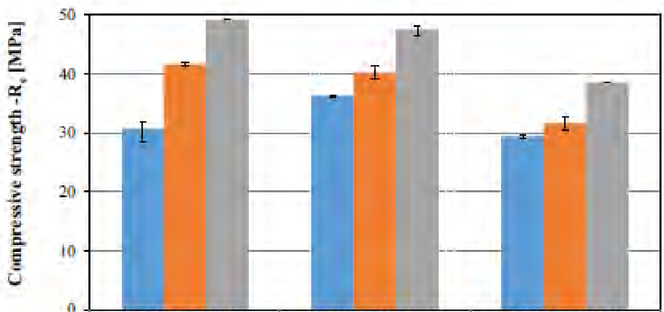
Figure 5.14 shows the compressive strength from the study (Pepe 2016), where the ratio for the concrete mix design was found. The RCA30 are with RCA in fraction (9.5-19 mm) and are significantly higher than the % replacement of RCA (4-8 mm) seen in this report. Similarities are however, seen when comparing the RCA (4-8 mm) to RCA60 from the study (where there are both RCA in fraction (4.75-9.5 mm) and (9.5-16 mm)).

The results found in the study shows a generally higher compressive strength for the 30 % RCA replacement with 0.5 w/c-ratio for both dry and saturated RCA.



	0.50NATSAT	0.50RAC30SAT	0.50RAC60SAT
1 day	23.16	25.24	20.15
3 days	38.06	34.73	27.79
28 days	47.00	40.88	31.66

(a)



	0.50NATDRY	0.50RAC30DRY	0.50RAC60DRY
1 day	30.67	36.29	29.35
3 days	41.65	40.20	31.65
28 days	49.12	47.55	38.57

(b)

Figure 5.14: Time evolution of compressive strength (Pepe 2016).

CHAPTER 6

Conclusion

To for see the resource shortage around bigger cities, RCA can be used to meet the demand of an expanding building industry and lowering the need of extraction of raw materials and disposal of concrete waste, while decreasing the transportation costs.
This project investigated the replacement of NA with RCA (4-8 mm) for 30 % and 50 % in concrete. Through testing for the compressive strength and workability of different mix design concretes the processing procedure of the RCA was examined. For the second phase of the mix designing the concrete mixtures the characteristics of the RCA (4-8 mm) was investigated.
Characteristics of RCA (4-8 mm) show that the aggregates had a higher open porosity, lower density and significantly higher water absorption than other studies of RCA. However, the AM was very similar to other studies, the properties for the open porosity, density and water absorption can therefore be due to the contaminants of the asphalt in the crushed concrete.
The high water absorption makes it hard to control the free water for the cement, by the proposed mix design methodology, it demonstrates that the deviation of the compressive strength and the workability of RAC can be met, by the RCA being saturated, in this thesis by pre-soaking.
The results for the compressive strength show that the maximum requirement according to DS/EN206 for RCA of an unknown source can be used and even exceed to 50 %.

6.1 Suggestion for Further Research

The investigations performed in this report has provided a lot of interesting results, however it has also triggered a number of new research fields that future investigations could seek to explore further.

A basic technical study and documentation of the mechanical properties of new concrete with various fraction of coarse aggregates, including determination of e-module, creep and shrinkage.

An assessment of market demands, opportunities and barriers for recycling of concrete aggregates in new concrete, as well as an examination of whether it is economical and environmental more advisable to recycle concrete waste as aggregates to new concrete compared with previous recycling of concrete in unbound form through a comprehensive Life Cycle Assessment. In addition there of, there is a need to define more quality categories similar to what already exist in the field of soil. It is important with definitions of clear national application criteria and defined limit values for different contaminants categories of concrete.

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APPENDIX A
Method Theory

This Appendix contains following additions to the method theory described in Chapter 4:

- Mean and Standard Deviation
- Porosity and Density (LBM Test Method 2)
- Cement Content (TI-B 9 (85))

A.1 Mean and Standard Deviation

The mean and standard deviation are used in the results for test that has been performed on at least two observations under the same conditions. This section describes how they were calculated. The mean, μ, (also called average or arithmetic mean) is calculated by:

$$\mu = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i \tag{A.1}$$

where n is the number of observations and x_i is the value for each observation. The standard deviation, σ, is calculated by:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \mu)^2}{n}} \tag{A.2}$$

where μ is the mean, n is the number of observations and x_i is the value for each observation. Extreme results, e.g. a very low compressive strength (with a standard deviation above 2 is considered high), are still included in the calculations but it will result in a higher standard deviation for the whole measurement.

A.2 Porosity and Density (LBM Test Method 2)

The LBM test method 2 used for calculating the open porosity and density.

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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/m³			
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)

A.3 Cement Content (TI-B 9 (85))

The TI-B 9 (85) test method used for calculating the cement content of the aggregates with acidification of concrete. The test was scaled to test portions of 20 g.

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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 B

Experimental Procedure

This Appendix contains following additions to the method described in Chapter 4:

- Particle size distribution
- Los Angeles abrasion
- Cement Content
- Porosity and Density (LBM test method 2)
- Density and Water absorption
- Water Content
- Mixing Procedure
- Compressive Strength

B.1 Particle size distribution

Two particle size distribution tests were performed, each test portion consisted of 10 kg crushed concrete. The test portions were prepared by being weighed and dried to a constant mass at 105 ^{o}C. This took 24 h. The test portions were weighed and sieved through sieve column, the fraction smaller than 1 mm was run through laser diffractometer.
Equipment:

- A ventilated oven
- Scale
- Sieve column (0, 1, 2, 4, 8, 16 and 31,5 mm)
- Mastersizer 2000 laser diffractor

Raw Data

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
Total	8823		

(a) Sieve column 1 (1-31.5 mm).

Fraction [mm]	Passing [g]	Passing [%]	Cumulative passing [%]
<1	1370	15,22	15,22
1	612	6,80	22,02
2	765	8,50	30,52
4	1016	11,29	41,81
8	1683	18,70	60,51
16	3377	37,52	98,03
31,5	177	1,97	100,00
Total	9000		

(b) Sieve column 2 (1-31.5 mm).

