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Recycled aggregates in new concrete

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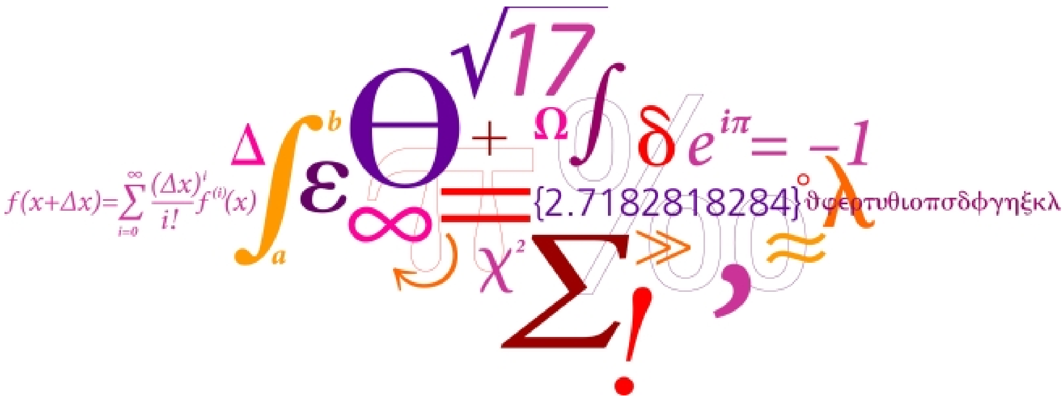

DTU Civil Engineering
Department of Civil Engineering

Preface

This thesis is executed under the department of Civil Engineering at DTU. The thesis is written in the fall semester, from 28 August to 28 January. The project accounts for 30 ECTS points.

This report was written using Latex and Microsoft Excel has been used for all data processing.

I would like to thank Lisbeth M. Ottosen and Gunvor Marie Kirkelund for being my supervisors and for being available and helpful throughout the project. Furthermore I would like to thank Louise Green Pedersen and Ebba Cederberg Schnell, who both assisted throughout this project. A special thanks should also be given to the technicians of the structural laboratory in building 119, and the help in the laboratory in building 118.

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Abstract

Recycled concrete aggregates (RCA) can be used as a partial replacement of the natural aggregates (NA). The RCA was collected in a near by location, and used to make recycled aggregates concrete (RAC). To get an understanding of the used materials, properties of both the RCA and RAC are examined.

Due to large uncertainties, it is not recommended to use fine RCA when casting RAC. However the particle size distribution curve did reveal that a significant amount of the fraction 0-4mm was present in the collected material. Therefore all fractions suited for a mould with a diameter of 100mm were used in this project.

The attached mortar (AM) was observed to increase with decreasing aggregate size. The AM was determined experimentally to be in the range of 15.4-27.8%. Furthermore it was found that this AM resulted in a higher water content and water absorption, which made it difficult to control the water to cement ratio.

The effects of replacing 20-50% of NA with RCA were tested. When the water content of the aggregates was subtracted from the mixing water, a replacement of 50% RCA resulted in a poor workability. However a replacement of 20% was acceptable both in terms of workability and compressive strength compared to the reference specimens, therefore variations with 20% of RCA were further examined, with regards to different combinations of size fractions.

The values for open porosity, density and modulus of elasticity remained within the acceptable range for concrete, however the use of RCA did result in a degradation compared to the reference specimens. Therefore these properties should always be thoroughly examined, when using RCA in new concrete.

The use of RCA from different sites requires thorough examination of especially the type and amount of attached mortar, due to it having a considerable impact on the properties of the RAC.

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Contents

1 Introduction

The increasing population and urbanization lead to demolishing of old buildings and construction of new ones. Mostly the low rise buildings are demolished to make room for new high rise buildings, which can contain more people. The concrete for the new constructions requires a huge amount of natural aggregates (NA). The demand of NA has increased with an alarming rate, and it is therefore necessary to use an alternative to the NA. This can for example be achieved by replacing some percentage of the NA with recycled concrete aggregates (RCA). RCA are aggregates which already has been used in a concrete mix and in some form of construction. When demolishing an old concrete building the concrete is crushed, and it is possible to deprive the aggregates. Normally the crushed concrete is used as road fill in Denmark, but when reusing RCA as a replacement for NA this will naturally decrease the demand of NA. This concept can in the future result in a more sustainable development of new buildings and cities. [Kisku et al., 2017]

In general the amount of waste and waste management is a big present concern. In Denmark the construction sector is accountable for 1/3 of the general waste per year. In 2015 the amount of waste from the construction sector was 4.2 million tons. [Miljøstyrelsen, 2017]

In the later years from 2011 - 2015 an increasing amount of waste from the construction sector has been noticed, whereas from 2008 - 2010 there was a clear decrease in the amount of waste. This clearly indicates that the amount of waste depends om the financial situation, since the financial crisis started in 2008. [Miljøstyrelsen, 2017]

In Denmark the recycling of waste has been up to 95% in the year 2000, but in the last 15 years the concern for pollutants from the industrial waste has been a crucial concern. This has caused the recycling of waste to be around 87% in 2015. Due to new requirements for the waste recycling is it expected, that the reuse will decrease to 70%. [Miljøstyrelsen, 2017]

Since concrete and asphalt is the most common waste from the construction sector in Denmark, it is desirable to develop new and sustainable ways to recycle these.

1.1 Objective

The purpose of this thesis is to investigate the technical possibilities and limits of using RCA in new concrete. The focus is on evaluation of different size fractions of the RCA, different fractions of NA will be replaced with RCA. The compressive strength of the new cast concrete with RCA will be tested after curing for either 7 or 28 days. The impact of RCA-replacement on the concretes' modulus of elasticity, will also be tested after 28 days of curing.

To get an understanding of the difference between the RCA and NA, various properties including attached mortar, water content, water absorption and density will be examined.

2 Theory

2.1 Concrete

Today concrete is the most used building material in the world, due to the low cost and its easiness to manufacture. This material is known for its high compressive strength and low tensile strength. Therefore, in order to compensate for the low tensile strength, the concrete is usually reinforced with steel bars, which have a high tensile strength.

Concrete mainly consist of the three components aggregates, water and cement, (which is a form for hydraulic binder). The aggregates are a granular material, such as sand and gravel, often the aggregates are divided into fine aggregates (particles smaller than 4mm) and coarse aggregates (particles larger than 4mm). The gravel is defined as the coarse aggregates resulting from natural disintegration by weathering of rocks [Mehta and Monteiro, 2006].

In modern concrete mixture is a fourth component often used called admixtures, which is defined as a material other than aggregates, water or cement.

2.2 Cement

As mentioned, cement is one of the essential components when creating concrete structures, and the most commonly used cement type is the Portland cement. Cement is a very fine and dry pulverized material, which when mixed with water develops the binding property, and is therefore called a hydraulic binder. To a certain extent it is possible to use fly ash or micro silica instead of cement, which both also are hydraulic binders.

2.3 Recycled concrete aggregates

RCA is obtained by crushing of concrete, RCA is therefore a product consisting of NA with attached mortar. Furthermore is the risk of contaminants such as Gypsum, asphalt and glass present when collection RCA. The quality and properties of the RCA will therefore always depend on the source of the original or parent concrete [Padmini et al., 2009]. An overview of some RCA properties are given in the Table in Figure 2.1 below.

Property		Fresh crushed granite aggregate			Recycled concrete aggregate of maximum size								
		Maximum size of aggregate			10 mm Derived from parent concrete of compressive strength			20 mm Derived from parent concrete of compressive strength			40 mm Derived from parent concrete of compressive strength		
		10 mm	20 mm	40 mm	35 MPa	49 MPa	56 MPa	37 MPa	50 MPa	58 MPa	31 MPa	45 MPa	52 MPa
Physical properties													
Specific gravity		2.8	2.8	2.8	2.46	2.4	2.38	2.52	2.51	2.48	2.56	2.53	2.52
Water absorption		0.3	0.3	0.3	4.60	4.8	5.0	3.65	4.1	4.86	2.2	2.5	2.8
Bulk density kg/m^3	Loose	1408	1462	1406	1338	1327	1324	1432	1421	1394	1341	1334	1329
	Rodded	1561	1625	1590	1468	1438	1427	1568	1536	1498	1480	1474	1470
Percentage	Loose	50	48	49	46	45	44	43	43	44	48	47	47
	Rodded	44	42	43	40	40	40	38	39	40	42	42	42
Mechanical properties													
Crushing value (%)		25	22	–	32	30	30	26	25	23	–	–	–
Impact value (%)		18	17	–	38	32	31	25	24	21	–	–	–
Abrasion value (%)		29	26	26	48	46	46	38	35	33	30	29	29

Figure 2.1: Properties of RCA, found in [Padmini et al., 2009].

2.3.1 Attached mortar

The most significant difference that separate RCA from NA is the attached mortar, which always in some form will be present when using RCA in new concrete, see Figure 2.2.

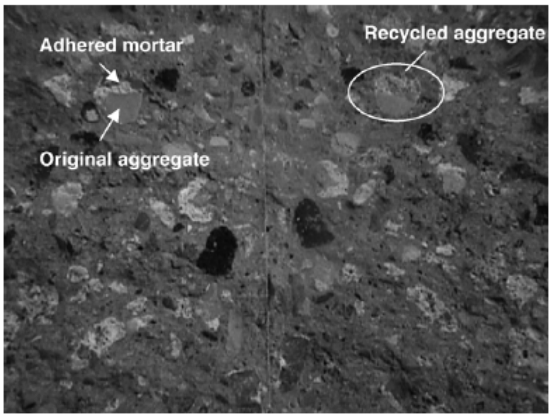


Figure 2.2: NA with attached mortar, taken from [Etxeberria et al., 2007].

Studies have shown that an increase in aggregate size will result in a decreasing amount of adhered mortar. The mortar content (percentage of volume) can vary between 25%-60% [Kisku et al., 2017] and [Hansen, 1992].

RCA with attached mortar is a very porous material, this porosity mainly results in a difference in the density and water absorption compared to NA.

In Figure 2.3 the correlation between the attached mortar [%] and open porosity [%] is shown, likewise the correlation between particle density $[kg/m^3]$ and attached mortar [%] shown in Figure 2.4, both found in [Pepe et al., 2016].

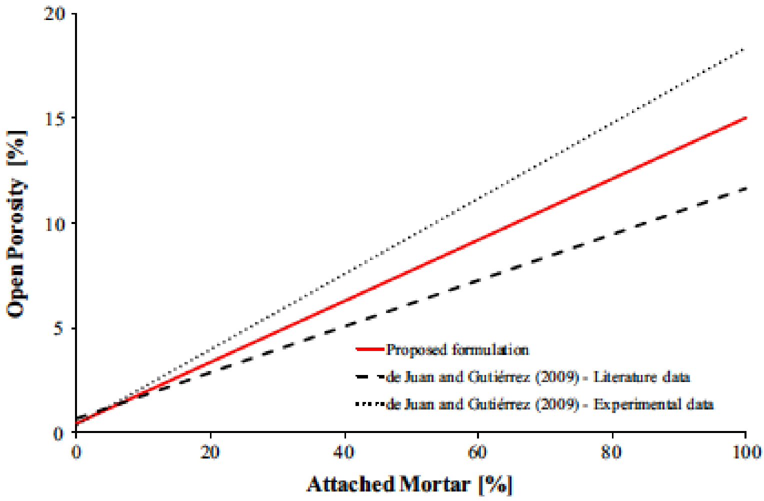


Figure 2.3: Correlation between attached mortar and open porosity [Pepe et al., 2016].

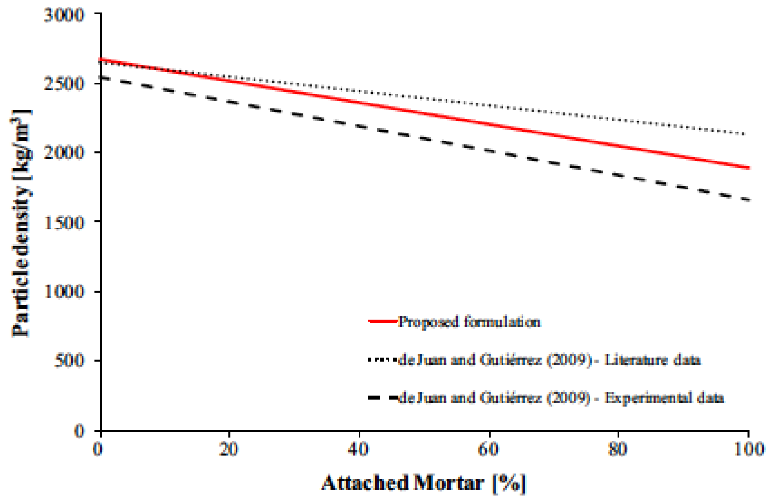


Figure 2.4: Correlation between attached mortar and particle density [Pepe et al., 2016].

2.3.2 Water absorption

Due to the attached mortar RCA have a much higher water absorption capacity compared to NA, in [Hansen, 1992] is a parabolic relation between water absoprtion [%] and density $[kg/m^3]$ presented, this relation is seen in Figure 2.5.

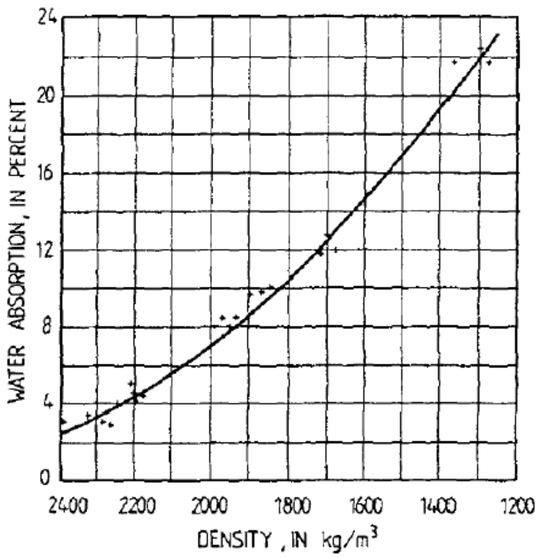


Figure 2.5: Correlation between density and water absorption [Hansen, 1992].

According to [Hansen, 1992] the absorption of the RCA should be determined before used in a new concrete mix. However this was proven difficult especially for the fine RCA (0-4mm), and different studies have found various absorption values for this fraction. In [Hansen, 1992] the use of fine RCA was not recommended since it documented to increase the water demand of fresh concrete and lower the strength and the durability of the hardened concrete. To compensate for the high absorption, an option is to pre-soak the aggregates [Hansen, 1992]. A practical way to do this could be by sprinkling as explained in [Goeb, 1985].

In Figure 2.6 and Table 2.1 seen below is different states of the aggregates water content illustrated and explained. The desired state for the aggregates when mixing the fresh concrete is the saturated-surface-dry (SSD) state. This can be explanied by the fact, that the aggregates in this state will neither absorb or add water to the mix, i.e. the aggregates will not affect the water to cement ratio.

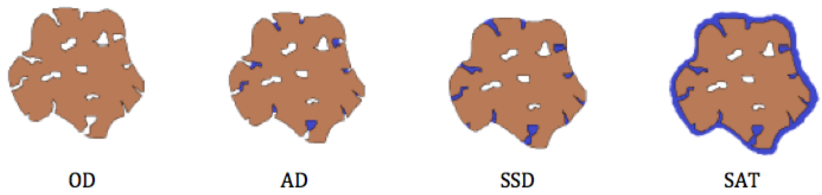


Figure 2.6: Different states of aggregates, found in [Betonhåndbogen, 2013] .

Table 2.1: Survey of the states for the aggregates.

Aggregates states	Notation	Description
Oven-dry	OD	Empty open pores will absorb water from the cement paste.
Air-dry	AD	Open pores are partly full, and will absorb some water from the cement paste.
Saturated-surface-dry	SSD	The pores are full, and water will therefor not be absorb from the cement paste.
Saturated aggregates	SAT	Water from the surface of the aggregate, will add water to the cement paste.

2.3.3 Los Angeles abrasion

The wear resistance of aggregates can by classified by the Los Angeles abrasion, a high L.A. abrasion value is obtained for aggregates with a poor wear resistance. In general a higher L.A. abrasion value is found for RCA compared to NA. The L.A. abrasion value depends on the amount of attached mortar, since the attached mortar is powdered in the L.A. abrasion test [De Juan and Gutiérrez, 2009]. Furthermore it is found that the L.A. abrasion value varies depending on the original concrete, i.e. high strength concrete will have a lower L.A. abrasion value [Hansen, 1992].

2.4 Recycled aggregate concrete

The most significant different between the fresh state properties of RAC and NAC is the workability, which can be compared by measuring the slump drop [Kisku et al., 2017]. As previously mentioned the RCA will absorb much more water compared to NA, and thereby "take" some water from the water to cement ratio. This will naturally result in a lower water to cement ratio, which leads to a higher compressive strength. However the low slump value causes many difficulties when casting the concrete, maybe even cause the concrete to be completely unusable.

2.4.1 Compressive strength

In [Kisku et al., 2017] various experimental studies investigating the compressive strength are gathered and compared, this is seen in Figure 2.7.

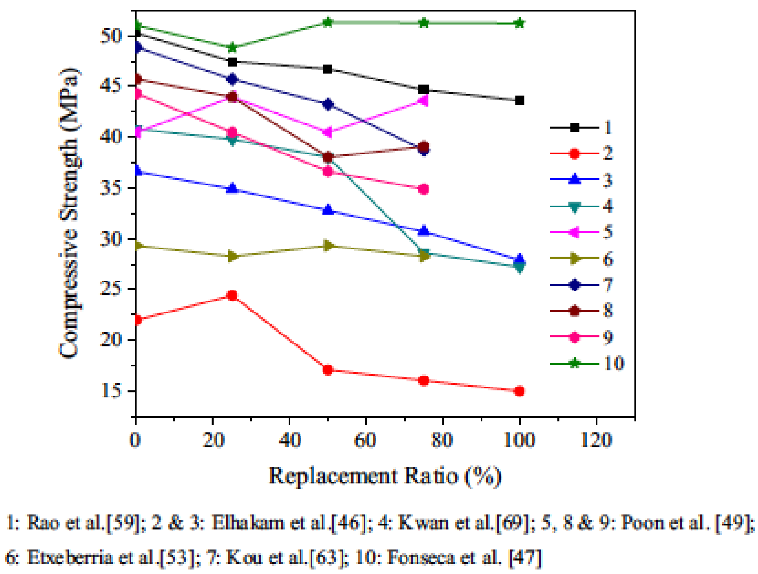


Figure 2.7: Compressive strength for RAC [Kisku et al., 2017].

From this it should be noticed, that the overall tendency when using RCA in new concrete, is that the compressive strength will decrease when increasing the amount of RCA.

In NAC the compressive strength, f_c is primarily controlled by the water to cement ratio and the days of curing [Portland, 2012].

Bolomey's formula can be used to calculate f_c, given in equation (2.1) below.

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

where

f_c	is the compressive strength of the concrete [MPa]
K	is a constant which depends on the type of cement and the curing time [−], see Table 2.2
w/c	is the water-cement ratio [−]
α	is a constant which depends on the type of cement and the curing time [−], see Table 2.2

In Table 2.2, the constants related to Bolomey's formula from equation (2.1) are presented.

Table 2.2: Constants related to Bolomey's formula from equation (2.1) [Portland, 2012].

Type of cement	M_{20} [d]	K [−]	α [−]
Basis cement	1	17	0.9
	7	26	0.6
	28	30	0.5
Rapid cement	1	13	0.9
	7	24	0.6
	28	30	0.5
Low-alkali sulphate-resistant cement	1	5	0.8
	7	19	0.8
	28	29	0.7
Aalborg white	1	14	1.0
	7	28	0.8
	28	35	0.7
Basis Aalborg cement	1	13	1.0
	7	24	0.7
	28	29	0.6

In order to understand the effect and influence's the w/c-ratio has on the final compressive strength, a graph for this is shown in Figure 2.8. The graph illustrate the theoretical expected values for the compressive strength both after 7 and 28 days of curing, when using the Basis Aalborg cement.

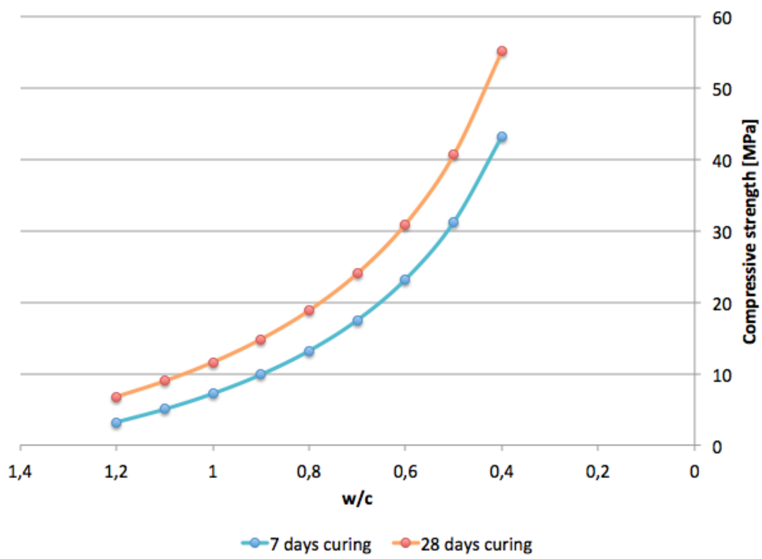


Figure 2.8: Theoretical expected values for the compressive strength.

2.4.2 Modulus of elasticity

The modulus of elasticity will decrease with increasing RCA content, and a decreasing up to 45% may occur [Mehta and Monteiro, 2006].

The modulus of elasticity can be calculated by using Hookes law, but only for small tensions where the stress-strain curve still is linear.

When loading up to 30% of the total compressive strength the stress strain ratio should remain constant for both the aggregates and cement paste. Exceeding this value the curve will start to crumb due to formation of small cracks in the concrete, this is illustrated in Figure 2.9.

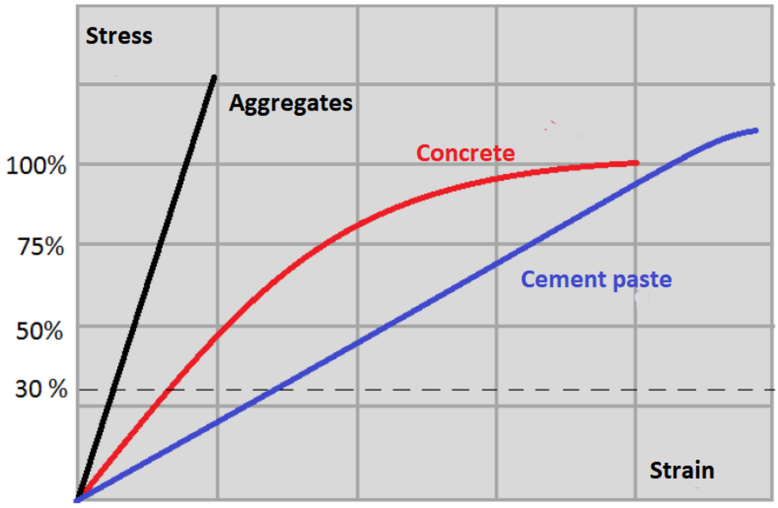


Figure 2.9: stress strain ratio for aggregates, cement paste and concrete [Betonhåndbogen, 2013] (translated).