Laser diffractometer 1

Raw data		Treated data			
µm	mm	Passing [%	Cumul. passir	Relative pa	Relative cumul. passing [%]
1,65959	0,00166	0	0	0	0
1,90546	0,00191	0,022552	0,022552	0,0040023	0,0040023
2,18776	0,00219	0,046498	0,06905	0,008252	0,0122543
2,51189	0,00251	0,054734	0,123784	0,0097136	0,021968
2,88403	0,00288	0,079926	0,20371	0,0141845	0,0361524
3,31131	0,00331	0,095818	0,299528	0,0170048	0,0531572
3,80189	0,0038	0,105932	0,40546	0,0187998	0,071957
4,36516	0,00437	0,11846	0,52392	0,0210231	0,0929801
5,01187	0,00501	0,130255	0,654175	0,0231164	0,1160965
5,7544	0,00575	0,142234	0,796409	0,0252423	0,1413387
6,60693	0,00661	0,154245	0,950654	0,0273739	0,1687126
7,58578	0,00759	0,166169	1,116823	0,02949	0,1982026
8,70964	0,00871	0,178326	1,295149	0,0316475	0,2298501
10	0,01	0,190497	1,485646	0,0338075	0,2636576
11,4815	0,01148	0,203187	1,688833	0,0360596	0,2997172
13,1826	0,01318	0,216151	1,904984	0,0383603	0,3380776
15,1356	0,01514	0,229951	2,134935	0,0408094	0,378887
17,378	0,01738	0,244447	2,379382	0,043382	0,422269
19,9526	0,01995	0,260414	2,639796	0,0462157	0,4684847
22,9087	0,02291	0,278373	2,918169	0,0494029	0,5178876
26,3027	0,0263	0,300124	3,218293	0,053263	0,5711506
30,1995	0,0302	0,327472	3,545765	0,0581165	0,629267
34,6737	0,03467	0,36315	3,908915	0,0644482	0,6937153
39,8107	0,03981	0,40925	4,318165	0,0726296	0,7663449
45,7088	0,04571	0,467938	4,786103	0,083045	0,8493899
52,4807	0,05248	0,540715	5,326818	0,0959607	0,9453506
60,256	0,06026	0,628629	5,955447	0,1115628	1,0569134
69,1831	0,06918	0,733648	6,689095	0,1302005	1,1871139
79,4328	0,07943	0,857468	7,546563	0,1521749	1,3392888
91,2011	0,0912	1,006511	8,553074	0,1786255	1,5179143
104,713	0,10471	1,186596	9,73967	0,2105852	1,7284996
120,226	0,12023	1,414083	11,153753	0,2509574	1,9794569
138,038	0,13804	1,702404	12,856157	0,3021257	2,2815826
158,489	0,15849	2,082315	14,938472	0,3695485	2,6511311
181,97	0,18197	2,566036	17,504508	0,4553945	3,1065256
208,93	0,20893	3,184601	20,689109	0,5651712	3,6716969
239,883	0,23988	3,9185	24,607609	0,6954163	4,3671132
275,423	0,27542	4,762717	29,370326	0,8452395	5,2123527
316,228	0,31623	5,640117	35,010443	1,0009518	6,2133045
363,078	0,36308	6,485966	41,496409	1,1510646	7,3643691
416,869	0,41687	7,183188	48,679597	1,2748006	8,6391697
478,63	0,47863	7,640761	56,320358	1,3560061	9,9951758
549,541	0,54954	7,770526	64,090884	1,3790355	11,374211
630,957	0,63096	7,531783	71,622667	1,3366658	12,710877
724,436	0,72444	6,936016	78,558683	1,230935	13,941812
831,764	0,83176	6,0475	84,606183	1,07325	15,015062
954,993	0,95499	4,974461	89,580644	0,8828178	15,89788
1096,48	1,09648	3,85005	93,430694	0,6832685	16,581148
1258,93	1,25893	2,788742	96,219436	0,4949181	17,076067
1445,44	1,44544	1,886057	98,105493	0,3347186	17,410785
1659,59	1,65959	1,174452	99,279945	0,20843	17,619215
1905,46	1,90546	0,589239	99,869184	0,1045723	17,723787
2187,76	2,18776	0,130817	100,000001	0,0232161	17,747004
2511,89	2,51189	0	100,000001	0	17,747004

(c) Laser diffractometer 1 (<1 mm).

Laser diffractometer 2

Raw data		Treated data			
µm	mm	Passing [%	Cumul. passir	Relative pa	Relative cumul. passing [%]
1,65959	0,00166	0	0	0	0
1,90546	0,00191	0	0	0	0
2,18776	0,00219	0,061173	0,061173	0,0094987	0,0094987
2,51189	0,00251	0,069693	0,130866	0,0108216	0,0203203
2,88403	0,00288	0,081457	0,212323	0,0126483	0,0329687
3,31131	0,00331	0,091868	0,304191	0,0142649	0,0472336
3,80189	0,0038	0,103595	0,407786	0,0160858	0,0633194
4,36516	0,00437	0,114675	0,522461	0,0178063	0,0811256
5,01187	0,00501	0,125963	0,648424	0,019559	0,1006847
5,7544	0,00575	0,137021	0,785445	0,0212761	0,1219607
6,60693	0,00661	0,148146	0,933591	0,0230035	0,1449643
7,58578	0,00759	0,159164	1,092755	0,0247143	0,1696786
8,70964	0,00871	0,1705	1,263255	0,0264746	0,1961532
10	0,01	0,182079	1,445334	0,0282725	0,2244257
11,4815	0,01148	0,194565	1,639899	0,0302113	0,2546369
13,1826	0,01318	0,207917	1,847816	0,0322845	0,2869214
15,1356	0,01514	0,222881	2,070697	0,0346081	0,3215295
17,378	0,01738	0,239312	2,310009	0,0371594	0,3586889
19,9526	0,01995	0,257727	2,567736	0,0400188	0,3987077
22,9087	0,02291	0,277791	2,845527	0,0431343	0,441842
26,3027	0,0263	0,299913	3,14544	0,0465693	0,4884113
30,1995	0,0302	0,324061	3,469501	0,0503189	0,5387302
34,6737	0,03467	0,351193	3,820694	0,0545318	0,593262
39,8107	0,03981	0,382402	4,203096	0,0593778	0,6526399
45,7088	0,04571	0,419842	4,622938	0,0651914	0,7178312
52,4807	0,05248	0,466186	5,089124	0,0723875	0,7902187
60,256	0,06026	0,524489	5,613613	0,0814405	0,8716593
69,1831	0,06918	0,598383	6,211996	0,0929145	0,9645738
79,4328	0,07943	0,69019	6,902186	0,1071699	1,0717437
91,2011	0,0912	0,803893	7,706079	0,1248253	1,196569
104,713	0,10471	0,941234	8,647313	0,146151	1,34272
120,226	0,12023	1,110501	9,757814	0,1724341	1,5151542
138,038	0,13804	1,317136	11,07495	0,2045196	1,7196738
158,489	0,15849	1,580175	12,655125	0,2453632	1,965037
181,97	0,18197	1,909655	14,56478	0,2965236	2,2615605
208,93	0,20893	2,335623	16,900403	0,3626662	2,6242267
239,883	0,23988	2,862229	19,762632	0,4444354	3,0686621
275,423	0,27542	3,513032	23,275664	0,5454895	3,6141516
316,228	0,31623	4,26335	27,539014	0,6619959	4,2761475
363,078	0,36308	5,098186	32,6372	0,7916258	5,0677733
416,869	0,41687	5,9436	38,5808	0,9228983	5,9906717
478,63	0,47863	6,728981	45,309781	1,0448491	7,0355208
549,541	0,54954	7,344881	52,654662	1,1404836	8,1760044
630,957	0,63096	7,699278	60,35394	1,195513	9,3715174
724,436	0,72444	7,715628	68,069568	1,1980517	10,569569
831,764	0,83176	7,365644	75,435212	1,1437076	11,713277
954,993	0,95499	6,675813	82,111025	1,0365934	12,74987
1096,48	1,09648	5,72937	87,840395	0,8896336	13,639504
1258,93	1,25893	4,631198	92,471593	0,7191138	14,358618
1445,44	1,44544	3,498882	95,970475	0,5432923	14,90191
1659,59	1,65959	2,418107	98,388582	0,3754739	15,277384
1905,46	1,90546	1,308372	99,696954	0,2031587	15,480543
2187,76	2,18776	0,303046	100	0,0470558	15,527598
2511,89	2,51189	0	100	0	15,527598

(d) Laser diffractometer 2 (<1 mm).

Figure B.1: Test schemes for Particle size distribution.