From the graph in Figure 2.9 it is noticed that cement paste have a lower modulus of elasticity compared to concrete. Due to the overall increased content of mortar in RAC the modulus of elasticity can therefor be expected to be lower than for conventional concrete. In [Safiuddin et al., 2013] the effect of replacement of NA by RCA on the modulus of elasticity is illustrated.

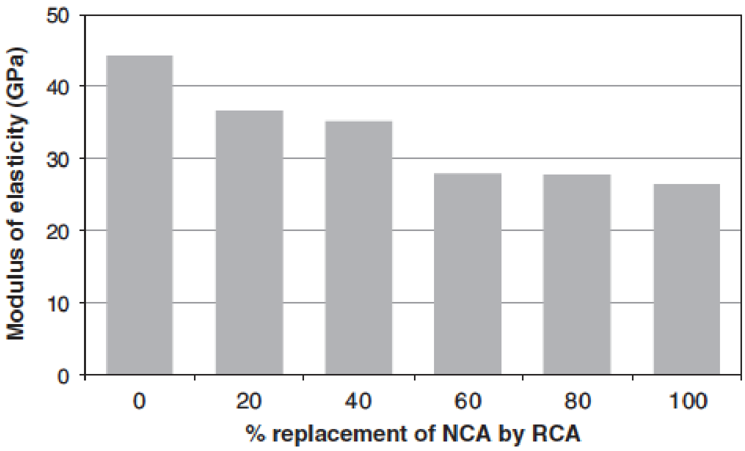


Figure 2.10: The effect of replacement of NA by RCA on the modulus of elasticity, found in [Safiuddin et al., 2013].

2.4.3 Density & Porosity

It was found in [Pepe et al., 2016] that the RCA had a higher open porosity and a lower density compared to NA due to the attached mortar. As this applies for the RCA, the same tendency can be expected for the hardened RAC. In [Thomas et al., 2013] the open porosity for different water to cement ratio is documented, these results are found after 28 days of curing.

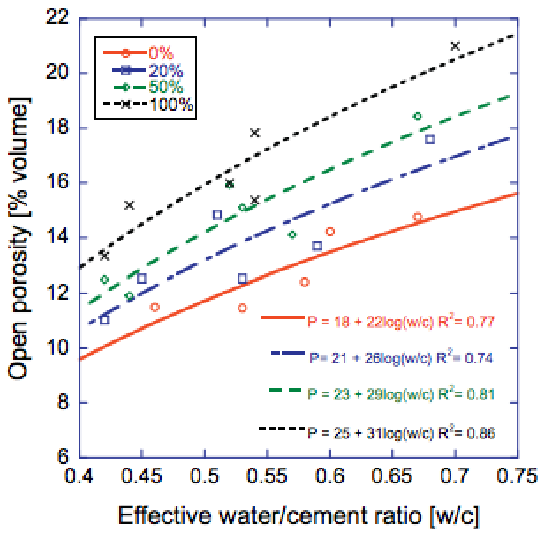


Figure 2.11: Correlation between the open porosity and percentage replacement of RCA, found in [Thomas et al., 2013].

In [Thomas et al., 2013] the porosity was also found for specimens that had been curing for more than 28 days. For these specimens the open porosity was found lower. This is caused by the structure development of the cement paste [Hansen, 2012], this is shown in Figure 2.12.

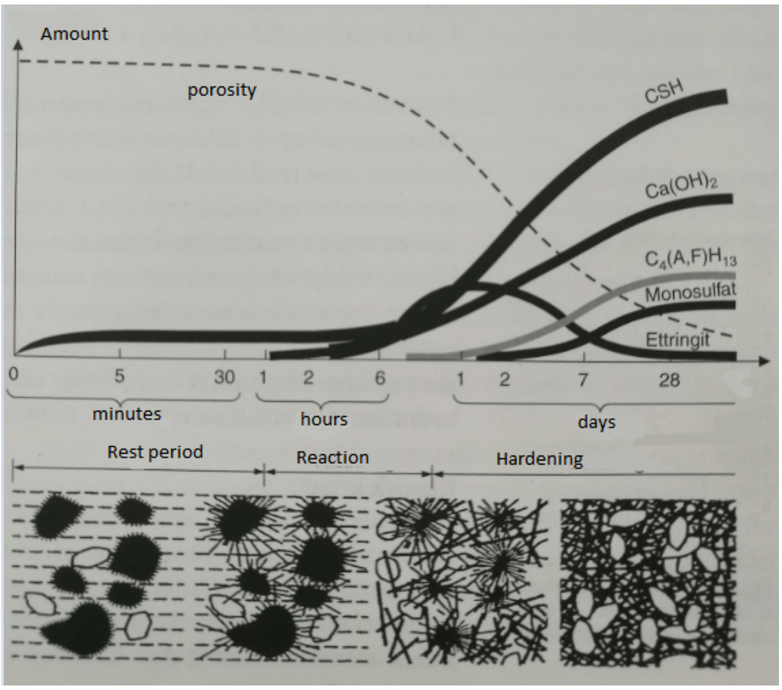


Figure 2.12: Correlation between the open porosity and the structure development of the cement paste, [Hansen, 2012] (translated)

From Figure 2.12 is it clear to seen that the porosity decreases with time. The structure development of the cement paste is divided into 3 stages.

- Rest period: The short time after the concrete is being cast.
- Reaction: Chemical reaction between cement and water, the cement hydrates, and a structural skeleton is created.
- Hardening: The skeleton grows and the porosity decreases as the strength increases.

2.5 Standards concerning replacement of NA by RCA

In order to ensure the durability of the concrete when replacing NA by RCA some standards are developed, different requirements are valid depending on use and environment.

Primarily the concrete should follow the standard [DS/EN11992-1-1, 2011], which describes that the aggregates must meet [DS/EN12620+A1, 2008] and be divided into fine aggregates (0-4mm) and coarse aggregates (4-32mm).

In [DS/EN206, 2013] Annex E Table E.2 some values for replacement are given, these are shown in Figure 2.13

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 2.13: DS/EN206 Annex E.

This standard suggest that up to 50% replacement is possible for RAC in a passive exposure class. Furthermore is it noticed that the Table divides the RCA into two types, A and B. Type A is RCA from a known source, and type B is RCA which should not be used in concrete with a compressive strength above class C30/37. R_c stands for concrete products and $X0$ and $XC1$ are passive exposure classes. In Appendix A Chapter 7 tables are shown describing all the abbreviations.

The Danish standard [DS2426, 2011] describes the rules for application of [DS/EN206, 2013] in Denmark. This standard dictates that RCA only can be used in a passive exposure class, however a replacement of 30% for fine aggregates and 100% for coarse aggregates is possible, as long as the RCA fulfill the requirements in Table 2426-3, see Figure 7.4 in Appendix A.

In November 2017 a draft was released [DSF/EN206-DK-NA, 2017]. This standard are replacing [DS2426, 2011], and should be used together with [DS/EN206, 2013] and the other relevant standards. As previously the recycled aggregates are only allowed to be used in passive exposure classes, however if more than 5% aggregates are used, other guidelines and rules are applicable. For RAC with a compressive strength up to class C30/37 is 10% fine and 20% coarse aggregates allowed. For RAC with compressive strength above class C30/37 is 10% fine and only 10% coarse aggregates allowed. Finally is 10% fine and 30% coarse aggregates allowed, if the modulus of elasticity, creep and drying shrinkage are documented and rated acceptable in relation to the compressive strength.

Table 2.3: Survey of the allowable replacement according to [DSF/EN206-DK-NA, 2017].

Compressive strength classes	Fine aggregates	Coarse aggregates	Comments
$\leq$ C30/37	10%	20%	-
$>$ C30/37	10%	10%	-
$>$ C30/37	10%	30%	The E-modulus, creep and drying shrinkage has to be documented

3 Methodology

In this section the different considerations for each concrete mix will be explained. Furthermore it is stated which tests were performed on which samples. In Figure 3.1 a diagram showing the experimental process throughout the project is presented. On the left side are numbers showing the steps. These steps are explained in Table 3.1 on the following page.

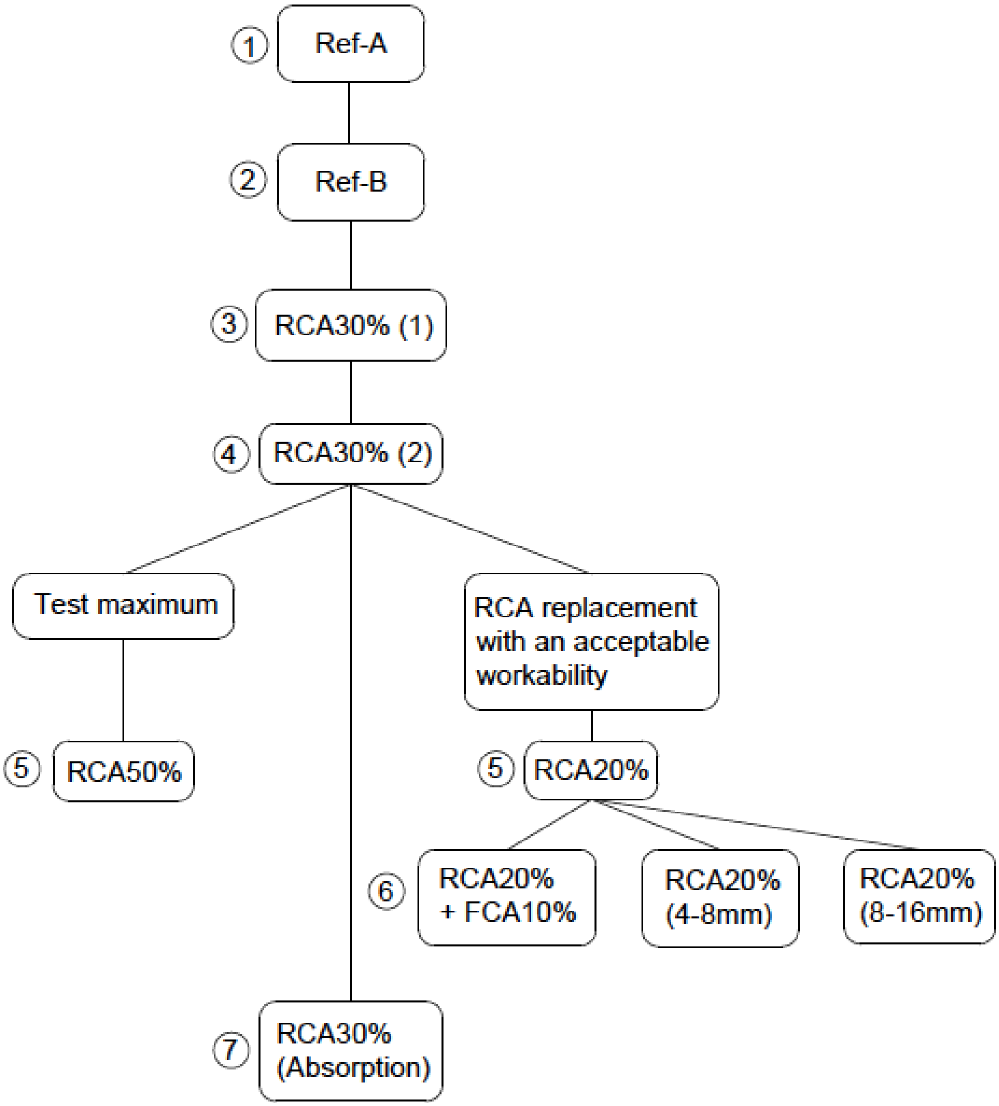


Figure 3.1: Diagram showing the experimental process throughout the project.

Table 3.1: Survey of the concrete series in this project.

Concrete	Description	Tests
1 Ref-A	This was the first try to make a proper concrete design mix	Compressive strength
2 Ref-B (1)	It was decided that the Ref-A was too dry, therefore a new recipe was made, see Appendix B	Compressive strength
2 Ref-B (2)	Identical to Ref-B (1) this was made to test the modulus of elasticity	Compressive strength E-modulus (28) Density and porosity (7)
3 RCA30% (1)	A 30% RCA replacement of the fraction 4-8mm and 8-16mm was cast	Compressive strength E-modulus (28)
4 RCA30% (2)	In RCA30% (1) the water content was not included, therefore a 30% replacement was cast again	Compressive strength E-modulus (28)
5 RCA20%	The correction for the water content, resulted in a to low workability, therefore a replacement of only 20% was made	Compressive strength E-modulus (28)
5 RCA50%	To test an absolute maximal replacement, it was experimented with a 50% replacement (still only for the coarse aggregates)	Compressive strength E-modulus (28) Density and porosity (7)
6 RCA20%+FCA10%	Since only the replacement of 20% resulted in a proper workability it was further experimented with this, together with a replacement of 10% for the fine aggregates	Compressive strength E-modulus (28) Density and porosity (7)
6 RCA20% (4-8mm)	A replacement for only the fraction 4-8mm was done	Compressive strength E-modulus (28) Density and porosity (7)
6 RCA20% (8-16mm)	A replacement for only the fraction 8-16mm was done	Compressive strength E-modulus (28) Density and porosity (7)
7 RCA30% (Absorption)	Ones again a replacement of 30% was done (coarse fraction). This time both the absorption and water content of the aggregates was included	Compressive strength

4 Methods and materials

The RCA used in this project were collected from Islevgaard Alle 5 in Rødovre. The crushed concrete was taken from a demolished building, which used to be a school. The data from this former building is unfortunately limited, but from the building permit it is found, that some of the beams should have had a compressive strength of 34 MPa [Pedersen, 2017].

All the crushed concrete for this project were collected on the 21th of September. All the material were collected in 24 buckets of approximate 20 kg each. The pile itself and the collecting process is seen in Figure 4.1.

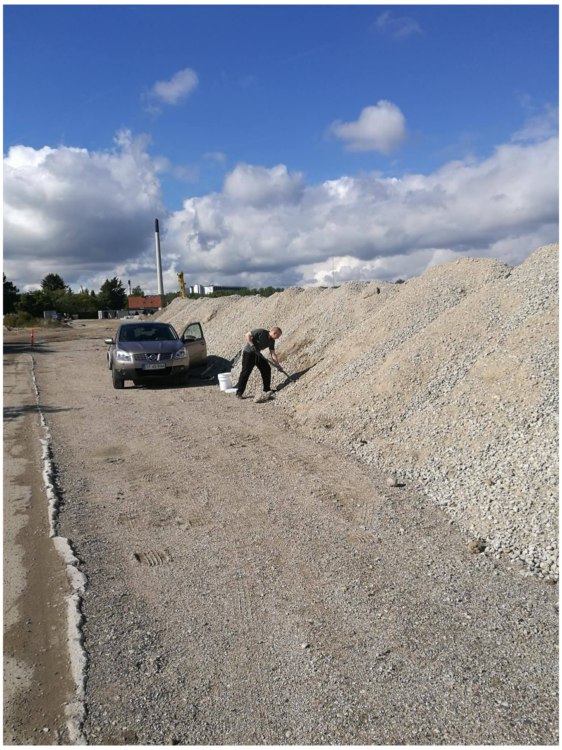


Figure 4.1: Collecting of the crushed concrete.

The crushed concrete will be treated and used for production of new concrete, the crushed concrete will in this context be refered to as recycled concrete aggregates (RCA). Different concrete batches will be produced, and for each batch will 8 cylinders be cast and tested. With this the ability of the RCA will be examined.

The cement type used in this project is the "Basis Aalborg cement", which have the following cement designation.

CEM 11/A - LL 52.5 N (IS/LA/$\leq$2)

4.1 Preparation of the recycled aggregates

The RCA in this project, in contrast to the previously projects from DTU, will not be treated and prepared to the same extent [Pedersen, 2017]. The main preparation of the RCA, that has to be made in order to be able to cast the new concrete will be sieving.

4.1.1 Sieving

In order to get the desired recycled aggregates it was necessary to sieve all the collected buckets. The desired aggregates sizes was the fractions 0-4mm, 4-8mm and 8-16mm, the used sieve sizes is seen on Figure 4.2.

(a) 4 mm sieve **(b)** 8 mm sieve **(c)** 16 mm sieve

Figure 4.2: Sieve sizes

The sieves was placed on top of each other, so that the 4mm sieve was at the bottom, the 8mm sieve in the middle and the 16mm sieve at the top. Together these were placed on a bucket, which could collect all the fractions below 4mm.

When starting the sieving process the bucket and sieves were placed on a vibration table, turned on to approximate 60 Hz, while filling the crushed concrete in. Together with the vibration the sieves were also shaken by hand. The set-up of this sieving process is shown on Figure 4.3.

(a) **(b)**

Figure 4.3: Bucket with sieves placed on the vibration table.

When the fractions were sorted sufficiently all the aggregates with a diameter above 16mm was thrown away, then all aggregates with a diameter between 16mm and 8mm was collected. The same procedure was done for the 4-8mm and 0-4mm aggregates.

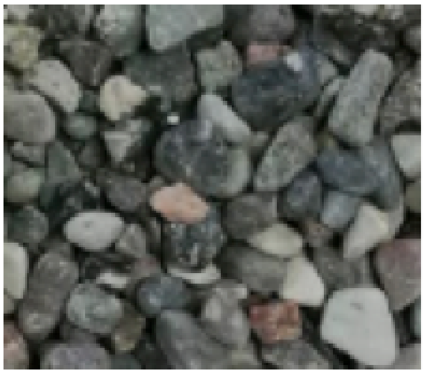
Besides sand and gravel a number of other material were found, while sorting the content of the buckets. This was material such as glass, wood, plastic and paper, as much as possible these was removed from the aggregates.

Figure 4.4: The found material besides sand and gravel.

Furthermore some asphalt was also found together with the RCA.

A visible difference between the RCA and the NA was clear, this can be seen in Figure 4.5.

(a) RCA (8-16mm).



(b) NA (8-16mm).

Figure 4.5: Visible difference between the RCA and the NA.

From Figure 4.5 it should be noticed that the RCA are more angular compared to the NA, this is partly caused by the attached mortar, in addition to that the aggregates originates from different sources. The NA used in this project originates from the ocean (sømaterialer), whereas the RCA originates from a gravel pit (bakkematerialer).

4.2 Particle size distribution

The particle size distribution of the crushed concrete is investigated according to the method described in [DS/EN933-1, 2012]. Following this standard a sample of 10 kg is necessary to get a representative particle size distribution, since the amount of sample is controlled by the largest diameter of aggregate, which is 32mm for these RCA.

The aggregates should be oven dried for 24 hours (until constant mass) before being run through the following used sieve sizes: 31.5mm, 16mm, 8mm, 4mm, 2mm and 1mm, the test setup for this experiment is seen in Figure 4.6a.

The particles with a diameter below 1mm was gathered, and the laser Mastersizer 2000 was used to determine the particle size distribution for these. A small sample of approximate 5g was used, this was mixed with natrium-pyro-phosphat to prevent that the small particles didn't stick together. Afterwards the sample was ready to be put in the mastersizer 2000, see Figure 4.6b.

(a) Sieving column, RCA > 1mm. **(b)** Mastersizer 2000 laser, RCA < 1mm.

Figure 4.6: Particle size distribution for aggregates

4.3 Water content

The water content was found by taken 3 samples, each consisting of 200g for the respective fractions in their air-dry state (AD), afterwards the samples was dried in an oven. The samples should be dried until a constant mass was achieved, normally this would take approximate 24 hours. The state of the aggregates is then defined as oven-dry (OD). For these investigations the oven was set to 105 °C ± 5 °C

This method follows the [DS/EN1097-5, 2008] and should be found for a more detailed description.

The water content in this project is calculated by using equation (4.1).

$$Water\ content = \frac{m_0 - m_1}{m_0} \cdot 100 \tag{4.1}$$

Where

- m_0 is the mass of the wet aggregates.
- m_1 is the mass of the oven dried aggregates.

4.4 Water absorption

The absorption for the fraction 0-4mm was found by taking 1 kg of fully saturated sand, which then was dried on a pan. The sand should be dried until SSD (saturated-surface-dry) state was obtained, this is checked by putting the sand in a small cone, which then is compacted 25 times. The shape of the sand when the cone is removed determines the current state of the sand, on Figure 4.7 the different states is illustrated.

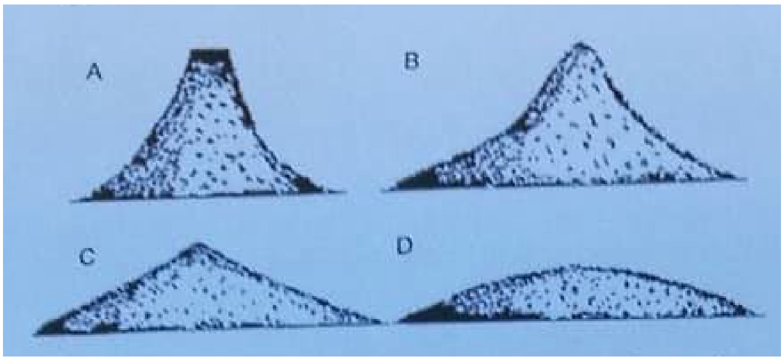


Figure 4.7: Different states for the sand, the desired state (SSD) is C.

(a) Wet sand on the pan. **(b)** State A. **(c)** State C.

Figure 4.8

When the SSD state was obtained, the sand was weighed, and afterwards dried until constant mass similar to the water content experiment.

This method was only possible for the fraction 0-4mm, for the two remaining fractions, a sample of oven dried RCA was weighed, and then put in water for 24 hours. Afterwards the aggregates was dried with a cloth (to achieve SSD state) and weighed again. The difference between the dry and SSD state was then defined as the water absorption.

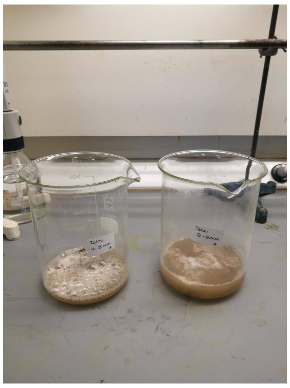
4.5 Attached mortar

When using RCA in new concrete some old mortar will always be attached to the aggregates. As described in the theory the old mortar will have a significant influence on the properties of the new concrete, therefore it is necessary to determine the amount of attached mortar.