B.2 Los Angeles

To test the wear resistance of the RCA (4-8 mm) the LA abrasion tests was conducted following DS/EN1097-2. Equipment:

- Los Angeles abrasion machine
- 8 steel balls
- 1.4 mm sieve
- Scale

The test portions was the two fractions of RCA (4-8 mm) from the particle size distribution test. The test portion was tested in a Los Angeles abrasion Machine with a speed of 30-33 rpm in 16.6 min. There was used 8 steel balls, with a diameter of 46 mm. Afterwards was the test portion sieved on a 1.4 mm sieve and the retained mass was weighed.

Raw Data

	m_0	m_1	LA abrasion loss [%]	Mean [%]	σ [%]
Portion 1	1533	708,1	53,80952381	55,62436	1,283281
Portion 2	1036	440,93	57,43918919		

Figure B.2: Test scheme for Los Angeles abrasion.

B.3 Cement content

The test studied the cement content of the RCA (4-8 mm) following first part of TI-B 9 (85).
Equipment:

- Conical flask
- Filter
- Beaker
- Scale
- Boiled, de-mineralised water
- HNO_3
- Pipette

- Fume cupboard

Three test portions were tested for respectively hole RCA (4-8 mm) and crushed RCA (4-8 mm), crushed vibratory disc mill in 20 sec. The test portions were prepared being weighed in beaker. The test portions were mixed with warm de-mineralised water. HNO_3 was added a bit at the time and mixed again each time. The HNO_3 is continuingly added in small dosage until there is no more air development. The solution was filtered through a filter into a beaker.
The drained filtered solution was dried to a constant mass at 105 ^oC. The dried test portion was then weighed again.

Raw Data

	m_0 [g]	Filter [g]	Petri dish [g]	Total [g]	m_1 [g]	Cement [%]	Mean	σ
RCA 1	20,02	1,92	107,6	124,14	14,62	26,973027		
RCA 2	20,046	1,938	112,96	131,85	16,952	15,4345006	19,51535	5,281202
RCA 3	20,07	1,962	110,867	129,66	16,831	16,1385152		
Crushed RCA 1	20,001	3,8	112,94	130,69	13,95	30,2534873		
Crushed RCA 2	20,682	1,951	106,29	124,39	16,149	21,9176095	24,45941	4,107287
Crushed RCA 3	20,031	1,955	107,082	124,82	15,783	21,207129		

Figure B.3: Test scheme for Cement Content.

B.4 Porosity and Density (LBM Test Method 2)

The test studied RCA (4-8 mm)'s density and porosity following the LBM test method 2 (Laboratoriet for Bygningsmaterialer - Prøvemetode 2).

Equipment:

- A ventilated oven
- Weighing instrument, over and under water
- Thermometer
- Net (with elastic)
- Desiccator
- Vacuum pump
- Cloth
- Boiled, de-mineralised water

Three test specimens were tested, one from each batch from the construction site. The test specimens were prepared by being washed and dried to a constant mass at 50 ^{o}C. This took 24 h. The specimens were weighed at room temperature (m_d) and evacuated in a desiccator for three hours in complete vacuum. After three hours, the specimens were covered with boiled, de-mineralised water cooled to room temperature covering 30 mm above the test specimens and they were left soaking still in vacuum. After one hour, the atmospheric pressure was re-established and the test specimens were left soaking overnight, approximately 18 h. Next day the specimens were weighed under water (m_{sw}) and with the surfaced dried (m_{ssd}).
The test specimens were weighed in water. Water with a temperature of 20 ^{o}C has an corresponding density of 998.2 $kg/m^3(rho_w)$, which was used for the calculations.

Raw Data

Specimens		1	2	3	Mean	σ
m105(50)	[kg]	0,10266	0,10002	0,10005		
mssd	[kg]	0,11057	0,10975	0,11308		
msw	[kg]	0,06054	0,06029	0,05979		
V	[m³]	0,00005	0,00005	0,00005	0,00005	0,00
Vpo	[m³]	0,00001	0,00001	0,00001	0,00001	0,00
P0	[m³/m³]	0,15811	0,19672	0,24451	0,19978	0,04
ρd	[kg/m³]	2048,27527	2018,60016	1874,08351	1980,31965	76,09
ρf	[kg/m³]	2432,93476	2512,96159	2480,62370	2475,50668	32,87
ρssd	[kg/m³]	2206,09582	2214,97068	2118,15455	2179,74035	43,70
ussd	[kg/kg]	0,07705	0,09728	0,13023	0,10152	0,02

Figure B.4: Test scheme for Porosity and Density (LBM Method 2).

B.5 Density and Water Absorption (Pycnometer)

To test the water absorption and the density of the RCA (4-8 mm) pycnometer tests were conducted following .
Equipment:

- 500 mL pycnometer
- De-mineralised water
- Scale
- Desiccator
- Vacuum pump
- Beaker

The test specimens were prepared by being washed and dried to a constant mass at 50 ^{o}C. This took 24 h. The specimens were weighed at room temperature (m_4) and put in a pycnometer filled $frac34$ with de-minieralised water. The open pycnometer and a beaker with de-mineralised water were evacuated in a desiccator for 18 hours in complete vacuum. After the 18 hours the pycnometer was overfilled with the water from the beaker, closed and dried on the outside before it was weighed. Afterwards the the specimens were removed from the water and dried to s.s.d. conditions in order to calculate the water absorption.

Raw Data

				1	2	3
Fra kalibrering af pyknometer						
Pyknometer nummer				40	30	40
Pykn. + prop (tomt)		m_0	g	363,67	363,67	363,67
Pykn. + prop (vandfyldt)	W_2	m_1	g	944,15	944,15	944,15
Temperatur ved kalibrering	T_k	T_1	°C	22	22	22
Densitet af vand ved T_k *	$\rho_{w,k}$	$\rho_{w;1}$	g/cm^3	0,9978	0,9978	0,9978
Måling						
Pykn.+ prop + jord + vand	W_1	m_3	g	1032,54	1029,25	1031,75
Temperatur	T	T_3	°C	22	22	22
Densitet af vand ved T *	$\rho_{w,t}$	$\rho_{w;3}$	g/cm^3	0,9978	0,9978	0,9978
Bærger ID				20	30	40
Bæger			g	294,58	294,07	294,68
Bæger + jord			g	444,63	444,3	444,71
Jord - masse	W_s	m_4	g	150,05	150,23	150,03
Vand - masse	W_1-W_3	m_3-m_2	g	518,82	515,35	518,05
Jord - volumen	V_s		cm^3	61,796	65,2736	62,5676
Korndensitet	ρ_s	ρ_s	g/cm^3	2,42815	2,30154	2,39788
Resultat - middel	ρ_s	ρ_s	g/cm^3	**2,3759**		
Jord - s.s.d. Masse	m_5		g	171,24	171,51	168,13
Vand absorption	WA		%	14,122	14,1649	12,0643
Vand absoption: middel	WA		%	13,4504		

Figure B.5: Test scheme for pycnometer.

B.6 Water Content

The test studied the RCA (4-8 mm)' water content following DS/EN1097-5.
Equipment:

- A ventilated oven
- Containers (tins)
- Scale

Three test specimens were tested. The test specimens were of untreated RCA (4-8 mm). They were weighed and dried to a constant mass at 105 ^{o}C. This took 24 h days and then weighed again.

Raw Data

Specimen	Before [g]	After [g]	Water content [%]	Mean [%]	σ [%]
1	200	173	13,5		
2	200	180	10	12,5	1,779513
3	200	172	14		

Figure B.6: Test scheme for water content.