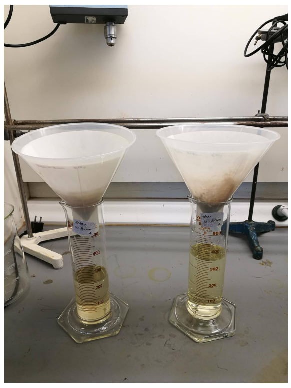
For this experiment, no standard procedure was found, which resulted in making one inspired from the ”syreoplukning af beton”. The fully described procedure and the modified used method can be seen in appendix A.

Samples of approximate 20g for the fractions 4-8mm and 50g for the fractions 0-4mm and 8-16mm was put in beakers, hereafter the samples was covered with distilled water, with a temperature of approximately 50 °C. Afterwards concentrated nitric acid (HNO3) was poured into the beakers. When no more air development was present in the beakers, i.e. no more reaction between the acid and mortar, the fluid was poured from the remaining RCA, see Figure 4.9.

(a) Fraction 4-8mm and 8-16mm cover with water.



(b) Nitric acid reacting with the attached mortar.



(c) Fluid poured from the remaining RCA.

Figure 4.9

Afterwards the filter with the remaining aggregates was placed on a petri dish and put in a oven for 24 hours at 105 °C. At the following day the RCA was weighed and it was possible to determine the amount of attached mortar, the results can be seen in chapter 5

4.6 Los Angeles abration

The Los Angeles abration for the fractions 4-8mm and 8-16mm was tested both for the RCA and NA. The test portion was put in the LA machine, see Figure 4.10a. Together with the aggregates was 8 steel balls (for the fraction 4-8mm) and 12 steel balls (for the fraction 8-16mm) put in the machine, see Figure 4.10b. This procedure follows the [DS/EN1097-2, 2010], and the LA abration loss, LA[%] is determined by equation (4.2).

$$LA = \frac{m_0 - m_1}{m_0} \cdot 100 \tag{4.2}$$

Where

- m_0 is the mass of the test portion
- m_1 is the mass of the retain material on a 1.4mm sieve after the test.

According to [DS/EN1097-2, 2010] should a 1.7mm sieve be used, when collecting the retained material, however this sieve sizes was not available at DTU therefore the 1.4mm sieve was used instead.

(a) LA machine.

(b) Steel balls.

Figure 4.10

4.7 Density of the aggregates (pycnometer)

The pycnometer test is used to determine the density of the aggregates, this method follows the [DS/EN1097-6, 2013]. Three samples for each fraction was investigated, and the mean of these was defined as the density.

Prior to the experiment the aggregates was washed, and afterwards dried in an oven until a constant mass was achieved. Samples of 150g was put in 500ml pycnometers and weight, afterwards the pycnometer was filled 75% with distilled water. The three pycnometers was then put in a desiccator, furthermore a beaker just filled with distilled water was put in an other desiccator. The vacuum machine was started and run for approximate 24 hours, this set-up is shown in Figure 4.11.

Figure 4.11: Test set-up.

The following day the pressure in the desiccators was released, and the distilled water from the beaker, which then was air free, was poured in the pycnometers. The pycnometers lid was put on, and water on the surface of the pycnometers was wiped off, see Figure 4.12.

Figure 4.12: Pycnometer filled with air free distilled water.

Hereafter the pycnometer was weighted, and it was then possible to determine the density of the aggregates, which is done by using the following equation found in [DS/CEN-ISO/TS17892-3, 2004].

$$\rho_s = \frac{m_4}{\frac{m_1 - m_0}{\rho_{w;1}} - \frac{m_3 - m_2}{\rho_{w;3}}} \tag{4.3}$$

Below is the the different values described, and in Appendix A is an Excel sheet with the different values used for the calculations.

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

4.8 Casting of concrete cylinders

The first concrete mixture in this project is identical to the one presented in [Pepe et al., 2016], the mix design is shown below. This mix design is called Ref-A throughout the project.

- Cement: 287 $\frac{kg}{m^3}$ for w/c 0.6
- Water: 172 $\frac{kg}{m^3}$
- Sand (0-4 mm): 762 $\frac{kg}{m^3}$
- Fine aggregates (4-8 mm): 554 $\frac{kg}{m^3}$
- Coarse aggregates (8-16 mm): 554 $\frac{kg}{m^3}$

Earlier projects from DTU working with RCA have used the recipe described above, therefore this recipe was the starting point for casting the concrete cylinders.

Based on experience from previous experiments performed at DTU it was learned, that the water to cement ratio should be 0.6, since a lower water to cement ratio results in a to dry and low workable concrete mix, especially when working with the RCA. [Pedersen, 2017] This water to cement ratio of 0.6 is considered acceptable, since the general purpose for the RAC was not to be a high performance concrete. [Kisku et al., 2017]

Even though having a water to cement ratio of 0.6 the slump value was very low (around 2cm for the first 2 castings). Before moving on to casting with the RCA it was therefore decided that a new recipe should be made, since a lower slump and less workability was expected for the casting with the RCA. The goal with the new recipe was therefore to achieve a higher slump value, and to retain a water to cement ratio of 0.6. The new mix design is shown below, and the calculations and assumptions for making this is described in Appendix B. This mix design is called Ref-B throughout the project.

- Cement: 346 $\frac{kg}{m^3}$ for w/c 0.6
- Water: 208 $\frac{kg}{m^3}$
- Sand (0-4 mm): 872 $\frac{kg}{m^3}$
- Fine aggregates (4-8 mm): 486 $\frac{kg}{m^3}$
- Coarse aggregates (8-16 mm): 486 $\frac{kg}{m^3}$

As mentioned 8 concrete cylinders for each batch should be prepared. Furthermore there should be enough material to perform a slump test and examine the air content. An overview of the replacement is shown in Table 4.1.

Table 4.1: Survey of the amount of replacement of NA by RCA.

Mix design	Sand 0-4mm [kg]	NA 4-8mm [kg]	NA 8-16mm [kg]	RCA 0-4mm [kg]	RCA 4-8mm [kg]	RCA 8-16mm [kg]
Ref-A (1)	30.48	22.16	22.16	-	-	-
Ref-A (2)	30.48	22.16	22.16	-	-	-
Ref-B (1)	30.54	17.02	17.02	-	-	-
Ref-B (2)	30.54	17.02	17.02	-	-	-
RCA30% (1)	30.54	11.91	11.91	-	5.11	5.11
RCA30% (2)	31.01	11.91	11.91	-	5.60	5.48
RCA20%	30.79	13.62	13.62	-	3.73	3.65
RCA50%	30.79	8.51	8.51	-	9.33	9.13
RCA20%+FCA10%	27.60	13.62	13.62	3.46	3.73	3.65
RCA20% (4-8mm)	30.67	10.21	17.02	-	7.46	-
RCA20% (8-16mm)	30.67	17.02	10.21	-	-	7.30
RCA30% (Absorption)	15.35	6.8	6.8	-	2.97	2.96

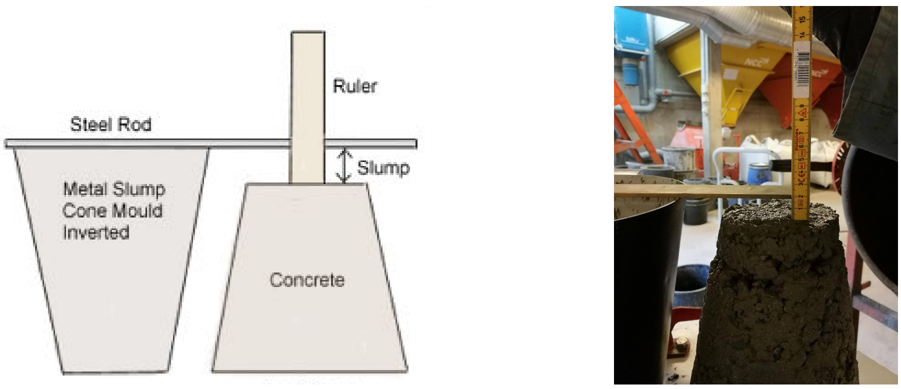
Since two different recipes was used in this project the one called "Ref-A" is the first described recipe. For "Ref-A" there was no replacement of NA with the RCA, since this mix design resulted in a to dry fresh concrete. However it was for the "Ref-A" experimented with the importance of whether the cylinders had been curing in a water bath or air curing. Since no significant difference was found concerning the compressive strength, it was decided to put the following cylinders in a water bath as described in [DS/EN12390-2, 2012].

For every mix design with replacing of NA by RCA, it is in the name indicated how large an amount that is replaced, see Table 4.1. In one mix design it was experimented with using recycled fine concrete aggregates (FCA). In the remaining mix designs only the two coarse fractions were used.

4.8.1 Slump test

A slump test can be used to investigate the workability of the concrete. The workability is mainly affected by the water to cement ratio, i.e. two mixtures with different water to cement ratio, should have different slump values and thereby a different workability.

The desired workability depends on the intended use of the concrete, for example compacting the concrete is more energy consuming when the slump is low, and the other way around. The slump test is performed by filling a clamped cone up with concrete in 3 layers, after each layer the layer was compacted 25 times by the use of a steel rod. The used cone had a base diameter of 200 mm ± 2 mm, a top diameter of 100 mm ± 2 mm, and a height of 300 mm ± 2 mm.
Once the cone is filled, it is lifted up, whereafter the concrete should collapse a bit. The difference between the collapsed concrete and the cone is measured, and noted as the slump value, as described in [DS/EN12350-2, 2012].



(a) Slump test in theory. **(b)** Slump test in practice.

Figure 4.13

4.8.2 Air content

Another important factor affecting the compressive strength is the air content of the concrete. A high air content leads to a higher porosity, which finally results in a lower compressive strength. In natural concrete the air content is normally between 1-2 %[Portland, 2012].

The air content of the fresh concrete was measured according to [DS/EN12350-7, 2002] with the pressure gauge method.

Figure 4.14: Pressure gauge.

The container is filled with the concrete and vibrated on a vibration table at 60Hz. The pressure gauge was put on and clamped on top of the container. The valves are open, and water is filled in through one valve until it comes out of the other valve. Finally air is pumped in using the red handle, followed by pressing the green bottom, and the air content is to be noted.

4.9 Compressive strength of the concrete cylinders

The compressive strength of the concrete cylinders was tested in a Toni Technik 3000 machine, as described in [DS/EN12390-3, 2009]. The cylinder had either hardened for 7 or 28 days. The obtained strength after 28 days is normally the value, which is used in calculations formulas [Jensen, 2012].

When testing the cylinders, they were centered in the middle of the machine, and the input parameters could be entered, such as height, diameter and pressure rate. According to [DS/EN12390-3, 2009] the pressure rate should be set to 0.6 MPa, which had to be converted to kN/s when using the Toni Technik 3000 machine, this is seen in the Equations 4.4 - 4.6 below.

$$P_{rate} = \pi \cdot \left(\frac{D}{2}\right)^2 \cdot 0.6 \cdot \left(\frac{N}{mm^2 \cdot s}\right) \tag{4.4}$$

$$P_{rate} = \pi \cdot \left(\frac{100mm}{2}\right)^2 \cdot 0.6 \cdot \left(\frac{N}{mm^2 \cdot s}\right) \tag{4.5}$$

$$P_{rate} = 4.71 \frac{kN}{s} \tag{4.6}$$

Furthermore the fracture detection was set to 5%, which determines how clear the fracture of the concrete cylinder should be. This can be helpful when investigating if the crack pattern is acceptable or not. Examples of acceptable crack patterns are shown on Figure 4.15 below.

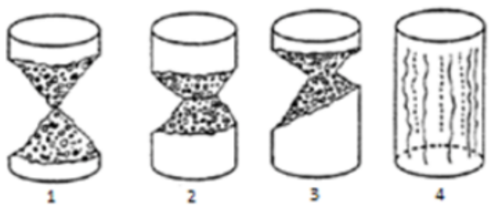
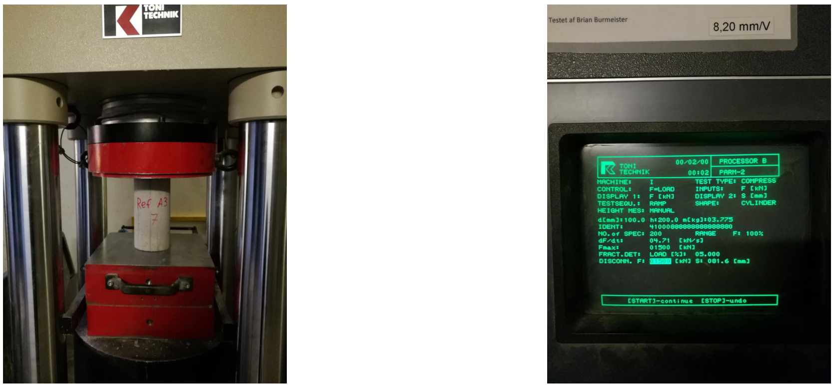


Figure 4.15: Satisfying crack patterns for cylinders, according to [DS/EN12390-3, 2009].

When achieving a satisfied crack pattern, it is a good indication that the aggregates are distributed homogeneous and correctly.

The test set-up for this experiment can be seen on Figure 4.16a and the input parameters can be seen on Figure 4.16b



(a) Cylinder placed in the Toni Technik 3000. **(b)** Display were the input parameters are chosen.

Figure 4.16

4.10 Modulus of elasticity

The modulus of elasticity was tested for the cylinders, which had been curing for 28 days. This was archived by placing two steel rings on the cylinder, which had a displacement gauge on each side, this is seen on Figure 4.17. The modulus of elasticity was examined for 3 cylinders in each series.

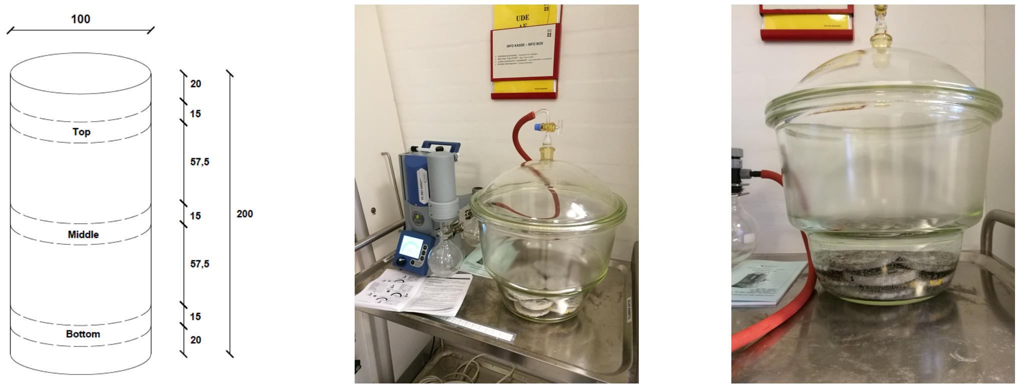
Figure 4.17: Equipment for measuring of the modulus of elasticity.

The measured displacement is noted by the data logger, and the data was analyzed in excel. To protect the equipment the test was stop at 40% of the expected failure load.

4.11 Porosity & Density of the hardened concrete

The porosity and density were determined for 5 series (Ref-B (2), RCA50%, RCA20%+FCA10%, RCA20% (4-8mm) and RCA20% (8-16mm)), which all had been curing for 7 days. A circular cut with a height of approximate 15mm was taken in the top, middle and bottom for each cylinder, this is illustrated in Figure 4.18a.

The discs had to dry in a oven for approximate 3 weeks at 50 °C, a higher temperature was not possible since this could result in a change of the pore structure in the concrete. When a constant mass m_{50} was achieved the discs was put in a desiccator, which was connected to a vacuum pump for three hours. Afterwards distilled water was poured in the desiccator approximate 3cm above the discs, this was left for one hour. Finally air was let in the desiccator by opening the valve, and the experiment was left overnight. The following day the discs was weighed first under water m_{sw} and above water m_{SSD} the results from this experiment can be found in chapter 5.



(a) Illustration of the cut discs, all measurements in mm.

(b) The desiccator connected to the vacuum pump.

(c) The discs covered with distilled water.

Figure 4.18

5 Results

5.1 Particle size distribution

The results from the particle size distribution test is shown in Table 5.1, furthermore graphic views of the results are shown in Figure 5.1, Figure 5.2 and Figure 5.3.

Table 5.1: Results from the particle size distribution test.

Fraction [mm]	Passing [g]	Passing [%]	Cumulative passing [%]
31.5	1722	17.28	100
16	3476	34.88	82.72
8	1691	16.96	47.85
4	856	8.59	30.88
2	627	6.29	22.29
1	1595	16	16

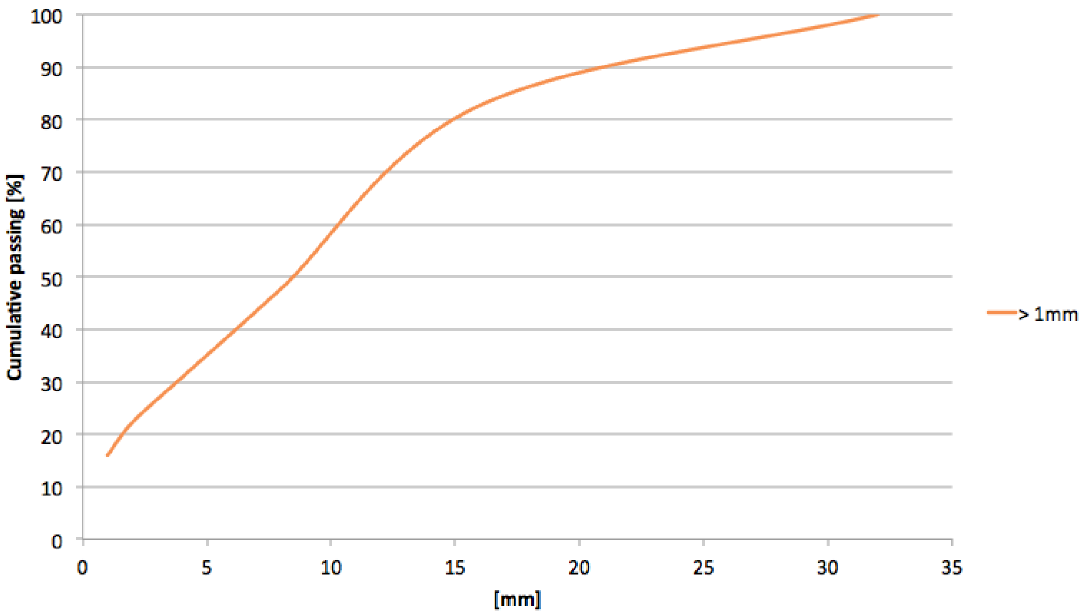


Figure 5.1: Particle size distribution for the aggregates with a diameter above 1 mm.

From Figure 5.1 it is noticed that no data is included from the diameter 0-1mm, since this fraction was analyzed in the laser, this data is shown on Figure 5.2.

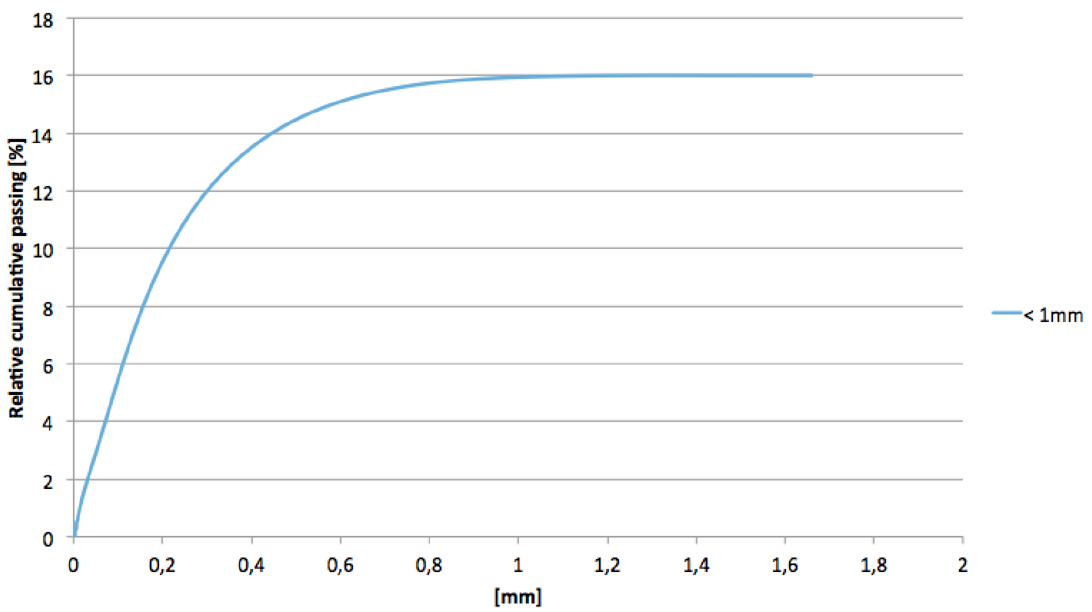


Figure 5.2: Particle size distribution for the aggregates with a diameter below 1 mm.

From Figure 5.2 it is noticed that the graph shows the relative cumulative passing in percentages, since 16% is the cumulative passing for the 1mm fraction. Furthermore it should be noticed that a higher millimeter than 1 is found on the graph, though 1mm should be the greatest millimeter in the laser machine. This could be due to the fact that some of the fine aggregates lay to close to each other, and thereby be perceived as one big sample and not to small ones.

Figure 5.3 is an combination of the two graphs shown in Figure 5.1 and Figure 5.2.

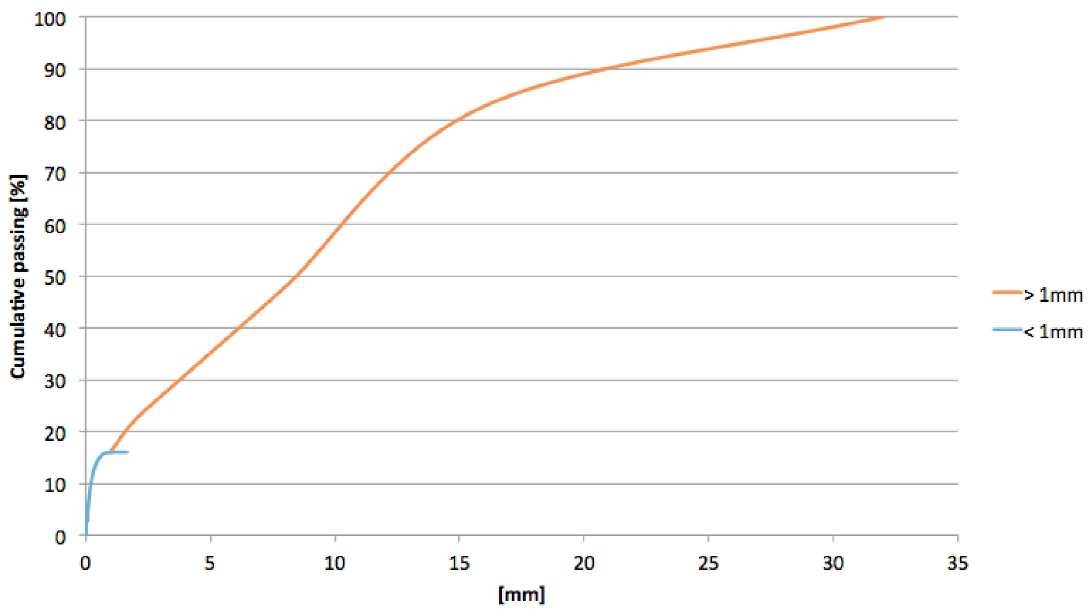


Figure 5.3: The combined particle size distribution (0-31.5mm).

5.2 Water content

The results from the water content experiment is seen in Table 5.2. The mean water content is based on three test portions measurements. It should be noticed that the standard deviation is very small.

Table 5.2: Survey of the results from the water content experiment.

Fractions	Mean water content [%]	Standard deviation
0-4mm	11.2	0.2
4-8mm	8.8	0.2
8-16mm	6.8	0.2

It should also be noted that the water content for the NA was measured multiple times throughout the project, see Appendix B. Especially the natural sand fraction varied a lot throughout the project.

5.3 Water absorption

The results from the water absorption experiments are shown in Table 5.3. In Appendix A a full table including the raw data is presented. The mean and standard deviation are based on three test portions.

Table 5.3: Survey of the results from the water absorption experiments.

Fractions	Mean water absorption [%]	Standard deviation
0-4mm	8.6	0.1
4-8mm	7.1	2.7
8-16mm	5.3	0.7

5.4 Attached mortar

In Table 5.4 the results from the attached mortar experiment are shown. As for the water content and water absorption the mean and standard deviation is based on three test portions. See Appendix A for the full Table.

Table 5.4: Survey of the results from the attached mortar experiment.

Fractions	Mean attached mortar [%]	Standard deviation
0-4mm	27.8	0.9
4-8mm	24.6	2.6
8-16mm	15.4	1.5

5.5 Los Angeles abrasion

The mean Los Angeles abrasion loss for both coarse fraction RCA are based on two test portions. Table 5.5 shows the results for the RCA and Table 5.6 shows the results for the NA. Full tables with the raw data can be found in Appendix A.

Table 5.5: Los Angeles abrasion loss - RCA.

Fractions	Mean LA [%]	Standard deviation [%]
4-8mm	56.5	1.1
8-16mm	58.9	1.0

Table 5.6: Los Angeles abrasion loss - NA.

Fractions	Mean LA [%]	Standard deviation [%]
4-8mm	27.4	0.5
8-16mm	35.4	0.5

5.6 Density of the aggregates (pycnometer)

The density for the RCA found using the pycnometer test are shown in the Table 5.7. Full tables with the raw data can be found in Appendix A.

Table 5.7: Density for the RCA found using the Pycnometer test.

Fractions	Mean $[\frac{kg}{m^3}]$	Standard deviation
0-4mm	2582.2	11.7
4-8mm	2554.6	6.7
8-16mm	2580.6	20.2

For comparison the values for the NA aggregates are shown in Table 5.8.

Table 5.8: Density for the NA, see Appendix B.

Fractions	Mean $[\frac{kg}{m^3}]$
0-4mm	2620
4-8mm	2610
8-16mm	2610

The density for the RCA is found to be lower than the NA, this corresponds well with the findings in [Pepe et al., 2016].

5.7 Recycled aggregate concrete

Since the workability of the concrete was one of the main challenges throughout this project, an overview of the slump values is given in Figure 5.4.

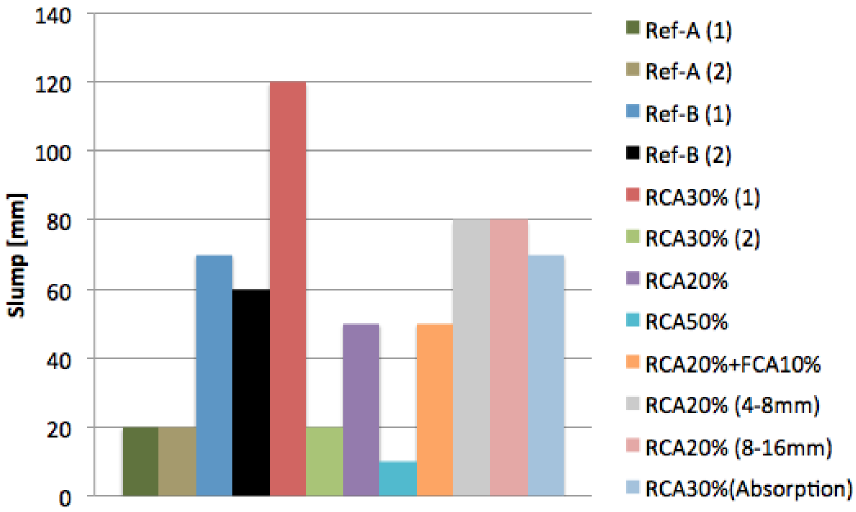


Figure 5.4: Slump value for all castings

From Figure 5.4 a big variation between the slumps is noticed. An acceptable slump value is around 50mm or above in terms of workability, when casting the chosen moulds. In general when the concrete is vibrated on site, a higher slump value is mostly required, and the concrete are normally delivered with a slump between 80-150mm depending on the purpose of the concrete [Betonhåndbogen, 2013].

The air content was examined for every concrete casting and was found in the range of 1.2-2.5% for all castings. A clear difference between the air content of NAC and RAC was not detected, the data can be found in Appendix C.

5.7.1 Compressive strength

In total 4 reference concrete mixes was made for this project, see Figure 5.5. All the results for the compressive strength tests are illustrated using bars, each bar is the mean value of 4 tested concrete cylinders. Furthermore the standard deviation is shown with error bars. All the raw data concerning the concrete cylinders can be found in Appendix C.

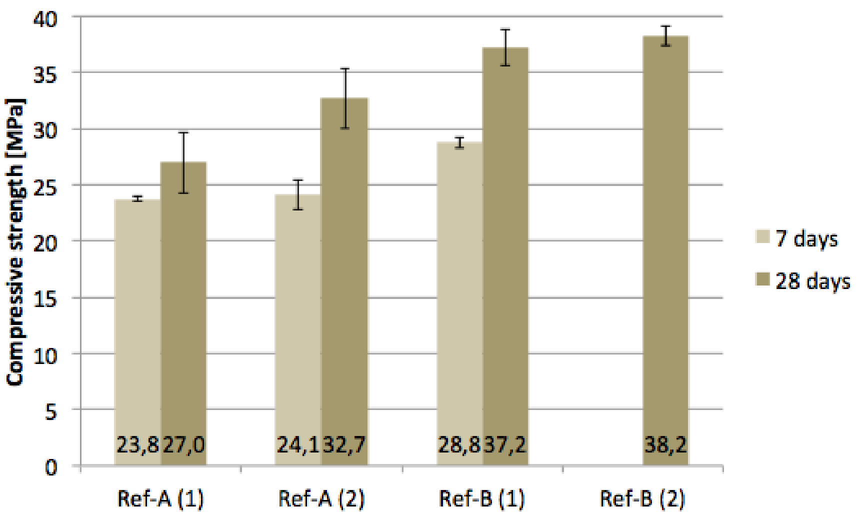


Figure 5.5: All reference specimens

Since an unsatisfying workability was achieved for both Ref-A mixes, no replacement was done for these. However the workability was acceptable for Ref-B (1), therefore the recipe for this mix was used further into the project. An extra Ref-B (2) mix was done later in the project mainly to test the modulus of elasticity, therefore no 7 days curing specimens were necessary. Furthermore it should be noticed, that the difference between the Ref-B (1) and Ref-B (2) was only 1 MPa for the 28 days cured specimens.

5.7.2 Initial testing

The first conducted tests was the RCA30% (1) and RCA30% (2) cured for 7 days, these are shown on Figure 5.6 together with Ref-B (1).

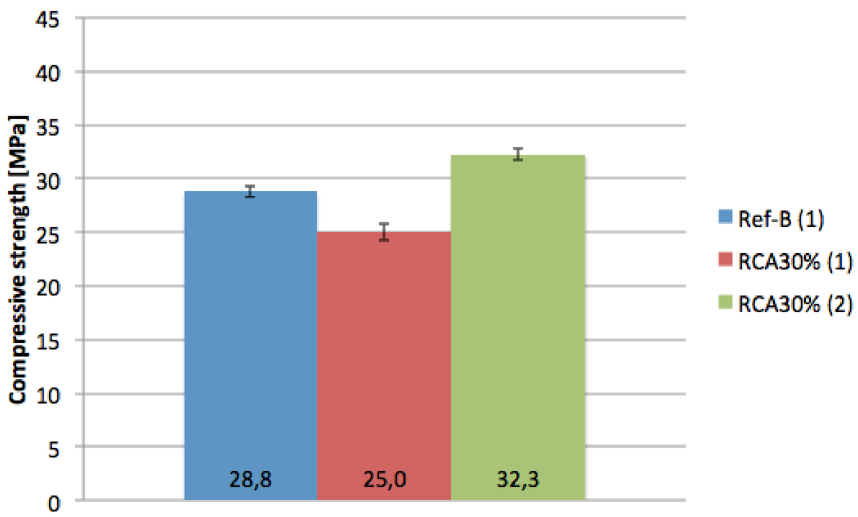


Figure 5.6: Results from the first conducted tests, cured for 7 days

From Figure 5.6 it is seen that RCA30% (1) had a significantly lower compressive strength compared to Ref-B (1). For this casting the water content was not included, i.e. the water to cement ratio can be expected to be higher than for Ref-B (1). Therefore the secondary RCA30% (2) was made, which had a higher compressive strength than the Ref-B (1), however the slump was significantly lower than the Ref-B (1) see figure 5.4.

In Chapter 2, the importance of knowing the water content of the RCA was described, in terms of being able to control the water to cement ratio. From the slump value Figure 5.4 and the compressive strength Figure 5.6 it is found, that the aggregates most likely are in a SAT state, since it resulted in a more wet fresh concrete for RCA30% (1). This indicates that the RCA delivers additional water to the mixture. Therefore was the water content of the RCA subtracted when casting the other specimens.

In Figure 5.7 the same amount of replacement is performed, but the concrete has cured for 28 days.

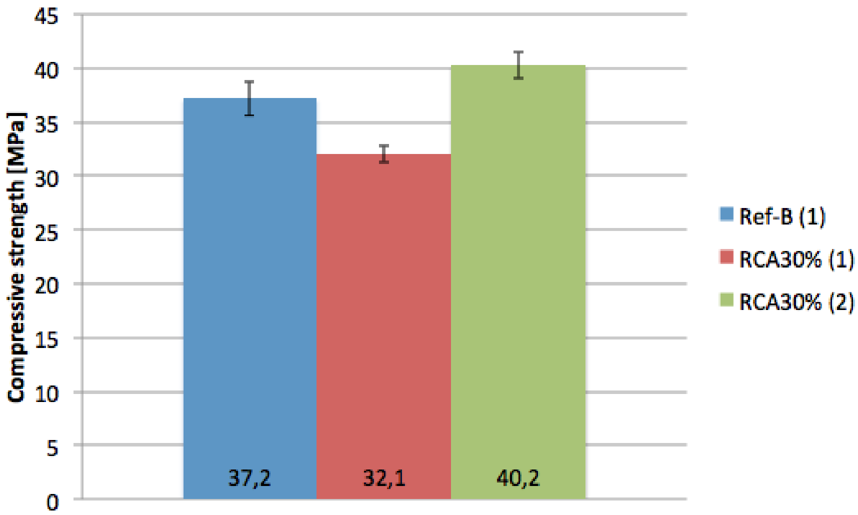


Figure 5.7: Results from the first conducted tests, cured for 28 days

From Figure 5.7 it is noticed that the same tendency applies for the 28 days cured specimens as for the 7 days cured specimens.

5.7.3 Further testing part 1

For this series of experiments the purpose was to test the maximum possible replacement RCA50% and to achieve an acceptable workability using RCA, RCA20%. The obtained results for the 7 days cured specimens is seen in Figure 5.8

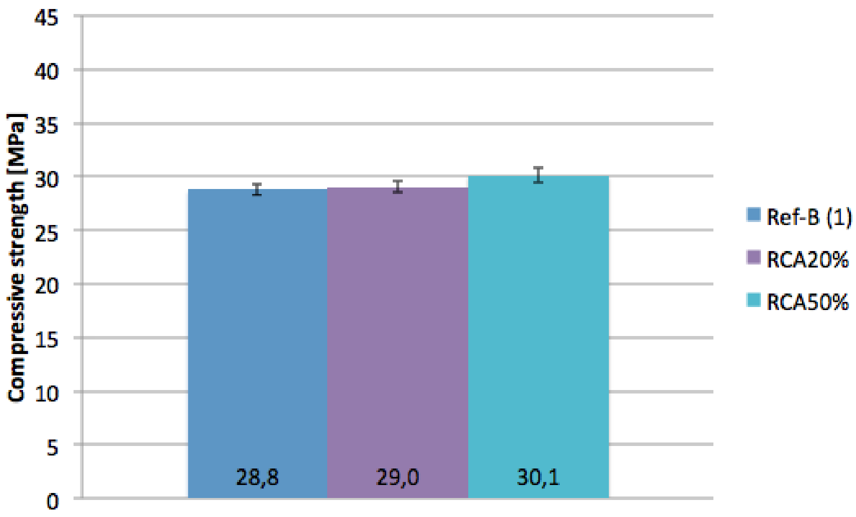


Figure 5.8: Results from the further testing part 1, cured for 7 days

Both the RCA50% and RCA20% achieved a minimal higher compressive strength than the Ref-B (1). The slump value was significantly lower for the RCA50%, and resulted in an unacceptable workability, therefore no further experiments with this replacement was done. However the RCA20% did show promising results, since both the compressive strength and workability was acceptable compared to Ref-B (1).

The specimens RCA50% and RCA20% cured for 28 days are shown in Figure 5.9.

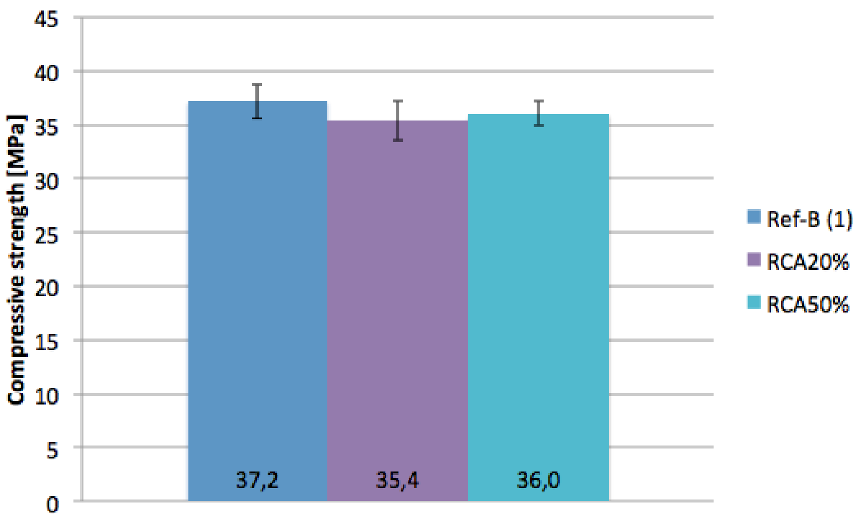


Figure 5.9: Results from the further testing part 1, cured for 28 days

From Figure 5.9 it is noticed that both RAC specimens lies slightly below the Ref-B (1) when all specimens have cured for 28 days. Whereas the opposite tendency was noticed for the 7 days cured specimens.

5.7.4 Further testing part 2

Since the RCA20% was considered acceptable compared to the Ref-B (1) further test within this replacement was investigated. First test, the fine fraction included RCA20%+FCA10% was performed. Hereafter, the significance of replacement of only one coarse fraction was investigated, RCA20% (4-8mm) and RCA20% (8-16mm). The results for the 7 days cured samples are shown in Figure 5.10.

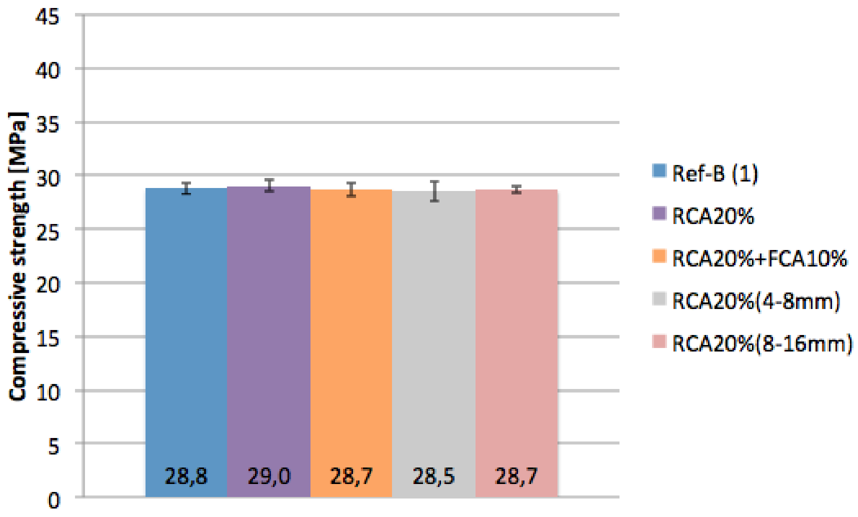


Figure 5.10: Results from the further testing part 2, cured for 7 days

The results in Figure 5.10 indicates that no significant difference in the compressive strength was obtained by these amounts of replacement. Furthermore it should from Figure 5.4 be observed that the slump and thus the workability still is acceptable.

The results for the corresponding specimens cured for 28 days are seen in Figure 5.11.

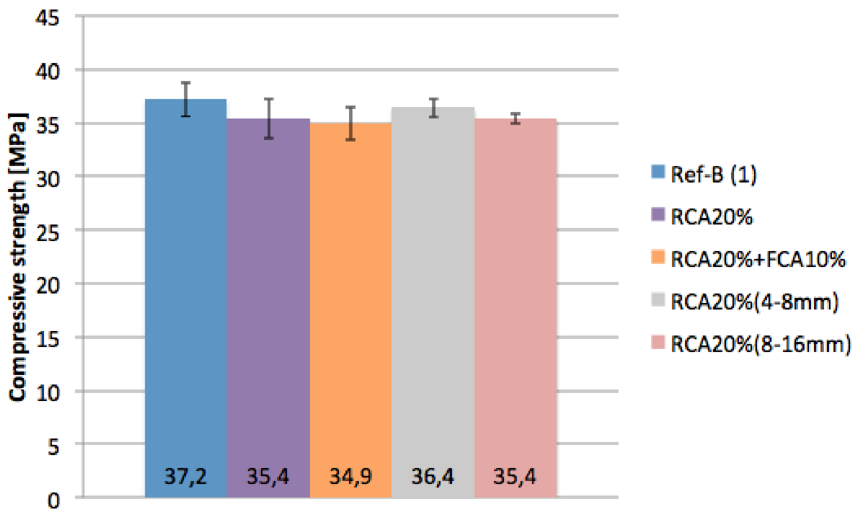


Figure 5.11: Results from the further testing part 2, cured for 28 days

For the specimens cured for 28 days it is noticed that the results varies more, and the compressive strength again lies slightly lower than Ref-B (1). However this variation is still very small, and the results still indicates that these replacements are possible.

5.7.5 Final testing

For the final testing a replacement with 30% was again investigated. The water content was still included, in addition to that the absorption was also taken into consideration, RCA30% (Absorption). This resulted in, that the water content of the RCA was subtracted from the mixing water, and the absorption of the RCA was added to the mixing water.

The specimens for this investigation had only cured for 7 days, and the results are shown in Figure 5.12 together with the other 30% replacement specimens and Ref-B (1).

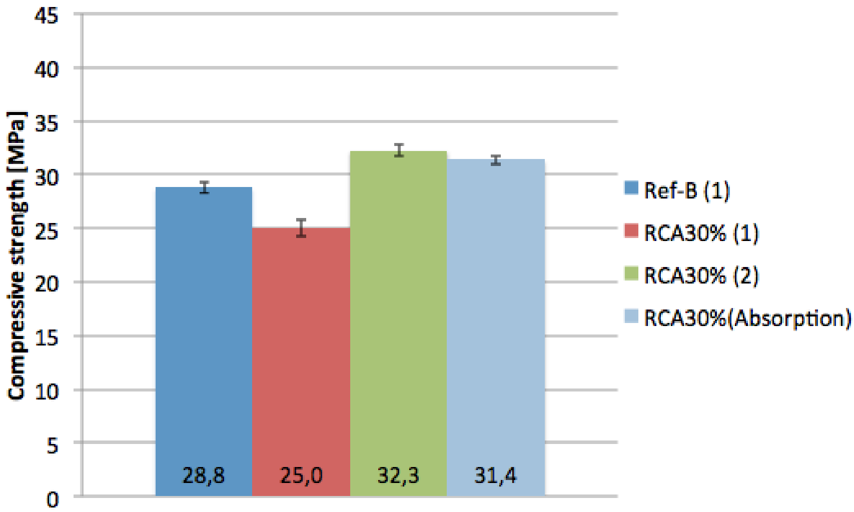


Figure 5.12: Results from the final testing, cured for 7 days.

As expected, the RCA30% (Absorption) obtain a higher compressive strength than RCA30% (1), due to the fact that the water to cement ratio is assumed to be lower for the RCA30% (Absorption). The compressive strength for RCA30% (Absorption) is surprisingly high compared to REF-B (1) (since it was attempted to achieve the same water to cement ratio). The compressive strength for the RCA30% (Absorption) is almost as high as the one for the RCA30% (2). These results could indicate that, the RCA was better than the NA, however this would be an unlikely/surprising conclusion. A more likely explanation could be that the water to cement ratio was lower than expected.

5.7.6 Fracture type of concrete cylinders

After testing the compressive strength of the concrete cylinders the fracture type for each cylinder was determined. An example of the fractures for RCA50% (28 days) are shown on Figure 5.13, where the fracture type is indicated below for each cylinder.