B.7 Mixing concrete cylinders

The casting of the different mix design concretes was conducted according to DS/EN12390-2 and DS/EN12390-3. Equipment:

- Scale
- Concrete mixer
- Slump cone
- Pressure gauge
- Vibration table
- Molds
- Buckets
- Oil for the molds

B.7.1 CEM II/A.LL 52,5 N

This section contains specifications of Basis Aalbog cement:

BASIS AALBORG CEMENT

BASIS® AALBORG CEMENT
CEM II/A-LL 52,5 N (LA)

PRODUKT
BASIS AALBORG CEMENT er en portlandkalkstenscement, styrkeklasse 52,5 N.
BASIS AALBORG CEMENT er fremstillet ved samformaling af portlandcementklinker og op til 20 % finkornet kalkfiller.

KVALITET OG EGENSKABER
Alkaliindhold - BASIS AALBORG CEMENT har et ækvivalent alkaliindhold på ≤ 0,6 %.

Sulfatbestandighed - BASIS AALBORG CEMENT betegnes som ikke sulfatbestandig, da det er en portlandkalkstenscement.

Kromatindhold - BASIS AALBORG CEMENT har et kromatindhold på ≤ 2 mg/kg.

BASIS AALBORG CEMENT har gennemgået en ANTI-KROM-EKSEM proces, hvor indholdet af vandopløseligt kromat vil være mindre end 2 mg/kg cement. Virkningen af kromneutraliseringen garanteres for sække på paller med ubrudt folie i 10 måneder; herefter i 2 måneder ved hensigtsmæssig opbevaring. Se afsnit vedrørende opbevaring.

Vejledende værdier
Nedenfor er anført vejledende værdier for de væsentligste egenskaber:

- Cementstyrker
  2 døgn: 33 MPa
  28 døgn: 60 MPa
- Afbinding:
  2:30 timer
- Bulkdensitet: 1100 kg/m^3
  Absolut densitet: 3100 kg/m^3

Figure B.7: Cement used for all mixtures.

B.7.2 Slump

The slump value was measured with a standard sized cone, with a height of 300 mm ± 2 mm, a base diameter of 200 mm ± 2 mm and a top diameter of 100 mm ± 2 mm. The cone is filled a third at a time and stomped 25 times with a metal rod before the next third is filled and finally topped off. The cone is then lifted and the amount of which the concrete set is measured.

B.7.3 Air Content

The pressure gauge designed to measure air content was filled with concrete and vibrated at 60 Hz on the vibration table. The lid was secured with hinges on top and then it was topped of with water through the pipes on the sides, followed by pumping air in until it was full. Then the green button was push and the air content was noted.

B.8 Compressive Strength

Equipment:

- TONI Technik
- Fiberboards
- Caliper
- Scale

B.8.1 Applied Load, TONI Technik

A constant rate of loading was selected, according to EN 12390-3, within the range of:

$$0.6 \pm 0.2MPa/s \tag{B.1}$$

Cross-sectional area of test specimen:

$$\pi \cdot r^2 = A \tag{B.2}$$

$$\pi \cdot \left(\frac{100}{2}\right)^2 = 7850mm^2 \tag{B.3}$$

Constant loading rate:

$$0.6 \cdot 7.85 = 4.71kN/s \tag{B.4}$$

Raw Data

Mix design	w/c	Cating	Curring	Slump [mm]	Air content [%]	Specimen	D [mm]	Area [mm2]	H [mm]	W [kg]	Load [kN]	[MPa]	Mean [Mpa]	σ	Displacement [mm]	Observation
0.5NA	0,5	13.02.17	28 days	60	1,4	1	100	7850	200	3,762	278	35,414	33,651746	5,2597	1,6	3 or 4
						2	100	7850	199	3,753	300	38,2166			1,6	3 or 4
						3	100	7850	200	3,722	194	24,7134			2,2	D
						4	99	7693,785	200	3,751	279	36,263			1,5	4
		01.05.17		60	1,5	1	100	7850	200	3,744	237	30,1911	36,910828	3,9133	1,6	3
						2	100	7850	199,5	3,74	301	38,3439			1,6	4
						3	100	7850	200	3,749	312	39,7452			2,1	J
						4	100	7850	200	3,754	309	39,3631			1,7	4
		28.02.17	7 days	40	1,5	1	100	7850	200	3,728	226	28,7898	27,101911	2,027		1
						2	100	7850	199	3,706	231	29,4268				3
						3	100	7850	199	3,733	195	24,8408				J
						4	100	7850	198	3,681	199	25,3503				4
0.5RCA30 DRY	0,5	02.05.17	28 days	30	1,4	1	100	7850	199	3,669	253	32,2293	30,509554	4,1762	1,2	I
						2	100	7850	199,5	3,666	261	33,2484			1,2	4
						3	100	7850	200	3,655	183	23,3121			1,4	4
						4	100	7850	199	3,682	261	33,2484			1,2	3
		10.03.17	7 days	10	2	1	100	7850	200	3,69	264	33,6306	31,077171	2,3313	1,6	4
						2	99	7693,785	200	3,686	211	27,4247			1,5	I
						3	99,5	7771,69625	199,5	3,663	252	32,4254			1,3	4
						4	100	7850	200	3,649	242	30,828			2,3	J
0.5RCA30 SAT	0,5	30.03.17	7 days	20	1,8	1	100	7850	200	3,672	179	22,8025	22,636413	0,6051	4,9	B
						2	99,5	7771,69625	199	3,637	177	22,775			2,4	4
						3	100	7850	200	3,673	183	23,3121			2,6	4
						4	100	7850	199,5	3,663	170	21,6561			2,5	4
0.5RCA30 SATC	0,5	02.05.17	28 days	40	1,3	1	100	7850	199	3,673	266	33,8854	34,458599	3,2158	1,2	3
						2	100	7850	199,5	3,688	313	39,8726			0,9	3
						3	100	7850	200	3,695	252	32,1019			1,1	I
						4	100	7850	199,5	3,653	251	31,9745			1,2	I
		14.03.17	7 days	20	1,5	1	100	7850	200	3,697	230	29,2994	28,385422	0,9151	1,3	3
						2	99,5	7771,69625	199	3,668	213	27,4071			2,2	I
						3	99,5	7771,69625	199	3,652	214	27,5358			1,8	I
						4	100	7850	200	3,691	230	29,2994			1,8	3
0.5RCA30 U.SATC	0,5	05.05.17	7 days	80	1,4	1	100	7850	199,5	3,649	159	20,2548	24,465176	4,225	2,8	D
						2	100	7850	200	3,665	159	20,2548			3,1	3
						3	100	7850	200	3,679	229	29,172			1,8	4
						4	99,5	7771,69625	200	3,673	219	28,1792			1,5	4
0.5RCA50 DRY	0,5	14.02.17	28 days	20	1,1	1	100	7850	200	3,678	229	29,172	34,525198	4,6214	2,2	3
						2	100	7850	198	3,622	241	30,7006			1,9	4
						3	99	7693,785	200	3,674	300	38,9925			1,7	I
						4	100	7850	200	3,675	308	39,2357			1,5	4
		28.02.17	7 days	0	2,1	1	100	7850	200	3,626	253	32,2293	29,872611	2,721	1,7	J
						2	100	7850	200	3,641	204	25,9873			1,7	Aor D
						3	100	7850	200	3,655	256	32,6115			1,5	J
						4	100	7850	200	3,612	225	28,6624			1,4	3
0.5RCA50 U	0,5	05.05.17	7 days	40	0,9	1	100	7850	200	3,642	204	25,9873	27,579618	2,2402	1,5	3
						2	100	7850	199,5	3,643	229	29,172			1,4	3
						3	100	7850	199,5	3,62	238	30,3185			1,3	1
						4	100	7850	200	3,623	195	24,8408			1,4	J

Figure B.8: Test scheme for compressive strength for 0.5 w/c-ratio.

Mix design	w/c	Cating	Curring	Slump [mm]	Air content [%]	Specimen	D [mm]	Area [mm2]	H [mm]	W [kg]	Load [kN]	[MPa]	Mean [Mpa]	σ	Displacement [mm]	Observation
0.6NA	0,6	13.02.17	28 days	130	1,2	1	99	7693,785	200	3,717	237	30,8041	29,9940146	0,8839	1,6	4
						2	100	7850	200	3,716	240	30,5732			1,5	H
						3	100	7850	199	3,702	236	30,0637			1,6	4
						4	100	7850	199	3,708	224	28,535			1,5	3 or 4
		01.03.17	7 days	30	1,7	1	100	7850	199	3,692	164	20,8917	24,532193	2,8657	1,7	3
						2	99,5	7771,69625	199,5	3,712	181	23,2896			2	I
						3	100	7850	198,5	3,693	198	25,2229			2,4	3
						4	99	7693,785	200	3,668	221	28,7245			2,4	4
0.6RCA30 DRY	0,6	02.05.17	28 days	40	1,3	1	100	7850	200	3,673	275	35,0318	32,9018032	3,6112	0,7	3
						2	100	7850	200	3,641	213	27,1338			1,5	3
						3	99	7693,785	200	3,653	252	32,7537			1,4	4
						4	100	7850	199,5	3,67	288	36,6879			0,7	3
		10.03.17	7 days	10	1,4	1	99	7693,785	198,5	3,651	208	27,0348	23,3846702	4,4796		3
						2	99,5	7771,69625	200	3,67	204	26,2491				3
						3	100	7850	200	3,689	192	24,4586				4
						4	100	7850	200	3,681	124	15,7962			2,3	4
0.6RCA30 SAT	0,6	30.03.17	7 days	10	1,7	1	99,5	7771,69625	199,5	3,655	153	19,6868	18,0287661	1,7941	1,8	3
						2	100	7850	199	3,627	126	16,051			1,9	3
						3	99,5	7771,69625	199	3,642	155	19,9442			1,8	4
						4	100	7850	199	3,656	129	16,4331			2,5	1
0.6RCA30 SATC	0,6	02.05.17	28 days	60	0,9	1	100	7850	200	3,744	237	30,1911	37,0099787	3,9787	1,6	3
						2	100	7850	199,5	3,74	301	38,3439			1,6	4
						3	100	7850	200	3,749	312	39,7452			2,1	J
						4	99,5	7771,69625	200	3,754	309	39,7597			1,7	4
		14.03.17	7 days	30	1,7	1	100	7850	200	3,662	176	22,4204	23,1528662	0,7975	1,6	I
						2	100	7850	198	3,673	188	23,949			1,5	3
						3	100	7850	200	3,678	188	23,949			2,4	3
						4	100	7850	200	3,678	175	22,293			1,4	I
0.6RCA30 U.SATC	0,6	05.05.17	7 days	10	1,3	1	100	7850	200	3,653	158	20,1274	20,1910828	0,4975	1,3	3
						2	100	7850	199,5	3,668	159	20,2548			1,4	3
						3	100	7850	199,5	3,66	164	20,8917			1,3	4
						4	100	7850	199,5	3,657	153	19,4904			1,1	H
0.6RCA50 DRY	0,6	15.02.17	28 days	20	2,1	1	100	7850	200	3,609	233	29,6815	29,9681529	2,9812	2,6	4
						2	100	7850	200	3,642	258	32,8662			2,4	3
						3	100	7850	200	3,622	252	32,1019			1,8	4
						4	100	7850	200	3,594	198	25,2229			1,4	3
		01.03.17	7 days	10	1,8	1	99,5	7771,69625	199	3,606	159	20,4589	21,8742466	1,8933	1,9	3
						2	99,5	7771,69625	199	3,599	184	23,6757			2	4
						3	99,5	7771,69625	197,5	3,776	152	19,5581			1,7	4
						4	99,5	7771,69625	199,5	3,59	185	23,8043			1,4	4
0.6RCA50 U	0,6	13.03.17	7 days	20	1,8	1	99,5	7771,69625	199	3,618	132	16,9847	17,3224322	2,2542	2,4	3
						2	99,5	7771,69625	200	3,642	150	19,3008			2	I or E
						3	99,5	7771,69625	200	3,605	107	13,7679			4	3
						4	99	7693,785	200	3,615	148	19,2363			2,4	I
0.6RCA50 SATC	0,6	09.03.17	7 days	20	1,5	1	99,5	7771,69625	200	3,638	163	20,9735	21,2964401	1,4838	1,3	1
						2	100	7850	200	3,646	164	20,8917			1,3	3
						3	99	7693,785	200	3,612	151	19,6262			1,3	3
						4	100	7850	200	3,639	186	23,6943			1,4	3

Figure B.9: Test scheme for compressive strength for 0.6 w/c-ratio.

APPENDIX C
Results: Elaborated Version

This appendix contains following additional results from the tests presented in Chapter 5.

- Particle size distribution
- Porosity and Density (LBM test method 2)
- Density and Water absorption
- Compressive strength

C.1 Particle Size Distribution

The results are based on DS/EN933-1. Figure C.5 to C.4 show the results from the four test conducted. The distribution of the fractions < 1 mm have very similar tendencies, but the second test portion is a bit lower which means it represents a lower percentage of the test portion (0-31.5 mm) than the fraction < 1 mm of the first test portion. The distribution of the fraction 1-31.5 mm variate from the fraction of 4 mm and up. These figures will appear in the thesis of KNJ as well.

As it can be seen on Figure C.5 and C.3 the measurements from the laser diffractometer exceeds 1 mm, the measurements have therefore been cropped to only include sizes up to 1 mm. When cropped the two different measurements, for both portion one and two, fit quite nice together. The particle size distribution curves can be considered complete from 0.01 μm - 31.5 mm.

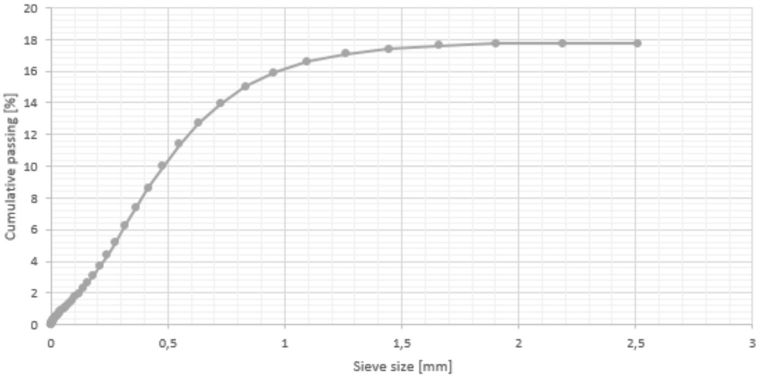


Figure C.1: Laser diffractometer 1 (< 1 mm).