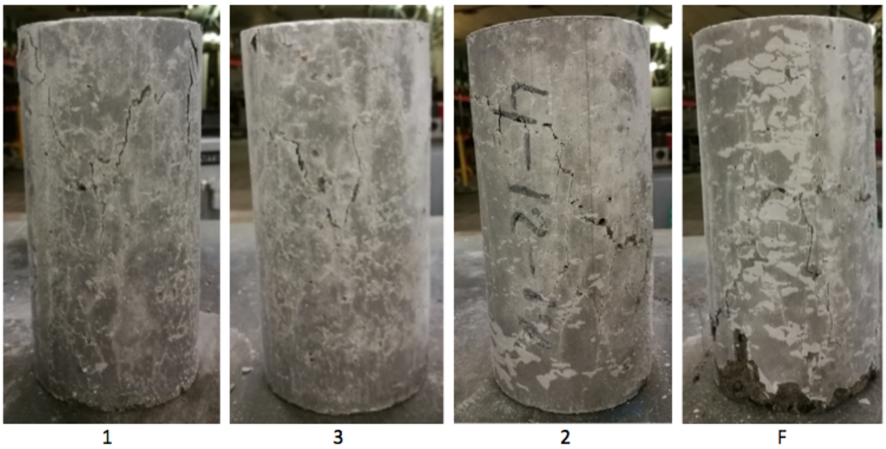


Figure 5.13: RCA50%, 28 days

It is noticed, that the fractures are unclear, therefore some cylinders was tested two times, this is seen on Figure 5.14. This was done in order to get clearer fractures, therefore the fracture type was always controlled by the specimens, which had been tested two times.

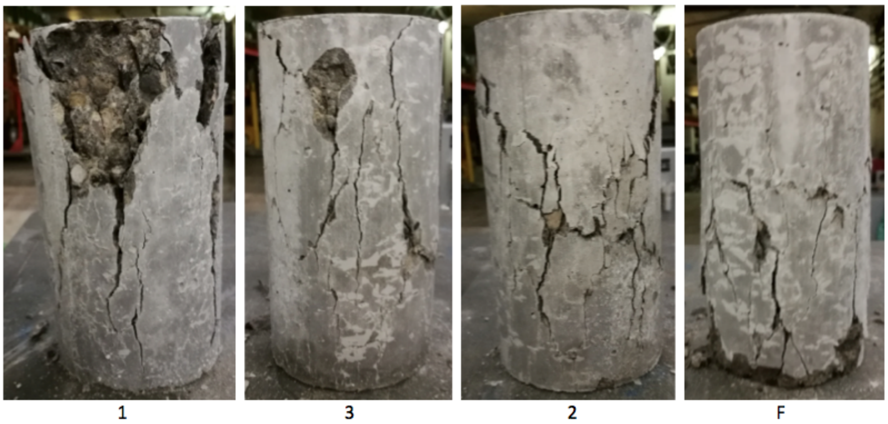


Figure 5.14: RCA50%, 28 days (tested two times)

An overview of all the concrete fractures are seen in Table 5.9, this Table indicates how many types of fractures there was for each concrete mix. Pictures of all tested concrete cylinders and their fracture type can be found in Appendix C together with an overview of the theoretical satisfying and unsatisfying fractures.

Table 5.9: Fracture types overview.

Mix	Satisfying fractures				Unsatisfying fractures
	1	2	3	4	
Ref-A (1)	3	1	2	2	
Ref-A (2)					
Ref-B (1)	2	1	4	1	
Ref-B (2)	2	2			
RCA30% (1)		5	1	1	J
RCA30% (2)	5		1	2	
RCA20%	2	1	2	2	K
RCA50%	1	2	3	1	F
RCA20%+FCA10%	1	1	1	4	K
RCA20% (4-8mm)	1	2	2	3	
RCA20% (8-16mm)	1	4	2	1	
RCA30% (Absorption)		2	2		
Total	18	21	20	17	

Based on all the fracture patterns found in this project it can be concluded, that the majority of the concrete cylinders failures, can be classified as satisfying fractures. Few unsatisfying fractures was noticed throughout this project, which could be the results of either over or under vibration when casting the concrete cylinders. Furthermore it is seen that the amount of satisfying fractures are almost equally divided between type 1, 2, 3 and 4.

5.8 Modulus of elasticity

As mention in section 4.10 the modulus of elasticity was examined for 3 concrete cylinders in each series. However the measuring equipment was very difficult to use, which resulted in much unreliable data. It was important that the cylinder was placed in the middle of the machine under compression. Furthermore it was crucial that the equipment was mounted correctly on the cylinder. This was difficult to see with the naked eye, and only the after-test data analysis could reveal whether the equipment was mounted correctly or not.

An example for both a successful and unsuccessful experiment when examine the modulus of elasticity is seen in Figure 5.15 and Figure 5.16.

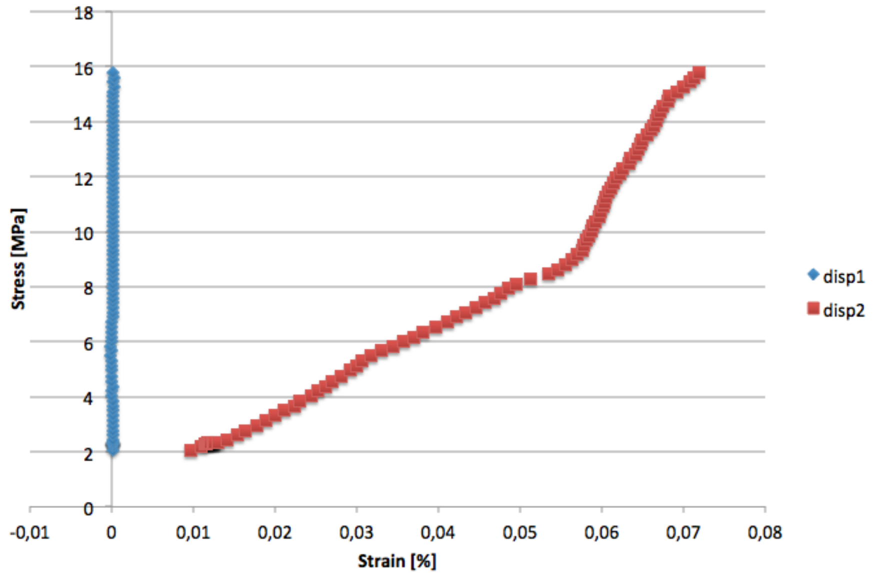


Figure 5.15: Unsuccessful example: Ref-B (2)

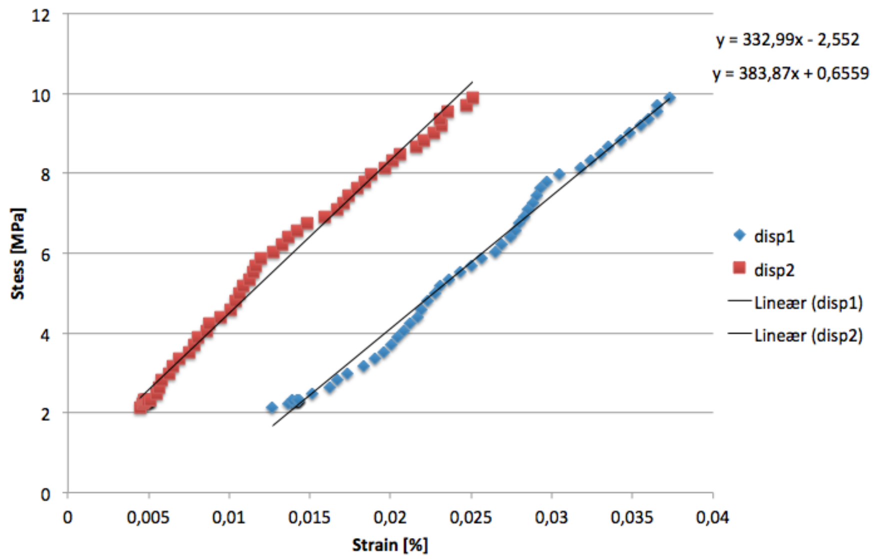


Figure 5.16: Successful example: Ref-B (2)

It should be noticed that the strain is presented in percentage and not permille, which results in the slope (E-modulus) of the linear functions has to be multiplied with 10^-1 GPa. Furthermore it should also be noticed that the functions does not go through (0.0), since data points for the stresses and strain was removed, because they were considered disruptive.

Unfortunately, for some series only one useful modulus of elasticity was found. A survey of the successful experiment are shown in Table 5.10 below.

Table 5.10: Survey of the E-modulus test.

Specimens \ E modules attempts	1	2	3	Mean
Ref-B (2)	35.9 GPa	x	x	35.9 GPa
RCA30% (1)	26.4 GPa	x	23.5 GPa	25.0 GPa
RCA30% (2)	x	x	24.3 GPa	24.3 GPa
RCA20%	x	31.1 GPa	x	31.1 GPa
RCA50%	26.7 GPa	24.9 GPa	x	25.8 GPa
RCA20%+FCA10%	x	28.7 GPa	31.1 GPa	29.9 GPa
RCA20% (4-8mm)	30.6 GPa	x	28.3 GPa	29.6 GPa
RCA20% (8-16mm)	x	29.3 GPa	29.2 GPa	29.3 GPa

All graphs for the modulus of elasticity are shown in Appendix D.

5.9 Porosity & Density of the hardened concrete

The results for the open porosity for the 7 days cured concrete are seen in Table 5.11. The raw data can be found in Appendix E.

Table 5.11: Porosity of the hardened concrete.

Specimens	Porosity $P_{open}[\%]$	Standard deviation
Ref-B (2)	13.3	0.6
RCA50%	17.0	0.6
RCA20%+FCA10%	15.5	1.1
RCA20% (4-8mm)	14.5	1.0
RCA20% (8-16mm)	15.1	0.5

It was desired to investigate if a difference could be found between the open porosity for the top, middle and bottom, this is seen on Figure 5.17.

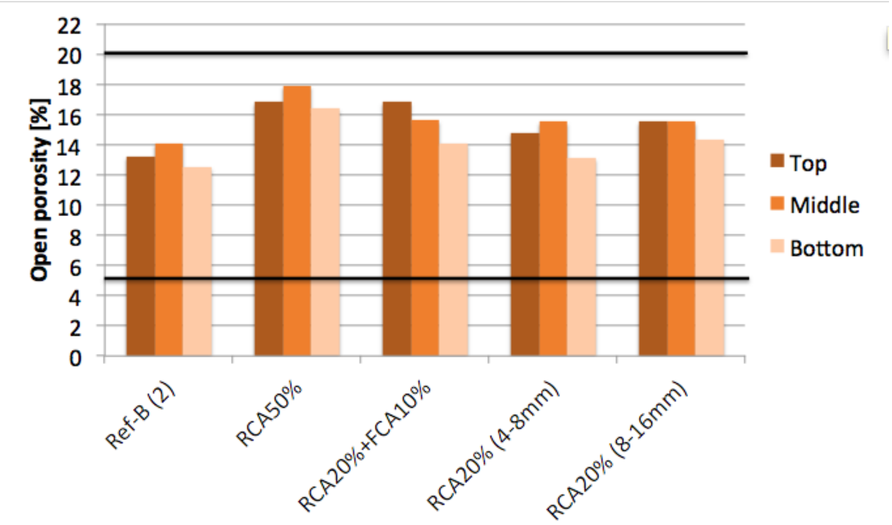


Figure 5.17: Open porosity for the top, middle and bottom

From Figure 5.17 it is seen that a higher porosity is applicable for either the top or middle compared to the bottom. The two black lines indicate the open porosity for NAC with a water to cement ratio between 0.4-0.6 found in [Gottfredsen and Nielsen, 1997]. From this it should be noticed that a clear degradation in open porosity is detected, however the values are still acceptable.

The results for the saturated surface-dry density for the 7 days cured concrete are seen in Table 5.12. The raw data can be found in Appendix E.

Table 5.12: Density of the hardened concrete.

Specimens	Density $\rho_{SSD}[\frac{kg}{m^3}]$	Standard deviation
Ref-B (2)	2402	12.4
RCA50%	2311	16.8
RCA20%+FCA10%	2359	26.9
RCA20% (4-8mm)	2377	20.7
RCA20% (8-16mm)	2368	12.1

The difference in density between the top, middle and bottom is also examined and illustrated in Figure 5.18.

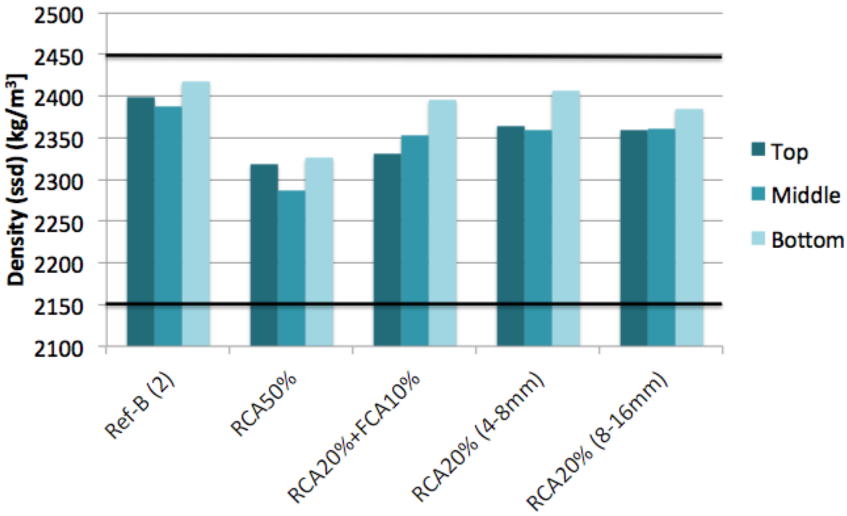
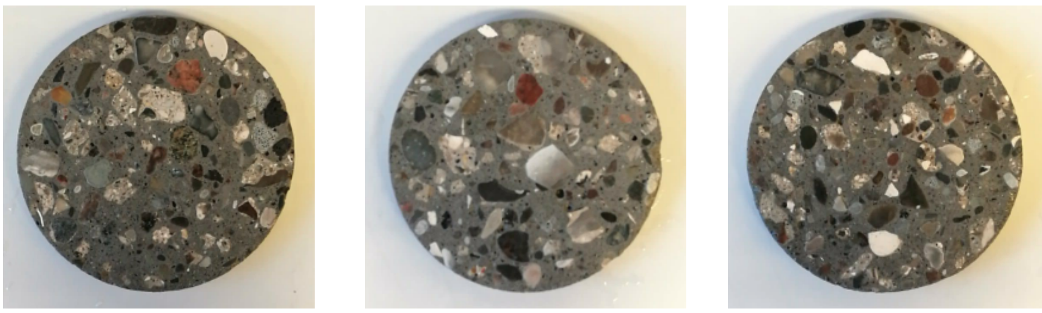


Figure 5.18: Saturated surface-dry density for the top, middle and bottom

These results are closely connected to the open porosity, since a higher density is found for the bottom, and a lower density for the top and middle. Again the values are acceptable according to [Gottfredsen and Nielsen, 1997] despite a clear negative development when replacing NA with RCA.

The values for both the open porosity and the saturated surface-dry density are based on three samples of cut concrete discs, an example for the cut discs are shown in Figure 5.19.



(a) Top **(b)** Middle **(c)** Bottom

Figure 5.19: Cut discs for the RCA50% specimen

These are a good example to demonstrate why a lower open porosity is found for the top or middle, since a greater amount of RCA can be seen on Figure 5.19a and Figure 5.19b compared to the bottom shown in Figure 5.19c.

6 Discussion

The results presented in Chapter 5 will be discussed and compared to other studies. When comparing with other studies it is (in most cases) only possible to compare the tendency that the results have. Since many factors of the RCA and RAC will be connected to its parent concrete.

6.1 Particle size distribution

From the combined particle size distribution curve in Figure 5.3 and Table 5.1 in Chapter 5 it is easy to get an overview of the percentage amount of aggregates in each fraction, which is seen in Table 6.1.

Table 6.1: Percentage amount of aggregates in each fraction.

Fractions	Distribution [%]
0-4mm	30.88
4-8mm	16.97
8-16mm	34.87
16-31.5mm	17.28

The used cylinder in this project had a diameter of 100mm therefore it was not possible to use the fraction 16-31.5mm, since 31.5 was a too big diameter for a 100mm mould according to [DS/EN12390-1, 2013]. From Table 6.1 it is noticed, that there are approximate twice as much of the fraction 8-16mm as there are of the fraction 4-8mm. This was also very clear when sieving the material.

Furthermore the found distribution is a good motivation for using the fine fraction (0-4mm), since a significant amount of these are present.

6.2 Water content, water absorption & attached mortar

The results from the water content, water absorption and attached mortar are shown in Table 6.2.

Table 6.2: Correlation between the amount of attached mortar, water content and water absorption.

Fractions	Mean attached mortar [%]	Mean water content [%]	Mean water absorption [%]
0-4mm	27.8	11.2	8.6
4-8mm	24.6	8.8	7.1
8-16mm	15.4	6.8	5.3

As it was found in various studies, the attached mortar was in this project observed to increase for decreasing aggregates size [Pepe et al., 2016], [Kisku et al., 2017] and [Hansen, 1992].

A clear link between the amount of attached mortar, water content and water absorption is observed. This corresponds well with the theory, since the more attached mortar is present the more water the aggregates can contain. Furthermore a higher percentage of absorption is found for the fine fraction and the smallest absorption for the biggest coarse fraction, see Table 6.2.

6.3 Los Angelse abrasion

The main results found in Chapter 5 are shown in Table 6.3.

Table 6.3: Los Angeles abrasion loss for RCA and NA.

Fractions	Mean LA - RCA [%]	Mean LA - NA [%]
4-8mm	56.5	27.4
8-16mm	58.9	35.4

As expected a significant higher Los Angeles abrasion loss is found for the RCA compared to the NA. It could have been expected that a higher Los Angeles abrasion loss would be found for the RCA fraction 4-8mm, since this fraction had a higher cement content as it was found in [Etxeberria et al., 2007]. However, the same tendency applies for the NA, i.e. that a higher Los Angeles abrasion loss is found for the bigger fraction.

For both the RCA and NA 12 steel balls were used for the fraction 8-16mm, whereas for the fraction 4-8mm only 8 steel balls were used, this could have an influence on the found Los Angeles abrasion loss, and help explaining why higher values are found for the bigger fraction.

6.4 Compressive strength of the recycled aggregate concrete

The tested compressive strength of the specimens is compared to the theoretical expected values, which are found by using Bolomey's formula as described in Chapter 2. However it was decided that only the comparison for the Ref-B was relevant. This is justified by the fact, that the water to cement ratio is paramount when using the Bolomey's formula. Only the water to cement ratio for the specimens in the Ref-B series are known, and it is determined to be 0.53 in Appendix B.

Table 6.4: Measured compressive strength compared to the theoretical expected compressive strength

Specimens	Measured [MPa]	Theoretical [MPa]	Deviation [%]
Ref-B (1) 7 days	28.8	28.5	1.1
Ref-B (1) 28 days	37.2	37.3	0.3
Ref-B (2) 28 days	38.2	37.3	2.4

From Table 6.4 it is noticed that the experimental found values has a minimal deviation from the theoretical calculated values. The given percentage is the percentage that the measured values deviate from the theoretical values.

Since it was considered that only the Ref-B series could be compared to the theoretical values, the RAC is like in Chapter 5, compared to Ref-B (1) and compared among themselves.

All the compressive strength test cured for 7 days are shown on Figure 6.1

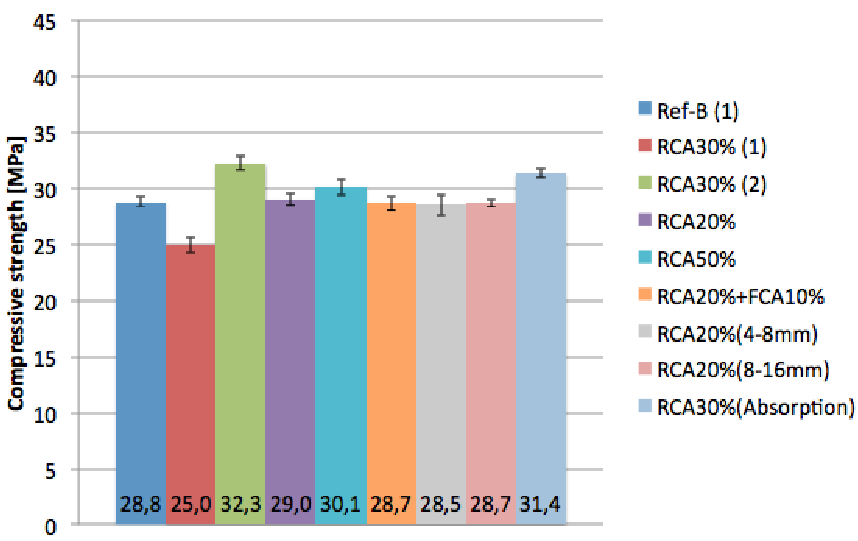


Figure 6.1: Compressive strength for all specimens cured for 7 days.

From the presented results in Figure 6.1 it should be noted that a degradation in terms of the compressive strength can not be proven, however a significant degradation in terms of the workability is observed. In [Kisku et al., 2017] experimental studies investigating similar properties were gathered and the overall tendency is that the compressive strength will decrease with increasing percentage of RCA replacement. However few studies have found that no degradation will take place, and even obtain a higher compressive strength when replacing NA by RCA, see Figure 2.7 in Chapter 2.

Again, a direct comparison is difficult, since no information of parent concrete and water to cement ratio, when making the RAC, are given. Furthermore replacement up to as much as 100% is carried out in [Kisku et al., 2017], which would not be possible for this project, if the water content are subtracted from the mixing water. This is a good example of the different properties of RCA and how important the processing of them are, since it must be assumed that the studies in [Kisku et al., 2017] have made something different from this project, since it was possible to make RAC with 100% RCA.

The comparable specimens cured for 28 days are seen on Figure 6.2

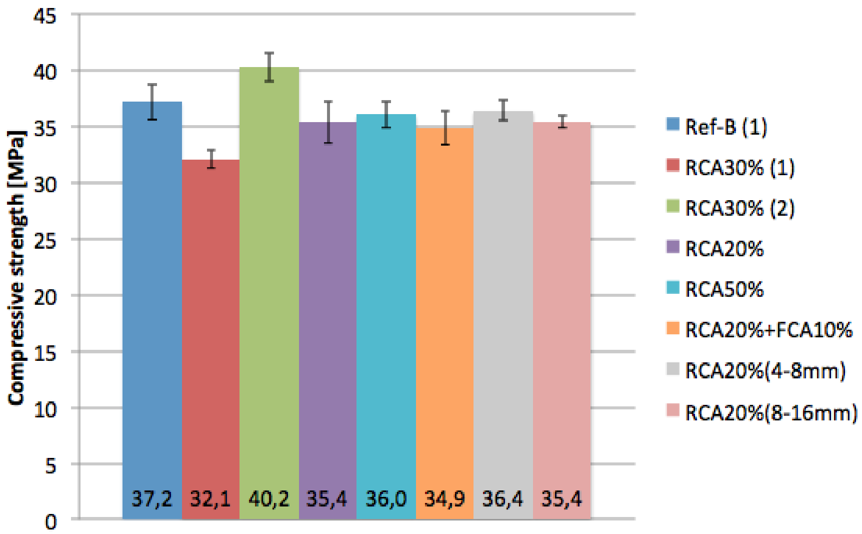


Figure 6.2: Compressive strength for all specimens cured for 28 days.