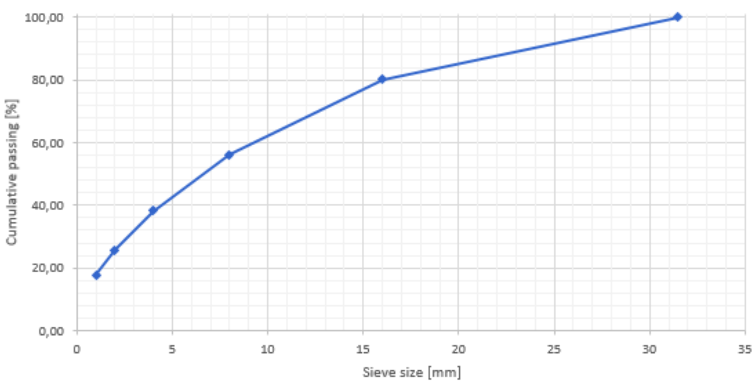


Figure C.2: Sieve column 1 (1-31.5 mm).

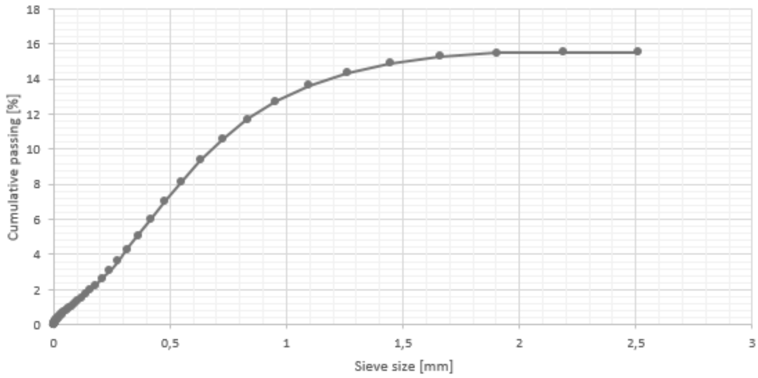


Figure C.3: Laser diffractometer 2 (< 1 mm).

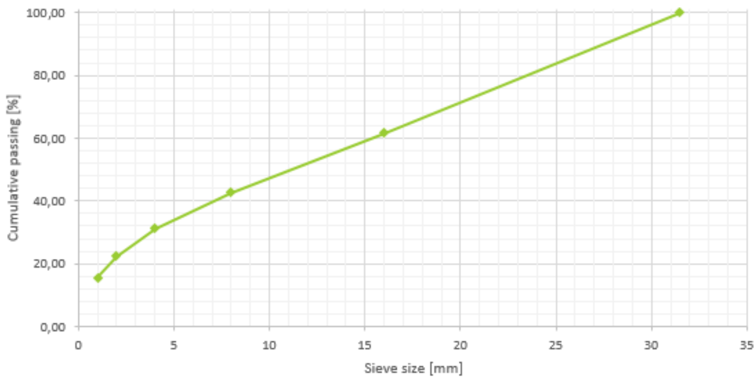


Figure C.4: Sieve column 2 (1-31.5 mm).

C.2 Density and Porosity

The test resuslts are based on the LBM test method 2. The equations are shown in Appendix A.

Property		**RCA (4-8 mm)**
Volume V	mm^3	55025.71
Pore volume V_{po}	mm^3	14248.98
Open porosity P_o	m^3/m^3	0,25817
Apparent density ρ_d	kg/m^3	1834.81
Real density ρ_f	kg/m^3	2475.51
Vacuum saturated density ρ_{ssd}	kg/m^3	2093.52
Water/solid ratio u_{ssd}	kg/kg	0.14117

Table C.1: Results from density and porosity test. The mean is based on results from three test specimens.

C.3 Compressive Strength

This section contains the test scheme for the different mix design concretes and the figures for the compressive strength for the RCA (8-16mm) investigated by KNJ.

Mix designs	**w/c**	**Curring** [d]	**Slump** $[mm]$	**Air content** [%]	**Mean** $[MPa]$	σ
0.5NA	0.5	28	60	1.4	33.65	5.26
0.5NA	0.5	7	40	1.5	27.11	2,03
0.5RCA30 DRY	0.5	7	10	2	31.08	2.33
0.5RCA30 SATC	0.5	7	20	1.5	28.39	0.92
0.5RCA50 DRY	0.5	28	20	1.1	34.53	4.62
0.5RCA50 DRY	0.5	7	0	2.1	29.87	2.72
0.6NA	0.6	28	130	1.2	29.99	0.88
0.6NA	0.6	7	30	1.7	24.53	2.87
0.6RCA30 DRY	0.6	7	10	1.4	23.38	4.48
0.6RCA30 SATC	0.6	7	30	1.7	23.15	0.8
0.6RCA50 DRY	0.6	28	20	2.1	29.97	2.98
0.6RCA50 DRY	0.6	7	10	1.8	21.87	1.89
0.6RCA50 U	0.6	7	20	1.8	17.32	2.25
0.6RCA50 SATC	0.6	7	20	1.5	21.3	1.48

Table C.2: Compressive strength for mix designs investigated for the screening.

Mix designs	**w/c**	**Curring [d]**	**Slump** $[mm]$	**Air content** [%]	**Mean** $[MPa]$	σ
0.5NA	0.5	28	60	1.5	36.91	3.91
0.5RCA30 DRY	0.5	28	30	1.4	30.51	4.18
0.5RCA30 SAT	0.5	7	20	1.8	22.64	0.61
0.5RCA30 SATC	0.5	28	40	1.3	34.46	3.22
0.5RCA30 U.SATC	0.5	7	80	1.4	24.47	4.23
0.5RCA50 U	0.5	7	40	0.9	27.58	2.24
0.6RCA30 DRY	0.6	28	40	1.3	32.9	3.61
0.6RCA30 SAT	0.6	7	10	1.7	18.03	1.79
0.6RCA30 SATC	0.6	28	60	0.9	37.01	3.98
0.6RCA30 U.SATC	0.6	7	10	1.3	20.19	0.5

Table C.3: Compressive strength for mix designs investigated after screening.

C.3.1 Bolomey Formula

Bolomey formula was calculated with the constants for Basis Aalbog cement for respectively 7 and 28 days of curing.

w/c	**Days of curing**	f_c **[MPa]**
0.5	7	31.2
0.5	28	40.6
0.6	7	23.2
0.6	28	30.9

Table C.4: Bolomey formula.

Danske Cementtyper	Termin [døgn]	K	α
Basis cement	1	17	0,9
	7	28	0,6
	28	30	0,5
Rapid cement	1	13	0,9
	7	24	0,6
	28	30	0,5
Lavalkali sulfatbestandig cement	1	5	0,8
	7	19	0,8
	28	29	0,7
Aalborg White	1	14	1,0
	7	25	0,8
	28	35	0,7
Basis Aalborg cement	1	13	1,0
	7	24	0,7
	28	29	0,6

Værdierne er gældende for søsten i klasse A og M. God kvalitet af granitsten giver op til 10 % højere 28-døgns styrker. For klasse P materialer skal 28-døgns styrken reduceres med 5-10 %.
Værdierne er kun gældende for rene cementbetoner. Hvis der anvendes flyveaske eller mikrosilica skal værdierne bestemmes for de aktuelle sammensætninger.

Figure C.5: Constants for Bolomeys formulas.