As mentioned in Chapter 5 the overall tendency between the specimens cured for 7 days and 28 days is very similar, and only a few deviations was observed. In general a higher standard deviation is found for the 28 days cured specimens, this was however also noticed for the concrete specimens with NA, see Figure 5.5.

6.5 Modulus of elasticity

In [Safiuddin et al., 2013] the effect of replacement of NA by RCA on the modulus of elasticity was also investigated, see Figure 6.3.

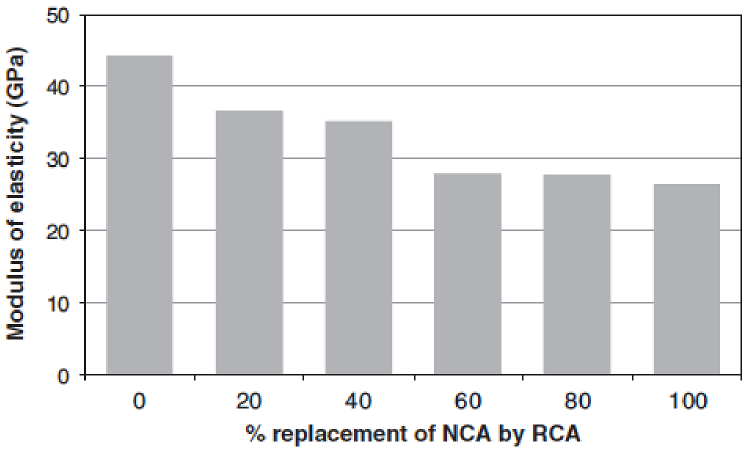


Figure 6.3: The effect of replacement of NA by RCA on the modulus of elasticity.

The results for the modulus of elasticity presented in Table 5.10 in Chapter 5 are graphic illustrated in the bar chart in Figure 6.4.

For comparison purposes the results are sorted by the amount of percentage replacement of RCA from left to right.

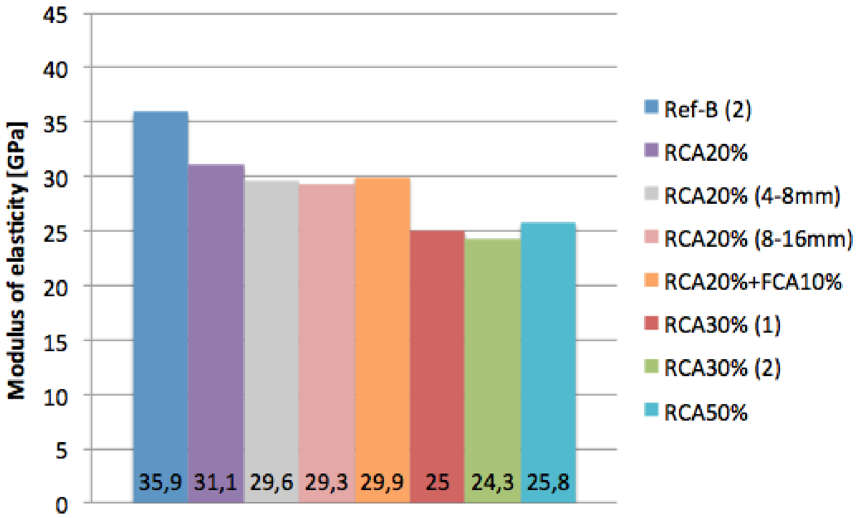


Figure 6.4: Modulus of elasticity

When comparing the findings from [Safiuddin et al., 2013] to the obtained results in this project, a very similar tendency is observed.

In [Safiuddin et al., 2013] it was found that replacing NA with 20% RCA resulted in a decrease of 18% in modulus of elasticity, whereas in this project a decrease of 13% was found. However it should be remembered that a direct comparison is not relevant, since the parent concrete also will have a great influence on the modulus of elasticity, as discussed in [Kisku et al., 2017].

From Figure 6.4 it can be seen that no significant difference is obtained among the specimens with 20% RCA replacement (RCA20%, RCA20% (4-8mm), RCA20% (8-16mm), RCA20%+FCA%). As expected a further deterioration in the modulus of elasticity is found for the two series with 30% RCA replacement (RCA30% (1) and RCA30% (2)). Finally the modulus of elasticity is surprising high for the RCA50%, since it could have been expected that it would lie significantly below the found values for the RCA30% (1) and RCA30% (2).

In general a higher modulus of elasticity will be found in stronger concrete, which clearly not is the case for RAC, as it is found in this project and various others. As explained in the theory in Chapter 2, the modulus of elasticity will decrease with increasing RCA percentage, due to the overall increased content of mortar. Therefore it should be noticed that for the equal 30% replacement of RCA, a slightly higher value is obtained for the RCA30% (1) compared to the RCA30% (2), although the RCA30% (2) had a significantly higher compressive strength.

Since a clear decrease in modulus of elasticity was detected, the found values are compared to the expected modulus of elasticity for concrete with a water to cement ratio between 0.4-0.6 found in [Gottfredsen and Nielsen, 1997].

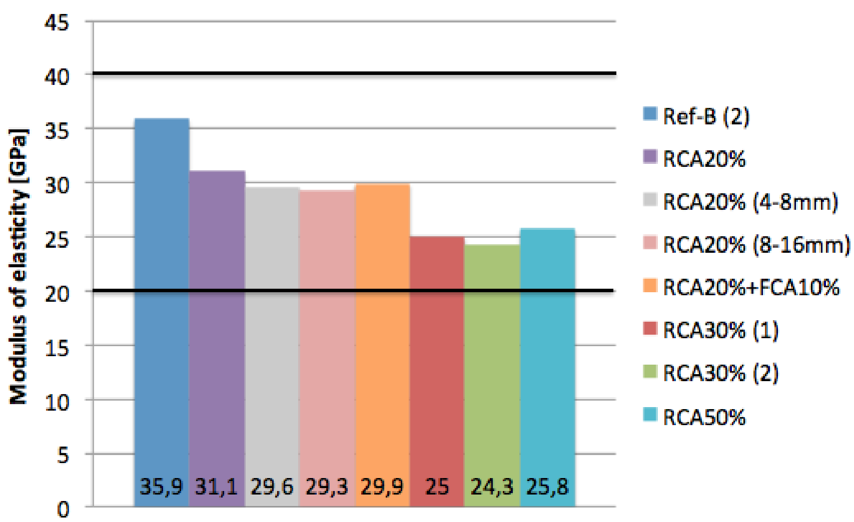


Figure 6.5: Modulus of elasticity with upper and lower limits.

From Figure 6.5 it should be noticed that despite a decreasing pattern in the values of modulus of elasticity, the values remain above the acceptable lower limit.

6.6 Porosity & Density of the hardened concrete

In the theory in Chapter 2 it was stated, that an increase in open porosity and a decrease in density would occur, this was however in [Pepe et al., 2016] only examined for the RCA and not RAC, see Figure 2.3 and Figure 2.4. Since a similar tendency would be expected for the RAC, this is examined with the results presented in Chapter 5. The found increase for the open porosity is shown in Figure 6.6, and the found decrease for the density is shown in Figure 6.7.

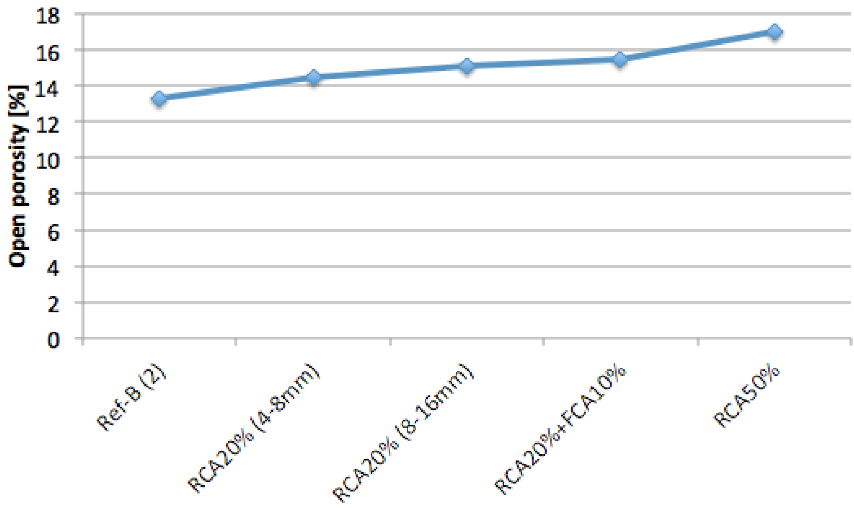


Figure 6.6: Open porosity.

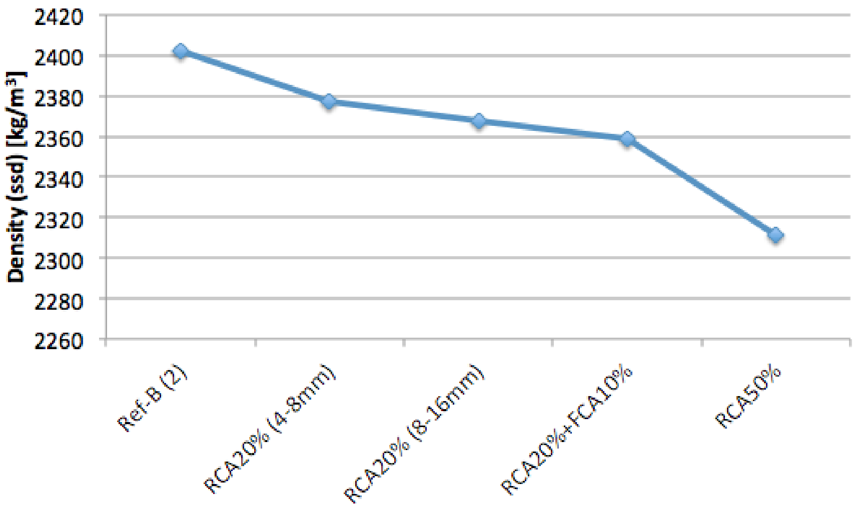


Figure 6.7: Saturated surface-dry density.

From the obtained results illustrated in Figure 6.6 and Figure 6.7 it can be seen that the assumed tendency are correct.

Furthermore it was in [Thomas et al., 2013] also found that the open porosity will increase with the increasing amount of RCA for the hardened concrete, which also corresponds well with the findings in this project. In [Thomas et al., 2013] the water to cement ratio was reported, but the specimens had cured for 28 days, where the specimens only had been curing for 7 days in this project. Therefore a direct comparison was still not possible, furthermore the amount of attached mortar was not given in [Thomas et al., 2013].

6.7 Further research

Since the replacement of NA by RCA shown some promising results it is ideal to improve the use of RCA.

Based on the findings in this project, it is seen that the workability is the most present problem. Therefore a solution to this is adjacent, this could be achieved by finding new ways to determine the water absorption for the RCA. Another suggestion could be by implementation of admixtures such as superplasticizers. This admixture has a positive influence on the workability without affecting the water to cement ratio. When the admixture is in contact with the cement, a negative charge will be developed. This lowers the surface tension of the surrounding water and thereby greatly increases the fluidity [Mehta and Monteiro, 2006].

7 Conclusion

Use of recycled concrete aggregates in new concrete can help reduce the shortage of natural aggregates. The technical possibilities and limits when using RCA was examined in this project.

The attached mortar was observed to increase with decreasing aggregate size. The amounts of attached mortar was found to be 27.8%, 24.6% and 15.4% for the 0-4mm, 4-8mm and 8-16mm respectively.

The water content was found to be in the range of 6.8-11.2%, where the highest water content was found for the smaller aggregates. In addition to these findings the water absorption was also found to be highest for the fraction 0-4mm, the absorption was found to be 8.6%, 7.1% and 5.3% for the 0-4mm, 4-8mm and 8-16mm respectively.

The attached mortar makes it difficult to control the water to cement ratio, which had a great impact on the compressive strength, this was clearly seen for the difference between the RCA30% (1) and RCA30% (2). However when the water content was subtracted from the mixing water, a replacement with 20% was still possible in terms of compressive strength and workability. When replacing 10% of the fine fraction together with 20% of the coarse fraction, no significant degradation was found. Likewise no degradation was observed when only replacing one coarse fraction (RCA20% (4-8mm) and RCA20% (8-16mm)).

The results from this project indicates if a replacement above 20% RCA is desired, it is necessary to include both the water content and water absorption, in order to maintain an acceptable workability.

A clear degradation in the modulus of elasticity was found. This degradation was already clear when replacing with 20% RCA. With increasing RCA-replacement a clear negative impact on the open porosity and density was observed. However the obtained values both for the modulus of elasticity, open porosity and density was within the general accepted values for concrete. From this it should be concluded that using RCA in new concrete in regards to these properties is possible, as long as they are thoroughly examined beforehand.

The results obtained in this project do indicate that partial RCA-replacement up to 20% RCA could reduce the demand for NA, without compromising the compressive strenght and workability. However the unique properties of RCA from various sources, especially with regards to attached mortar, should be thoroughly examined before applying it to new concrete.

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Appendix A
RCA properties

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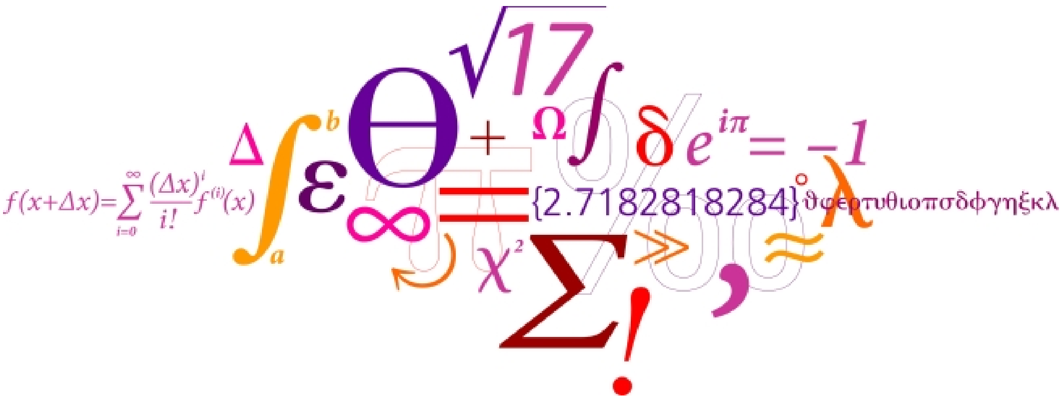
28-01-2018



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Contents

1 Particle size distribution

The raw data from the particle size distribution for the RCA with a diameter under 1mm are shown below.

um	mm	passing [%]	Cumulative passing [%]	Relative passing [%]	Relative cumulative passing [%]
1,905461	0,001905461	0	0	0	0
2,187762	0,002187762	0,085298	0,085298	0,013650239	0,013650239
2,511886	0,002511886	0,142748	0,228046	0,022843962	0,036494201
2,884031	0,002884031	0,206005	0,434051	0,03296698	0,069461182
3,311311	0,003311311	0,260971	0,695022	0,041763189	0,111224371
3,801894	0,003801894	0,312379	1,007401	0,049990011	0,161214382
4,365158	0,004365158	0,358022	1,365423	0,057294261	0,218508643
5,011872	0,005011872	0,401659	1,767082	0,06427749	0,282786132
5,754399	0,005754399	0,444392	2,211474	0,071116052	0,353902184
6,606934	0,006606934	0,488721	2,700195	0,078210022	0,432112206
7,585776	0,007585776	0,535163	3,235358	0,085642135	0,517754341
8,709636	0,008709636	0,586212	3,82157	0,093811506	0,611565847
10	0,01	0,641168	4,462738	0,102606115	0,714171962
11,481536	0,011481536	0,701929	5,164667	0,112329698	0,82650166
13,182567	0,013182567	0,766225	5,930892	0,122618987	0,949120647
15,135612	0,015135612	0,835287	6,766179	0,133670979	1,082791625
17,378008	0,017378008	0,906834	7,673013	0,145120645	1,22791227
19,952623	0,019952623	0,982983	8,655996	0,157306769	1,38521904
22,908677	0,022908677	1,064222	9,720218	0,170307447	1,555526487
26,30268	0,02630268	1,156307	10,876525	0,185043809	1,740570296
30,199517	0,030199517	1,265031	12,141556	0,202442911	1,943013207
34,673685	0,034673685	1,401455	13,543011	0,224274844	2,16728805
39,810717	0,039810717	1,576492	15,119503	0,252286015	2,419574065
45,708819	0,045708819	1,802975	16,922478	0,288530089	2,708104154
52,480746	0,052480746	2,090227	19,012705	0,334499027	3,042603181
60,255959	0,060255959	2,441366	21,454071	0,390691801	3,433294982
69,183097	0,069183097	2,853708	24,307779	0,456678891	3,889973873
79,432823	0,079432823	3,308891	27,61667	0,529521827	4,4194957
91,201084	0,091201084	3,787472	31,404142	0,606109144	5,025604844
104,712855	0,104712855	4,250527	35,654669	0,680211836	5,70581668
120,226443	0,120226443	4,671996	40,326665	0,74765952	6,4534762
138,038426	0,138038426	5,012641	45,339306	0,802172939	7,255649139
158,489319	0,158489319	5,2582	50,597506	0,841469746	8,097118885
181,970086	0,181970086	5,390881	55,988387	0,862702686	8,959821572
208,929613	0,208929613	5,413636	61,402023	0,866344169	9,826165741
239,883292	0,239883292	5,333071	66,735094	0,853451352	10,67961709
275,42287	0,27542287	5,159732	71,894826	0,825711912	11,505329
316,227766	0,316227766	4,910938	76,805764	0,785897408	12,29122641
363,078055	0,363078055	4,590607	81,396371	0,734634838	13,02586125
416,869383	0,416869383	4,207901	85,604272	0,673390397	13,69925165
478,630092	0,478630092	3,754945	89,359217	0,600903848	14,3001555
549,540874	0,549540874	3,235902	92,595119	0,517841397	14,81799689
630,957344	0,630957344	2,650334	95,245453	0,42413295	15,24212984
724,43596	0,72443596	2,02497	97,270423	0,324055949	15,56618579
831,763771	0,831763771	1,384205	98,654628	0,221514326	15,78770012
954,992586	0,954992586	0,802735	99,457363	0,128461682	15,9161618
1096,478196	1,096478196	0,383037	99,8404	0,061297411	15,97745921
1258,925412	1,258925412	0,153847	99,994247	0,024620135	16,00207935
1445,439771	1,445439771	0,005753	100	0,000920653	16,003

2 Water content

Table 2.1: Survey of the RCA results from the water content experiment.

Fractions	m_0 [g]	m_1 [g]	Water content [%]	Mean water content [%]	Standard deviation
0-4mm	200	177	11.5	11.2	0.2
	200	178	11.0		
	200	178	11.0		
4-8mm	200	182	9.0	8.8	0.2
	200	182	9.0		
	200	183	8.5		
8-16mm	200	187	6.5	6.8	0.2
	200	186	7.0		
	200	186	7.0		

3 Water absorption

Table 3.1: Results from the water absorption.

Fractions	SSD [g]	Dry [g]	Difference [%]	Mean [%]	Standard deviation
0-4mm	200.19	182.98	8.6	8.6	0.1
	200.50	183.47	8.5		
	200.20	182.63	8.8		
4-8mm	53.78	50	7.0	7.1	2.7
	51.99	50	3.8		
	55.79	50	10.4		
8-16mm	52.87	50	5.4	5.3	0.7
	53.20	50	6.0		
	52.30	50	4.4		

4 Attached mortar

For this experiment no standard procedure was found, which resulted in making one inspired from the "syreoplukning af beton", this procedure is seen on the following page. The result from this experiment is seen in Table 4.1.

Table 4.1: Survey of the results from the attached mortar experiment.

Fractions	Weight before [g]	Weight after [g]	Difference [%]	Mean [%]	Standard deviation [%]
0-4mm	50.63	36.75	27.41	27.8	0.9
	50.01	36.51	27.00		
	50.31	35.69	29.06		
4-8mm	20.24	14.63	27.72	24.6	2.6
	20.02	15.73	21.43		
	20.26	15.27	24.63		
8-16mm	50.05	41.35	17.38	15.4	1.5
	50.23	43.31	13.78		
	50.16	42.56	15.15		

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.

5 Los Angeles abration

Table 5.1: Survey of the LA experiment - RCA.

Fractions	m_0 [g]	m_1 [g]	LA [%]	Mean LA [%]	Standard deviation
4-8mm	1500 1500	636.35 669.63	57.6 55.4	56.5	1.1
8-16mm	1500 1300	601.38 547.54	59.9 57.9	58.9	1.0

Table 5.2: Survey of the LA experiment - NA.

Fractions	m_0 [g]	m_1 [g]	LA [%]	Mean LA [%]	Standard deviation
4-8mm	1500 1500	1097.23 1081.75	26.9 27.9	27.4	0.5
8-16mm	1500 1500	961.53 976.50	35.9 34.9	35.4	0.5

6 Density - Pycnometer

The raw data for the RCA fractions 0-4mm, 4-8mm and 8-16mm, are seen in Figure 6.1, Figure 6.2 and Figure 6.3 respectively.

				1	2	3
Fra kalibrering af pyknometer						
Pyknometer nummer				7	2	3
Pykn. + prop (tomt)		m_0	g	42,823	43,4429	45,9373
Pykn. + prop (vandfyldt)	W_2	m_1	g	142,2225	142,5256	145,1964
Temperatur ved kalibrering	T_k	T_1	YC	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		m_2	g	122,564	124,6470	123,027
Pykn.+ prop + jord + vand	W_1	m_3	g	191,384	192,342	192,405
Temperatur	T	T_3	YC	19	19	19
Densitet af vand ved T *	$\rho_{w,t}$	$\rho_{w;3}$	g/cm^3	0,99843	0,99843	0,99843
Jord - masse	W_s	m_4	g	79,741	81,2041	77,0897
Jord - volumen	V_s		cm^3	30,6904438	31,4997143	29,9908568
Korndensitet	ρ_s	ρ_s	g/cm^3	2,59823548	2,57793132	2,57044007
Resultat - middel	ρ_s	ρ_s	g/cm^3	**2,5822**		
Betegnelser fra	dgf15	DS				

Figure 6.1: Results for the fraction 0-4mm.