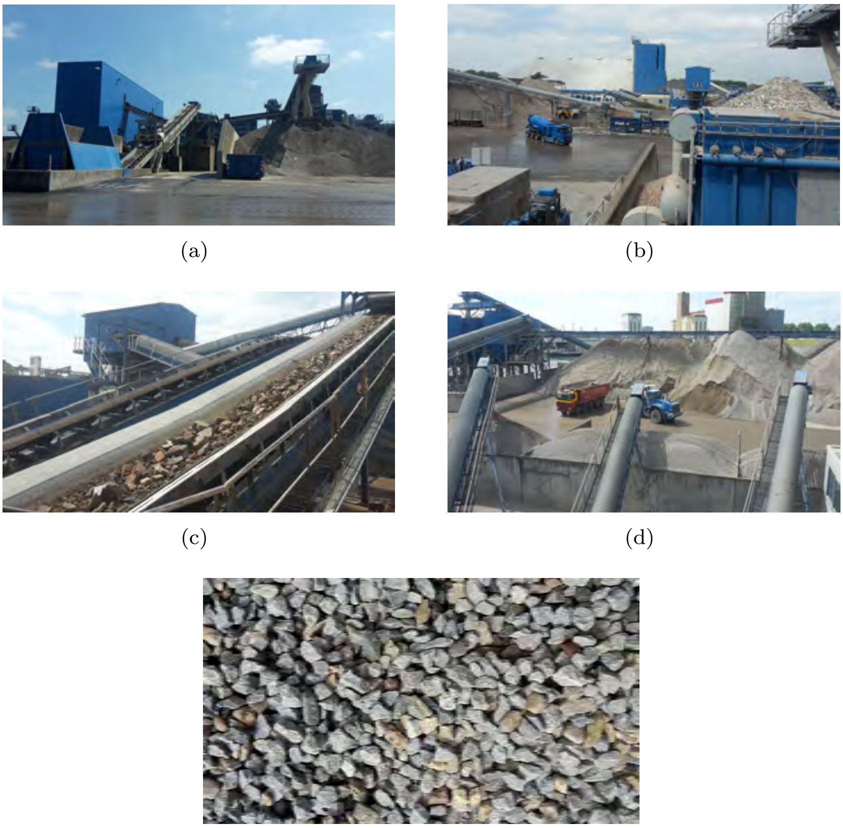
APPENDIX D
Field Trip to Holland

DAKOFA and Dansk Beton had together with Theo Pouw Group in Holland, organized a study trip to Holland from the 9th of May to the 11th of May. The field trip was a part of an initiative that DAKOFA and Dansk Beton have launched together in order to develop the basis conditions and Danish solutions for recycling concrete aggregates for production of new concrete with inspiration from the Dutch solutions. (DAKOFA 2017) gives a brief overview of some of the dividend they took home from the trip, including concrete national CE goals create stable framework, focus on CO_2 reduction gives points for project proposals and certification of demolition.

During the trip we visited two recycling concrete plants, the first one of Theo Pouw in Utrecht, see Figure D.2. Beside the plant they also do certified demolition which ensure control over the technical quality. This knowledge is used, together with receiving control, to decide further processing and treatment to ultimately achieve the best grades of recycled materials. Out of the concrete that they receive 70 % are used for road-fill and base layer and the other 30 % are used for recycling as RCA. The RCA from this plant consist of regenerating the coarse aggregates from the original concrete, see Figure D.1(e). The new concrete products mainly go to utility for roads. To ensure the quality of the aggregates they are tested 10 times per hour.

The second second recycling concrete plant, Rewinn just outside of Amsterdam, is a collaboration between Theo Pouw and Sagrex (Heidelberg cement). This plant was significantly smaller than the one in Utrecht and only focuses on concrete from and too Amsterdam. Here was the RCA more similar to the crushed concrete aggregates we see here in Denmark. Figure D.2(e) is the RCA fraction 8-24 mm after crushing, which looks like the aggregates we collected from Rødovre. Figure D.2(d) shows the aggregates after they were washed.

In order to capture some of the contaminants that has not been sorted from earlier in the process, they have two men to keep an eye on the aggregates. One just before the aggregates are washed, Figure D.2(b), and one after they were washed, Figure D.2(c).



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

Figure D.1: Theo Pouw Utrecht, concrete production processing by an extractive cleaner, stationary crusher and washing-crushing plant.

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

Figure D.2: Rewinn Amsterdam, concrete waste is crushed before it is processed in the granular washer.

APPENDIX E

Standards of Assessments

This Appendix contains additional tables to the relevant standards of assessment of RCA described in Chapter 2.

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 vandopløselige 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 miljøklasse: 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 E.1: EN 206-1 Table 2426-3.

The proportions of constituent materials in coarse recycled aggregate must be declared with the relevant categories specified in Figure E.2 with descriptions from Figure E.3.

Table 20 — Categories for constituents of coarse recycled aggregates

Constituent	Content Percentage by mass	Category
Rc	≥ 90	Rc_{90}
	≥ 80	Rc_{80}
	≥ 70	Rc_{70}
	≥ 50	Rc_{50}
	< 50	Rc_{Declared}
	No requirement	Rc_{NR}
Rc + Ru	≥ 95	Rcu_{95}
	≥ 90	Rcu_{90}
	≥ 70	Rcu_{70}
	≥ 50	Rcu_{50}
	< 50	Rcu_{Declared}
	No requirement	Rcu_{NR}
Rb	≤ 10	Rb_{10-}
	≤ 30	Rb_{30-}
	≤ 50	Rb_{50-}
	> 50	Rb_{Declared}
	No requirement	Rb_{NR}
Ra	≤ 1	Ra_{1-}
	≤ 5	Ra_{5-}
	≤ 10	Ra_{10-}
X + Rg	≤ 0,5	$XRg_{0,5-}$
	≤ 1	XRg_{1-}
	≤ 2	XRg_{2-}
	Content cm^3/Kg	
FL	≤ 0,2 [a]	$FL_{0,2-}$
	≤ 2	FL_{2-}
	≤ 5	FL_{5-}

[a] The ≤ 0,2 category is intended only for special applications requiring high quality surface finish.

Figure E.2: DS/EN 12620 Anneks E Table 20.

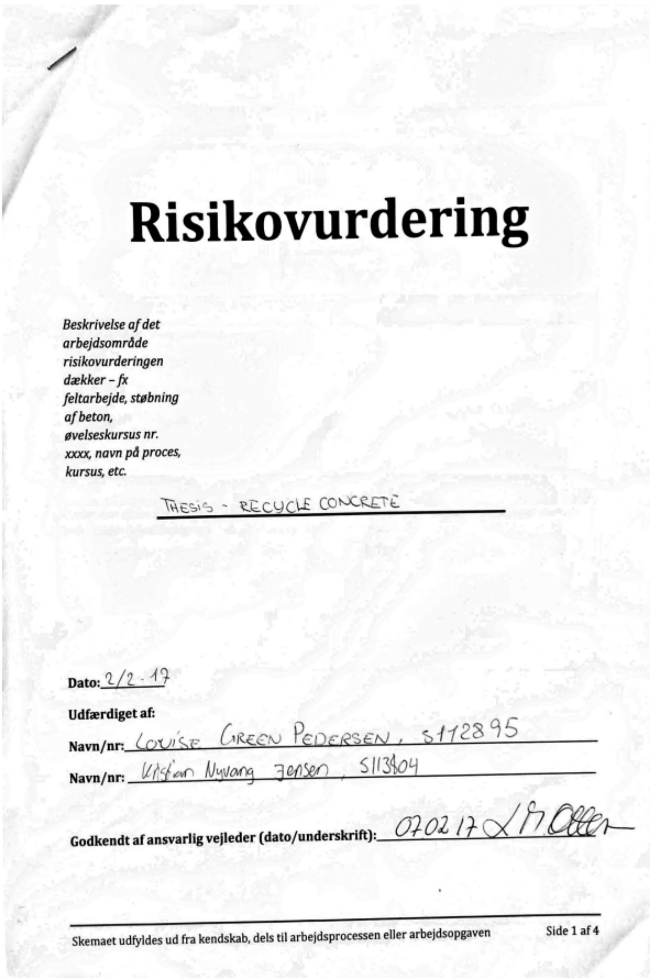
Constituent	Description
Rc	Concrete, concrete products, mortar Concrete masonry units
Ru	Unbound aggregate, natural stone Hydraulically bound aggregate
Rb	Clay masonry units (i.e. bricks and tiles) Calcium silicate masonry units Aerated non-floating concrete
Ra	Bituminous materials
FL	Floating material in volume
X	Other: Cohesive (i.e. clay and soil) Miscellaneous: metals (ferrous and non-ferrous), non-floating wood, plastic and rubber Gypsum plaster
Rg	Glass