				1	2	3
Fra kalibrering af pyknometer						
Pyknometer nummer				20	30	40
Pykn. + prop (tomt)		m_0	g	365,14	363,19	363,67
Pykn. + prop (vandfyldt)	W_2	m_1	g	946,1	943,06	944,15
Temperatur ved kalibrering	T_k	T_1	ΥC	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		m_2	g	519,26	515,6100	517,6
Pykn.+ prop + jord + vand	W_1	m_3	g	1040,16	1035,86	1038,25
Temperatur	T	T_3	ΥC	21	21	21
Densitet af vand ved T *	$\rho_{w,t}$	$\rho_{w;3}$	g/cm^3	0,99802	0,99802	0,99802
Jord - masse	W_s	m_4	g	154,12	152,42	153,93
Jord - volumen	V_s		cm^3	60,3075019	59,8663881	60,0769395
Korndensitet	ρ_s	ρ_s	g/cm^3	2,55556929	2,54600294	2,56221441
Resultat - middel	ρ_s	ρ_s	g/cm^3	**2,5546**		
Betegnelser fra	dgf15	DS				

Figure 6.2: Results for the fraction 4-8mm.

				1	2	3
Fra kalibrering af pyknometer						
Pyknometer nummer				20	30	40
Pykn. + prop (tomt)		m_0	g	365,14	363,19	363,67
Pykn. + prop (vandfyldt)	W_2	m_1	g	946,1	943,06	944,15
Temperatur ved kalibrering	T_k	T_1	ΥC	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		m_2	g	516	513,2000	514,2
Pykn.+ prop + jord + vand	W_1	m_3	g	1038,75	1035,55	1035,86
Temperatur	T	T_3	ΥC	22	22	22
Densitet af vand ved T *	$\rho_{w,t}$	$\rho_{w;3}$	g/cm^3	0,9978	0,9978	0,9978
Jord - masse	W_s	m_4	g	150,86	150,01	150,53
Jord - volumen	V_s		cm^3	58,3383444	57,646823	58,9496893
Korndensitet	ρ_s	ρ_s	g/cm^3	2,58594929	2,60222493	2,55353339
Resultat - middel	ρ_s	ρ_s	g/cm^3	**2,5806**		
Betegnelser fra	dgf15	DS				

Figure 6.3: Results for the fraction 8-16mm.

7 RCA standards

The relevant standards referred to in Chapter 2 (Theory) concerning RCA are presented in this section.

Figure 7.1 taken from DS/EN12620+A1

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 7.1: Table 20 - Categories for constituents of coarse recycled aggregates.

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 7.2: Description for Table 20.

Figure 7.3 from DS2426 - EN206-1 gives a survey of the different exposure classes.

Miljøklasse i henhold til DS 411	Passiv	Moderat	Aggressiv	Ekstra aggressiv
Omfatter følgende eksponerings-klasser i henhold til DS/EN 206-1	X0 XC1	XC2 XC3 XC4 XF1 XA1	XD1 XS1 XS2 XF2 XF3 XA2	XD2 XD3 XS3 XF4 XA3

Figure 7.3: Different exposure classes.

Tabel 2426-3 – Tilslag – Generelle krav

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

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

2) Chloridindholdet kan bestemmes ved anvendelse af teststrips.

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

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

Figure 7.4: Table from DS2426.

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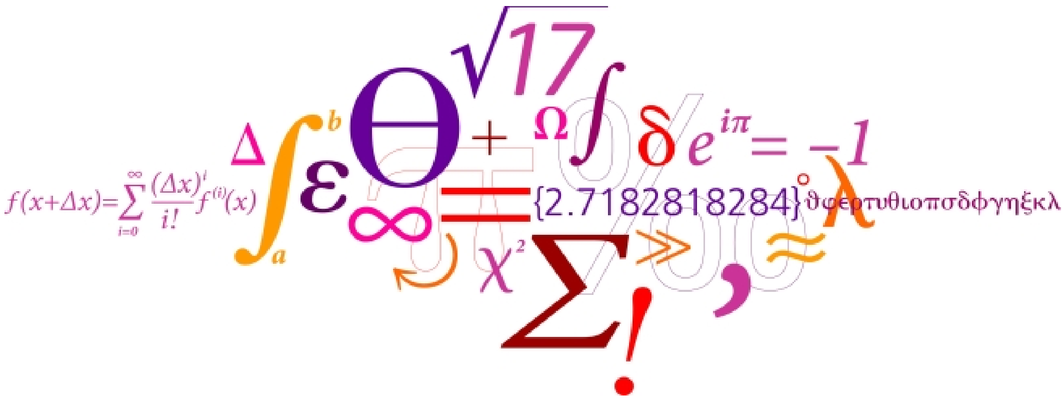
Appendix B
Mix design B

Nanna Johnsøn, s123837

28-01-2018



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Contents

1 Introduction

In this appendix the method and different steps of developing the mix design ”B” will be presented. The purpose of the new mix design ”B” was to archive a higher slump value. This method is based on the absorption of the aggregates and a desired water to cement ratio and slump value.

2 Methodology

For developing this new mix design a method from the DTU course "Construction Materials - use and testing" 11561 was used.

Some standard values are presented in Figure 2.1, which are used for later calculations.

	Fractions		
	Sand (0-4mm)	(4-8mm)	(8-16mm)
Density $[kg/m^3]$	2620	2610	2610
Absorption [%]	–	0.8±0.2	0.8±0.2

Figure 2.1

Step 1)

The water to cement ratio is chosen:

$$w/c = 0.6 \tag{2.1}$$

Step 2)

The amount of water (Volume) is determined based on the desired slump value. Due to the fact, that the aggregates was very dry is the highest possible slump value chosen, knowing that the slump value properly will be lower than the chosen one.

Tilslag		Vandbehov [l/m³]					
		Sætmål [mm]					
		0-30	30-60		60-100		100-150
d_{max}	Type	Naturligt luftind-hold	Naturligt luftind-hold	Indbland et luft	Naturligt luftind-hold	Indbland et luft	Naturligt luftind-hold
16 mm (Indblandet luft ~ 6 %)	Sømaterialer	148	165	160	175	170	183
	Bakkematerialer	152	170	165	180	175	188
	Skærver	166	186	180	197	191	206

Figure 2.2: Amount of water.

Based on the table in Figure 2.2 is the amount of water:

$$V_{water} = 183\frac{L}{m^3} \tag{2.2}$$

Step 3)

The mass of the water is:

$$m_{water} = 183\frac{kg}{m^3} \tag{2.3}$$

Step 4)

The amount of cement is calculated based on the water to cement ratio and the mass of water:

$$0.6 = \frac{w}{c} \tag{2.4}$$

$$0.6 = \frac{183\frac{kg}{m^3}}{c} \tag{2.5}$$

$$c = \frac{183\frac{kg}{m^3}}{0.6} \tag{2.6}$$

The mass of cement is:

$$m_{cement} = 305\frac{kg}{m^3} \tag{2.7}$$

Step 5)

Knowing the density of "Basis Aalborg cement":

$$p_{cement} = 3100\frac{kg}{m^3} \tag{2.8}$$

The volume of cement is determined:

$$V_{cement} = \frac{m_{cement}}{V_{cement}} = \frac{305\frac{kg}{m^3}}{3100\frac{kg}{m^3}} = 0.0984 \tag{2.9}$$

Step 6)

It is assumed that there always will be 1% of natural air present in the concrete:

$$V_{air} = 0.01m^3 \tag{2.10}$$

Step 7)

The percentage of sand is determine with the table in Figure 2.3 to be 47%

Cementindhold	Sandprocent				
	Største kornstørrelse [mm]				
[Kg/m³]	8	12	16	32	64
150	69	56	51	42	40
200	68	55	50	41	39
250	67	54	49	40	38
300	66	53	47	38	36
350	65	51	45	36	34
400	63	49	43	34	32
450	61	47	41	32	30

Figure 2.3: Sand percentage.

Step 8)

The total volume of cement, water and air is found (X):

$$X = 0.0984 + 0.183 + 0.01 = 0.2914m^3 \tag{2.11}$$

Step 9)

The total volume of the aggregates (sand and stone):

$$Y = 1 - 0.2914 = 0.7086m^3 \tag{2.12}$$

Step 10)

In step 7 was it found that the sand percentage should be 47%, furthermore is the same amount of the fractions 4-8mm and 8-16mm desired.

Sand:

$$0.333 \cdot 2620 = 872\frac{kg}{m^3} \tag{2.13}$$

4-8mm:

$$0.188 \cdot 2610 = 490\frac{kg}{m^3} \tag{2.14}$$

8-16mm:

$$0.188 \cdot 2610 = 490\frac{kg}{m^3} \tag{2.15}$$

Step 11)

It is necessary to know the water content of the aggregates, this is found by taken 3 samples of each 200g for the fractions 0-4mm, 4-8mm and 8-16mm in their air-dry state (AD), afterwards was the samples dried in a oven. The samples should be dried until a constant mass was achieved, normally this would take approximate 24 hours, the state of the aggregates is then defined as oven-dry (OD). For these investigations was the oven set to 105 °C ± 5 °C In table 2.1 is a survey of the NA aggregates shown, these are used to make the "Ref-B".

Table 2.1: Survey of the NA results from the water content experiment.

Fractions	Weight before [g]	Weight after [g]	Water content [%]	Mean water content [%]
0-4mm	200	200	0.0	0.2
	200	200	0.0	
	200	199	0.5	
4-8mm	200	200	0.0	0.2
	200	200	0.0	
	200	199	0.5	
8-16mm	200	200	0.0	0.2
	200	200	0.0	
	200	199	0.5	

Step 12)

Furthermore is it necessary to know the absorption of the aggregates, for the fractions 4-8mm and 8-16mm is an absorption of 1% assumed.

The absorption of the fraction 0-4mm is found by taking 1 kg of fully saturated sand, which had to be put on a pan and dried. The sand should be dried until ssd (saturated-surface-dry) state was obtained, this is checked by putting the sand in a small cone, which then is compacted 25 times. The shape of the sand when the cone is removed determines the current state of the sand, on Figure 2.4 is the different states illustrated.

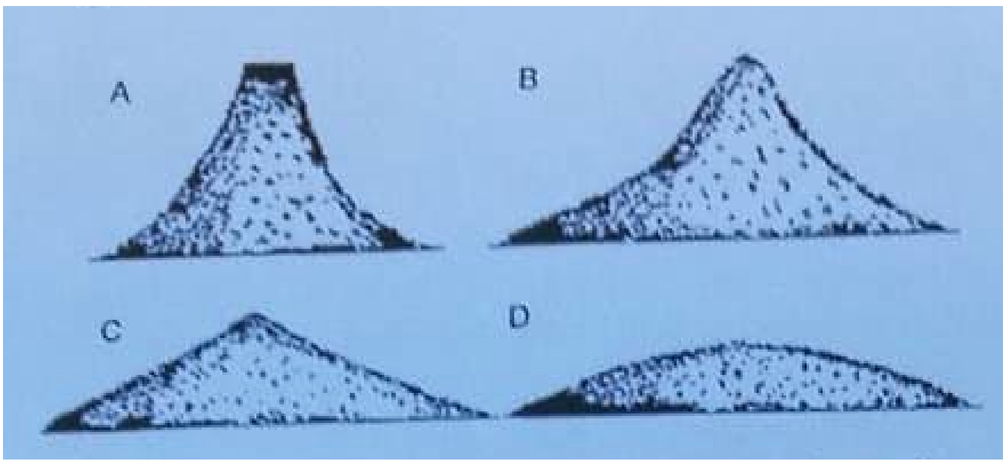


Figure 2.4: Different states for the sand, the desired state (ssd) is C.

(a) Wet sand on the pan. (b) State A. (c) State C.

Figure 2.5

When the ssd state is obtained, the sand is weighed, and afterwards dried until constant mass similar to the water content experiment.

Table 2.2: Water absorption for the sand (0-4mm).

Fractions	Weight before [g]	Weight after [g]	Water absorption [%]	Mean water absorption [%]
0-4mm	200.07	199.61	0.23	0.21
	200.15	197.68	0.24	
	200.01	199.68	0.17	

Step 13)

Finally it is necessary to make some adjusting for the moisture content in the aggregates, this is done for an example for making the mix design of 35L.

Cement:

$$\frac{305\frac{kg}{m^3} \cdot 35L}{1000} = 10.68kg \tag{2.16}$$

Water:

$$\frac{183\frac{kg}{m^3} \cdot 35L}{1000} = 6.41kg \tag{2.17}$$

Sand:

$$\frac{872\frac{kg}{m^3} \cdot 35L}{1000} = 30.54kg \tag{2.18}$$

4-8mm:

$$\frac{490\frac{kg}{m^3} \cdot 35L}{1000} = 17.15kg \tag{2.19}$$

8-16mm:

$$\frac{490\frac{kg}{m^3} \cdot 35L}{1000} = 17.15kg \tag{2.20}$$

The known data is put in the table, and the rest can be calculated with the shown equations.

Example for making 35 L	Fractions		
	Sand (0-4mm)	(4-8mm)	(8-16mm)
Water absorption [%] (A)	0.21	1	1
Water content [%] (B)	0.2	0.2	0.2
C = A – B	0.01	0.8	0.8
G = amount of aggregates [kg]	30.54	17.15	17.15
Aggregates adjusted for moisture $\left(\frac{100\% + B}{100\% + A}\right) \cdot G$	30.53	17.02	17.02
Adjusting of mixing water for moisture in the aggregates [L] $\left(\frac{C}{100\% + A}\right) \cdot G$	0.003	0.136	0.136
Amount of extra water [L] $\sum\left(\frac{C}{100\% + A}\right) \cdot G$	0.275		

Figure 2.6

The amount of extra water is added to the water calculated in equation (2.17). From this it was possible to start making the concrete for the "Ref-B" cylinders. However the slump value was not satisfying high, therefore some extra water was added (0.6 kg), and an equivalent amount of cement (0.99 kg) was added to maintain a water to cement ratio of 0.6.

The final mix design is shown below:

- Cement: 346 $\frac{kg}{m^3}$ for w/c 0.6
- Water: 208 $\frac{kg}{m^3}$
- Sand (0-4 mm): 872 $\frac{kg}{m^3}$
- Fine aggregates (4-8 mm): 486 $\frac{kg}{m^3}$
- Coarse aggregates (8-16 mm): 486 $\frac{kg}{m^3}$

In this mix design it was assumed that the absorption of the NA was 1%, however it was later learned that the absorption was 2.5%, this would naturally result in a lower water to cement ratio. The actual w/c - ratio for mix design B was calculated to 0.53, the properties of the NA fractions 0-4mm, 4-8mm and 8-16mm are seen on page 11-13.

3 Results

When comparing the two archived slump values from the two different mix designs, a significant higher value is obtained for mix design B. The value obtained with mix design B results in a 5cm higher slump value, which leads to a more wet and workable fresh concrete.

The slump value for mix design A is shown on Figure 3.1, and the slump value for mix design B is shown on Figure 3.2.

Figure 3.1: Slump test with the mix design A

Figure 3.2: Slump test with the mix design B

4 NA values

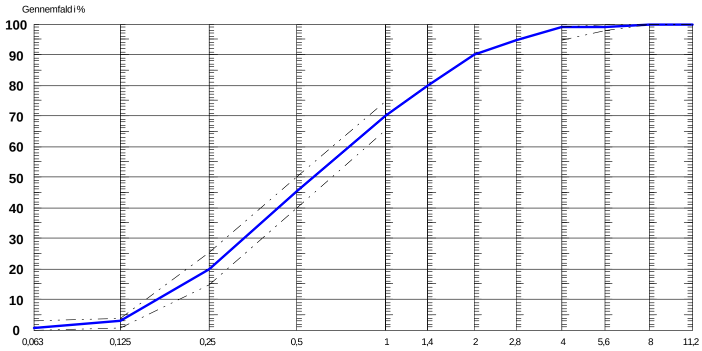
VAREDEKLARATION - BETON

Leverandør	Deklaration nr	Gyldig fra	Erstatter
NCC Roads A/S, Råstoffer RN Sten & Grus Stamholmen 225	14013-22 - 3 - BETON	13-04-11	01-12-08
Produktionssted RN Sten & Grus Stamholmen 225 2650 Hvidovre	Produktbetegnelse 0/4 mm betonsand, kl. E Produktbeskrivelse Søsand Attesteringsmetode Princip 2: Rullende kontrol		

Egenskab/prøvningsmetode	Forventet værdi	Min værdi	Max værdi
EN 1097-6 Korndensitet - VOT (Mg/m³)	2,62	2,58	2,66
EN 1097-6 Absorbtion (%)	0,2	0,1	0,4
DS/EN 1744 Chloridindhold (%) (Quantab)	0,014		0,020
Ækvivalent alkaliindhold (%)	0,012		0,020
DS/EN 1744 Humusindhold	Lysere		Lysere
TK-84 Kemisk svind (ml/kg)	0,08		0,20

EN 933-1 Kornstørrelsesfordeling

Min-værdi	Max-værdi	For-ventet	Sigte-serie
100	100	100	11,2
100	100	100	8
98	100	99	5,6
95	99	99	4
		95	2,8
85	95	90	2
		80	1,4
65	75	70	1
40	50	45	0,5
15	25	20	0,25
1	4	3	0,125
0,0	3,0	1,0	0,063



Bemærkninger
Kategori GF85, f3

CE-mærkning: www.tilslag.dk

Ulla Hansen, Laborant

FPC er Certificeret af Dancert
under notificeringsnr. 1073 (2+).
Produktet opfylder krav i overensstemmelse
med DS/EN 12620 og DS 2426.

NCC Roads A/S, Råstoffer
Laboratorie: Avedøre
Stamholmen 225
2650 Hvidovre

Telefon nr
36780500
Fax nummer
36780200

Figure 4.1: Data sheet for the fraction 0-4mm.

NCC

VAREDEKLARATION - BETON

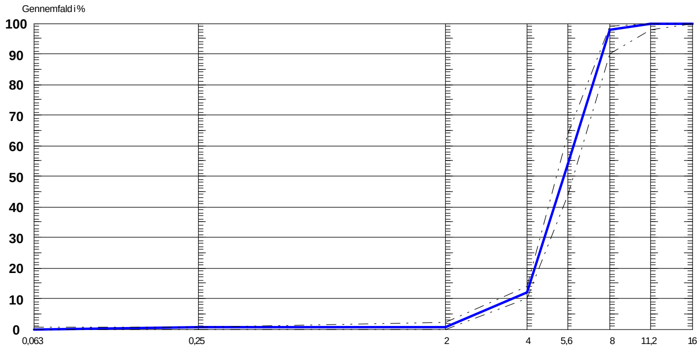
Leverandør	Deklaration nr	Gyldig fra	Erstatter
NCC Roads A/S, Råstoffer RN Sten & Grus Stamholmen 225	14021-22 - 3 - BETON	01-05-11	15-04-10

Produktionssted	Produktbetegnelse
RN Sten & Grus Stamholmen 225 2650 Hvidovre	4/8 mm perlesten kl. M. Produktbeskrivelse Jiggede søsten Attesteringsmetode Princip 2: Rullende kontrol

Egenskab/prøvningsmetode	Forventet værdi	Min værdi	Max værdi
EN 1097-6 Korndensitet - VOT (Mg/m³)	2,61	2,57	2,65
EN 1097-6 Absorbtion (%)	0,8	0,6	1,0
DS/EN 1744 Chloridindhold (%) (Quantab)	0,003		0,014
Ækvivalent alkaliindhold (%)	0,003		0,012
DS/EN 933-5 Totalt knust, >90% o.f.knust(%)	24		25
DS/EN 933-4 Formindex (%)	9		20
DS 405.4 Indhold af lette korn - < 2400 (%)	2,0		5,0
DS 405.4 Indhold af lette korn - < 2200 (%)	0,9		1,0
TI-B 75 Kritisk absorption (%)	0,9		2,5

EN 933-1 Kornstørrelsesfordeling

Min-værdi	Max-værdi	For-ventet	Sigte-serie
100	100	100	16
98	100	100	11,2
90	99	98	8
44	64	54	5,6
10	14	12	4
0	2	1	2
0	1	1	0,25
0,0	1,0	0,0	0,063



Bemærkninger

Kategori $G_c85/20$, G_T15, $f_{1,5}$

CE-mærkning: www.tilslag.dk

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Laboratorie: Avedøre
Stamholmen 225
2650 Hvidovre

Telefon nr
36780500
Fax nummer
36780200

Figure 4.2: Data sheet for the fraction 4-8mm.

NCC — **VAREDEKLARATION - BETON**

Leverandør	Deklaration nr	Gyldig fra	Erstatter
NCC Roads A/S, Råstoffer RN Sten & Grus Stamholmen 225	14031-22 - 3 - BETON	01-05-11	15-04-10

Produktionssted: **RN Sten & Grus, Stamholmen 225, 2650 Hvidovre**

Produktbetegnelse: **8/16 mm ærtesten, kl. M**

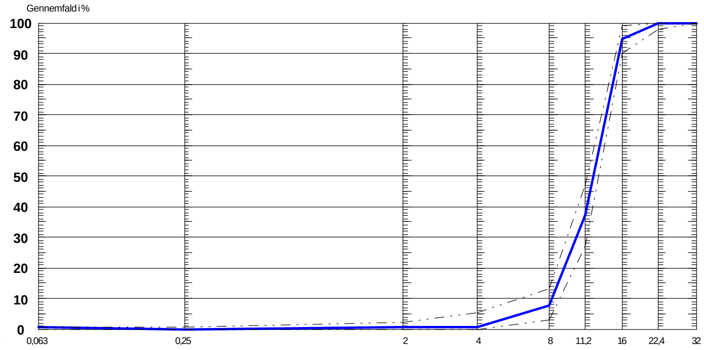
Produktbeskrivelse: **Jiggede søsten**

Attesteringsmetode: **Princip 2: Rullende kontrol**

Egenskab/prøvningsmetode	Forventet værdi	Min værdi	Max værdi
EN 1097-6 Korndensitet - VOT (Mg/m³)	2,61	2,57	2,65
EN 1097-6 Absorbtion (%)	0,8	0,6	1,0
DS/EN 1744 Chloridindhold (%) (Quantab)	0,002		0,020
Ækvivalent alkaliindhold (%)	0,002		0,020
DS/EN 933-5 Totalt knust, >90% o.f.knust(%)	11		25
DS/EN 933-4 Formindex (%)	10		20
DS 405.4 Indhold af lette korn - < 2400 (%)	0,9		5,0
DS 405.4 Indhold af lette korn - < 2200 (%)	0,9		1,0
TI-B 75 Kritisk absorption (%)	0,6		2,5

EN 933-1 Kornstørrelsesfordeling

Min-værdi	Max-værdi	For-ventet	Sigte-serie
100	100	100	32
98	100	100	22,4
90	99	95	16
27	47	37	11,2
3	13	8	8
0	5	1	4
0	2	1	2
0	1	0	0,25
0,0	1,0	1,0	0,063



Bemærkninger

Kategori $G_c85/20$, G_T15, $f_{1,5}$

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Fax nummer
36780200

Figure 4.3: Data sheet for the fraction 8-16mm.