Figure E.3: Description for DS/EN 12620 Anneks E Table 20.

APPENDIX F

Risk Assessments

This Appendix contains the necessary risk assessment for the laboratory.



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, s113404

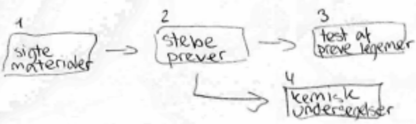
Godkendt af ansvarlig vejleder (dato/underskrift): 07 02 17 [illegible]

Skemaet udfyldes ud fra kendskab, dels til arbejdsprocessen eller arbejdsopgaven

Side 1 af 4

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.

Skemaet udfyldes ud fra kendskab, dels til arbejdsprocessen eller arbejdsopgaven   Side 2 af 4

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

Midtterm Presentation

This Appendix contains a poster from the midterm presentation.

DTU Civil Engineering
Department of Civil Engineering

DTU

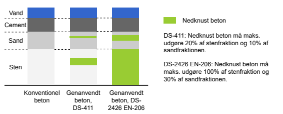
Genanvendelse af Betonaggregater

Introduktion

I 2013 blev der registreret 680.664 tons betonaffald i Danmark og ifølge Miljøstyrelsen udgør beton ca. 25% af bygge- og anlægsaffald. Dermed er beton den største fraktion indenfor bygge- og anlægsaffald.

I dag er den officielle genanvendelsesprocent for beton omkring 95%. Oftest sorteres og nedknuses betonen og genanvendes som stabilgrus i veje og fundering. Genbrugen af beton som bærelag er ikke med til at sænke CO_2 udledningen, da behovet for udvinding af naturlige råstoffer forbliver det samme.

Ved genanvendelse af betonaggregater som tilslag til ny beton, er der mulighed for en højere værdi for den genandenvdelige beton end for nedknust beton som stabilgrus. Ved genanvendelse af nedknust beton som tilslag spares samtidig på stenfraktioner fra udvinding af naturlige råstoffer.



Figur 1 - Genanvendelse af beton, blandingsforhold for genanvendelse af beton ihht. standarder.

Formål

Formålet med denne rapport er at undersøge brugen af genanvendte betonaggregater i størrelsen 4-8mm i ny beton. Der laves forskellige materialeundersøgelser af aggregaterne og samtidig undersøges trykstyrken for forskellige biarbejdelse og blandingsforhold.

Hypothese

For passiv miljøklasse op til styrkeklasse C30/37 er beton med genanvendte betonaggregater som stentilslag lige så velegnet til f.eks. ikke bærende vægge, pladsbelægning m.m., som beton med stentilslag af naturlige råstoffer.

Materialer og metode

Aggregaterne undersøgt er fra nedknust beton fra Islevgård Allé 5, betonens styrke var 34 MPa i hht. byggetilladelsen.
Den nedknuste beton er sigtet, vasket og tørret ved 55 celcius. Det nedknuste beton tilslag, sammenlignet med naturlige aggregater, er mere porøst og har vedhængende cement.

Figur 2 - Aggregater 4-8, fra højer mod venstre, vasket og tørret ved 55 grader celcius, vasket og ubehandlet.

Der anvendes forskellige metoder for de forskellige forsøg for materialeundersøgelserne og trykstyrke.

Følgende materialeundersøgelser foretages:
- Porøsitet, exivator
- Porøsitet, pychnometer
- Sigtekurve
- Cementindhold
- Vandindhold

Trykstyrketest er udført i hht. DS/EN 196-1.
Trykstyrken er undersøgt for følgende blandingsforhold med udskiftning af genanvendte betonaggregater 4-8mm:

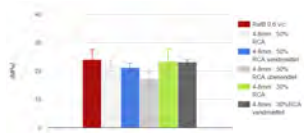
Blandig	v/c	Recycled Concrete Aggregates (RCA)	Note
0,5RCA50	0,5	50 %	
0,5RCA30	0,5	30 %	
0,5RCA30-W	0,5	30 %	vandmættet 24h
0,6RCA50	0,6	50 %	
0,6RCA50-W	0,6	50 %	vandmættet 24h
0,6RCA50-U	0,6	50 %	ubehandlet (minus vask og tørring)
0,6RCA30	0,6	30 %	
0,6RCA30-W	0,6	30%	vandmættet 24h

Tabel 1 - Blandinger.

Resultater

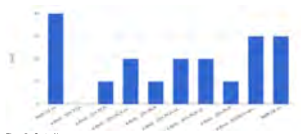
I projektet undersøges flere forhold omkring betonaggregaternes egenskaber og styrke. De forhold, der har vist sig interessante i forhold til det videre arbejde, samt forhold der beskriver bearbejdelighed, er præsenteret i følgende afsnit.


Figur 3 - Trykstyrke 0,5 v/c, 4-8mm betonaggregater fra Islevgård Alle 5.


Figur 4 - Trykstyrke 0,6 v/c, 4-8mm betonaggregater fra Islevgård Alle 5.

Det ses på både figur 3 og 5, at trykstyrken for de forbehandle betonaggregater ligger på ca. samme niveau som for referencerne. Det fremgår desuden tydeligt, at de ubehandle betonaggregater er meget svagere.
Sprædningen for trykstyrken falder for de vandmættede nedknuste beton aggregater.

Det ses fra figur 5 at betonen med genanvendte aggregater generelt har et lavere sætmål end referencerne. Dette giver et godt billede af hvor tør betonen har været at arbejde med.


Figur 5 - Sætmål.

Konklusion og videre undersøgelser

Ud fra disse resultater kan det indtil videre konkluderes, at genbrugs aggregater i 4-8mm, på baggrund af tryktesten, sagtens kan erstatte 30% af de naturlige stentilslag. Det ses at den vedhæftede cement på aggregaterne og vandmætning har stor indflydelse på styrken og bearbejdeligheden.
Tendensen i forsøgene understøtter den forudtagede teori for porøsiteten og sammenhængen mellem vandmætheden og styrken.

For det videre arbejde med 4-8mm genbrugsaggregat, vil følgende være i fokus:
- Forarbejdning af genbrugsaggregater
- Vandmæthed
- 30% RCA

Der vil yderligere blive undersøgt porøsitet, densitet, cementindhold, vandindhold og sigtekurve.

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