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Appendix C
Concrete cylinders

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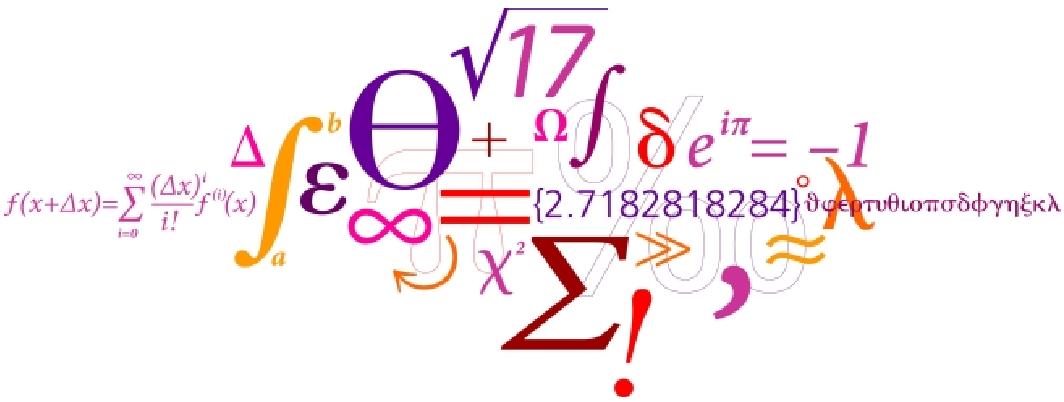
28-01-2018



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Contents

1 Concrete cylinders

All the raw data for the concrete cylinders are shown on the following page.

1. Concrete cylinders

Mix design [-]	Curring [-]	Slump [mm]	Air content [%]	Specimen [-]	Diameter [mm]	Area [mm^2]	Height [mm]	Weight [kg]	Load [kN]	Compressive strenght [MPa]	Mean [MPa]	Standard diveration [-]
Ref-A (1)	7 days	20	1,8	1	99,92	7841,4	200	3,666	186	23,7	23,8	0,29
				2	99,97	7849,3	200	3,653	188	24,0		
				3	100,02	7857,1	200	3,653	189	24,1		
				4	99,99	7852,4	199	3,645	183	23,3		
	28 days	20	2,1	1	100	7854,0	200	3,664	228	29,0	27,0	2,73
				2	99,98	7850,8	200	3,655	176	22,4		
				3	100,01	7855,6	200	3,654	229	29,2		
				4	99,9	7838,3	200	3,657	214	27,3		
Ref-A (2)	7 days	20	1,2	1	99,3	7744,4	200	3,744	183	23,6	24,1	1,30
				2	100	7854,0	200	3,73	193	24,6		
				3	100	7854,0	208	3,705	175	22,3		
				4	101	8011,8	199	3,735	207	25,8		
	28 days	20	1,5	1	99,67	7802,2	199	3,736	235	30,1	32,70	2,69
				2	100	7854,0	200	3,775	235	29,9		
				3	99,3	7744,4	200	3,727	272	35,1		
				4	100	7854,0	199	3,744	280	35,7		
Ref-B (1)	7 days	70	1,6	1	100	7854,0	199,3	3,67	225	28,6	28,8	0,50
				2	100	7854,0	200	3,673	226	28,8		
				3	100	7854,0	199,7	3,678	221	28,1		
				4	100	7854,0	199,3	3,683	232	29,5		
	28 days	70	1,6	1	99,96	7847,7	200	3,697	303	38,6	37,2	1,59
				2	100	7854,0	200	3,677	271	34,5		
				3	99,98	7850,8	199,9	3,67	298	38,0		
				4	99,98	7850,8	199,9	3,694	296	37,7		
RCA30% (1)	7 days	120	2,3	1	100	7854,0	200	3,618	198	25,2	25,0	0,75
				2	99,97	7849,3	199	3,606	191	24,3		
				3	99,9	7838,3	200	3,587	190	24,2		
				4	100	7854,0	200	3,606	205	26,1		
	28 days	120	2,3	1	99,97	7849,3	200	3,59	244	31,1	32,06	0,78
				2	100,01	7855,6	200	3,599	261	33,2		
				3	99,99	7852,4	199,9	3,607	253	32,2		
				4	100	7854,0	200	3,611	249	31,7		
RCA30% (2)	7 days	20	2,5	1	99,9	7838,3	200	3,641	246	31,4	32,3	0,59
				2	100	7854,0	200	3,647	257	32,7		
				3	100	7854,0	200	3,63	252	32,1		
				4	99,98	7850,8	200	3,62	258	32,9		
	28 days	20	2,5	1	100	7854,0	200	3,648	330	42,0	40,2	1,26
				2	99,99	7852,4	200	3,643	319	40,6		
				3	99,97	7849,3	200	3,618	312	39,7		
				4	100	7854,0	200	3,636	303	38,6		
RCA20%	7 days	50	1,3	1	100	7854,0	200	3,629	226	28,8	29,0	0,55
				2	100	7854,0	200	3,648	231	29,4		
				3	99,96	7847,7	200	3,652	233	29,7		
				4	100	7854,0	199	3,649	222	28,3		
	28 days	50	1,3	1	99,96	7847,7	200	3,647	269	34,3	35,38	1,87
				2	100	7854,0	199	3,639	262	33,4		
				3	99,98	7850,8	200	3,652	279	35,5		
				4	99,99	7852,4	200	3,651	301	38,3		
RCA50%	7 days	10	2,3	1	100	7854,0	200	3,581	230	29,3	30,1	0,75
				2	100,01	7855,6	200	3,578	232	29,5		
				3	99,9	7838,3	200	3,586	240	30,6		
				4	99,97	7849,3	200	3,584	244	31,1		
	28 days	10	2,3	1	100	7854,0	200	3,583	296	37,7	36,0	1,15
				2	100	7854,0	200	3,593	271	34,5		
				3	100	7854,0	200	3,591	285	36,3		
				4	100	7854,0	200	3,572	280	35,7		
RCA20%+FCA10%	7 days	50	1,9	1	99,98	7850,8	200	3,624	217	27,6	28,7	0,63
				2	100	7854,0	200	3,605	229	29,2		
				3	100	7854,0	200	3,637	227	28,9		
				4	100,01	7855,6	200	3,627	229	29,2		
	28 days	50	1,9	1	99,99	7852,4	200	3,626	258	32,9	34,89	1,50
				2	100	7854,0	200	3,616	276	35,1		
				3	100,01	7855,6	200	3,623	271	34,5		
				4	100	7854,0	200	3,614	291	37,1		
RCA20% (4-8mm)	7 days	80	2,4	1	100	7854,0	200	3,647	232	29,5	28,5	0,96
				2	100	7854,0	200	3,653	230	29,3		
				3	99,97	7849,3	200	3,636	221	28,2		
				4	100	7854,0	200	3,628	213	27,1		
	28 days	80	2,4	1	100	7854,0	200	3,639	289	36,8	36,4	0,90
				2	99,98	7850,8	200	3,64	274	34,9		
				3	99,98	7850,8	200	3,654	287	36,6		
				4	99,99	7852,4	200	3,654	293	37,3		
RCA20% (8-16mm)	7 days	80	2,5	1	100	7854,0	200	3,66	226	28,8	28,7	0,33
				2	99,99	7852,4	200	3,652	224	28,5		
				3	100	7854,0	200	3,658	229	29,2		
				4	100	7854,0	200	3,657	222	28,3		
	28 days	80	2,5	1	100	7854,0	200	3,668	284	36,2	35,40	0,52
				2	100	7854,0	200	3,658	273	34,8		
				3	100	7854,0	200	3,671	279	35,5		
				4	99,98	7850,8	200	3,655	276	35,2		
Ref-B (2)	28 days	60	1,6	1	100	7854,0	199,8	3,707	301	38,3	38,2	0,83
				2	100	7854,0	200	3,728	298	37,9		
				3	100	7854,0	200	3,732	310	39,5		
				4	100	7854,0	200	3,724	292	37,2		
RCA30%(Absorption)	7 days	70	1,7	1	100	7854,0	200	3,652	244	31,1	31,4	0,42
				2	100	7854,0	200	3,63	252	32,1		
				3	100	7854,0	200	3,631	246	31,3		
				4	100	7854,0	200	3,647	244	31,1		

Figure 1.1: Raw data for all concrete cylinders.

2 Cylinder fracture

The fracture of a concrete cylinder, is an indication for however the aggregates are properly distributed or not.

On Figure 2.1 is a number of satisfying (1-4) and unsatisfying (A-K) fracture types shown.

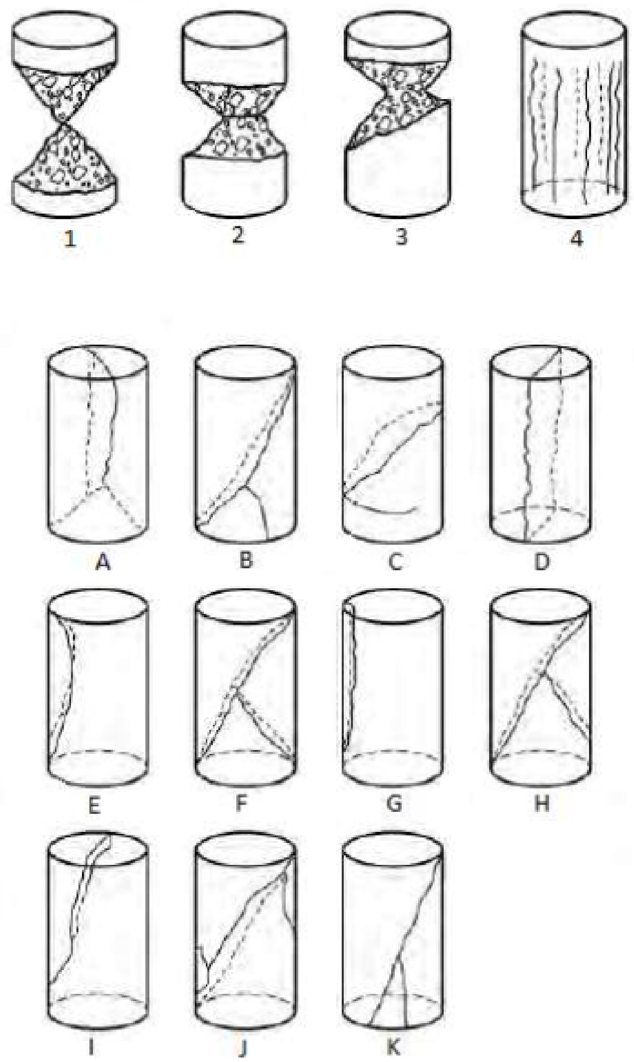


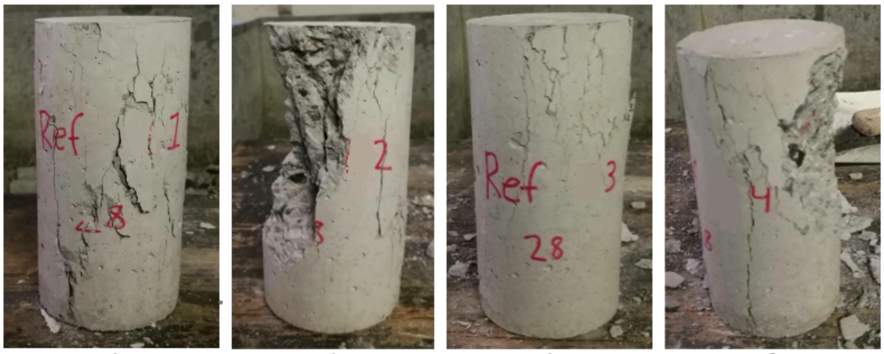
Figure 2.1: Fracture types of concrete cylinders.

The fracture type for each concrete cylinder are indicated in the following sections. As mentioned in the report 8 cylinders are tested for each concrete batch, 4 curing for 7 days and 4 curing for 28 days. The fracture type are indicated below the cylinder, each figure text give an explanation for the cylinders. Furthermore if a X is present, has the cylinder been tested two times, in order to get a more clear fracture shape.

2.1 REF-A1

1 3 2 1

Figure 2.2: REF-A1, 7 days



4 1 4 3

Figure 2.3: REF-A1, 28 days

2.2 REF-B1

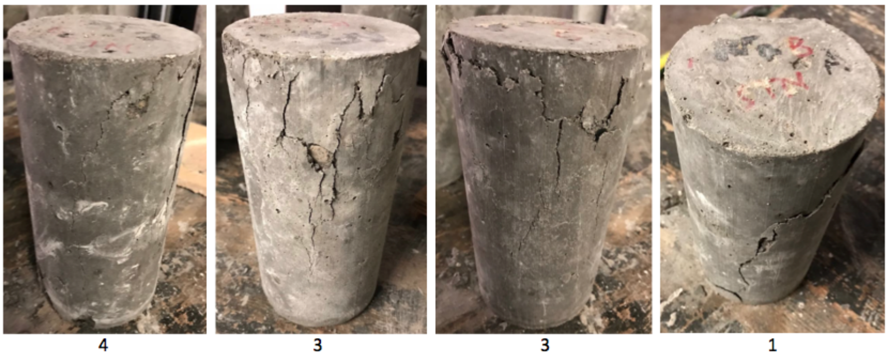


Figure 2.4: REF-B1, 7 days

Figure 2.5: REF-B1, 28 days

2.3 Ref-B2

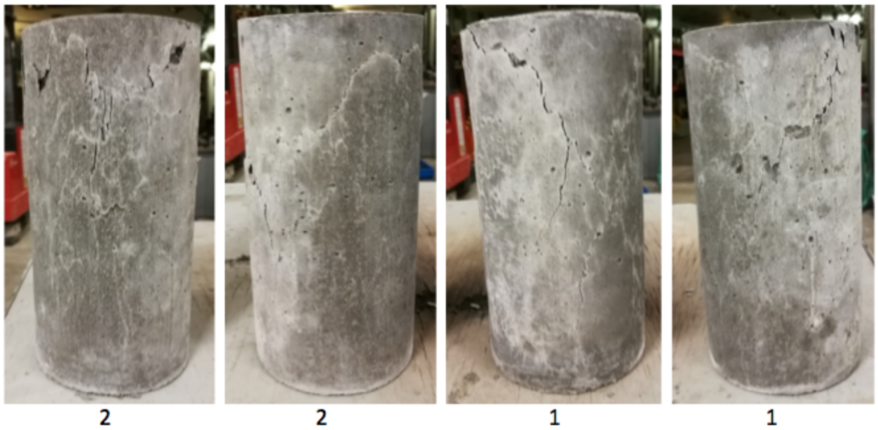


Figure 2.6: REF-B2, 28 days

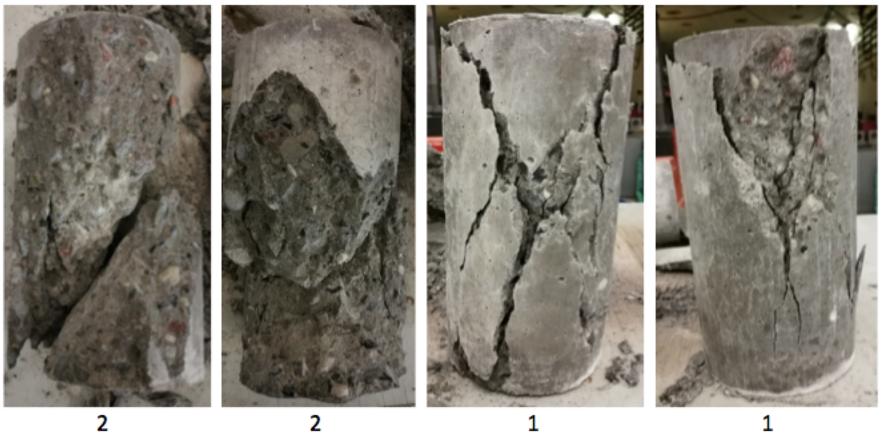


Figure 2.7: REF-B2, 28 days, X

2.4 RCA30% (1)

Figure 2.8: RCA30% (1), 7 days

Figure 2.9: RCA30% (1), 28 days

Figure 2.10: RCA30% (1), 28 days, X

2.5 RCA30% (2)

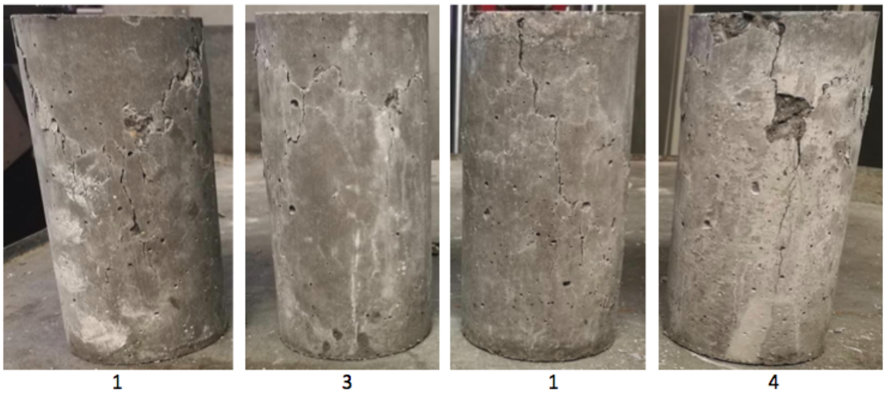


Figure 2.11: RCA30% (2), 7 days

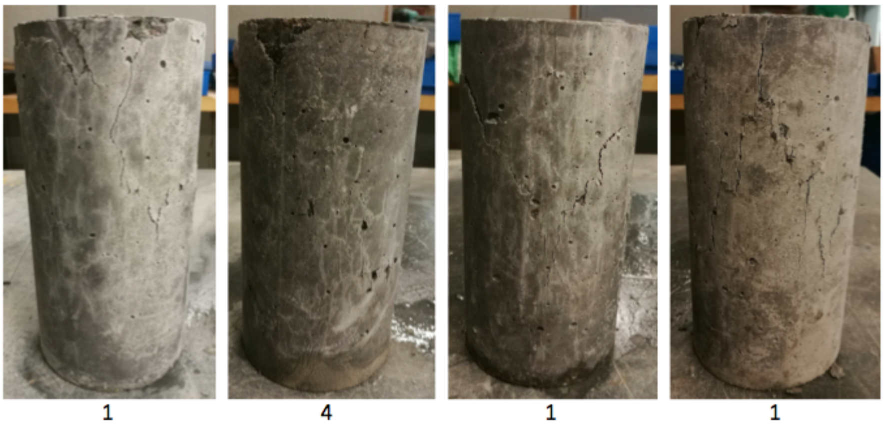


Figure 2.12: RCA30% (2), 28 days

Figure 2.13: RCA30% (2), 28 days, X

2.6 RCA20%

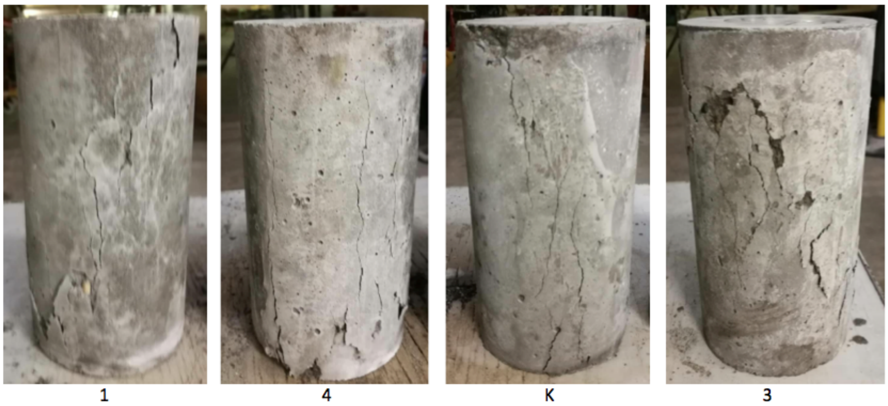


Figure 2.14: RCA20%, 7 days

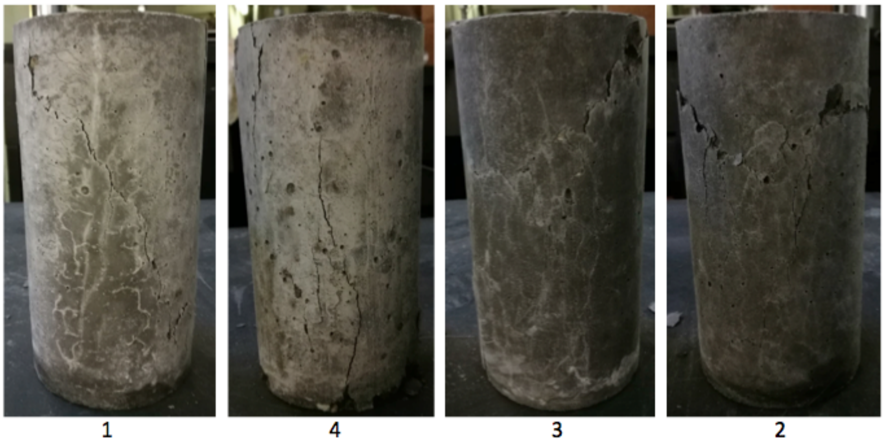


Figure 2.15: RCA20%, 28 days

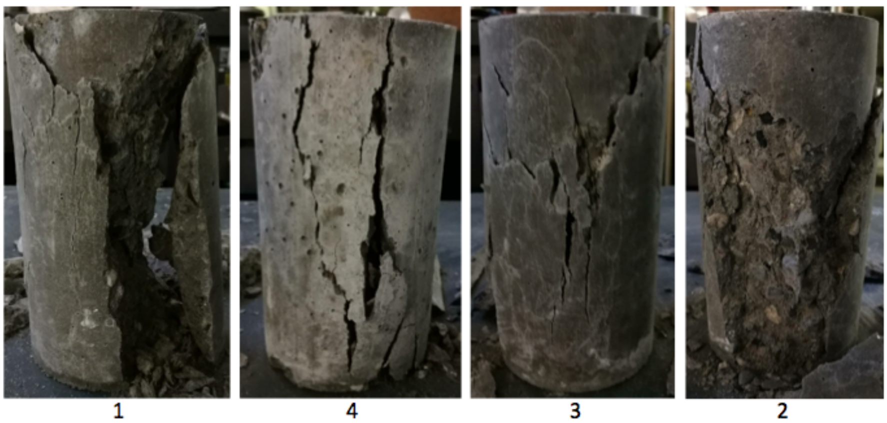


Figure 2.16: RCA20%, 28 days, X

2.7 RCA50%

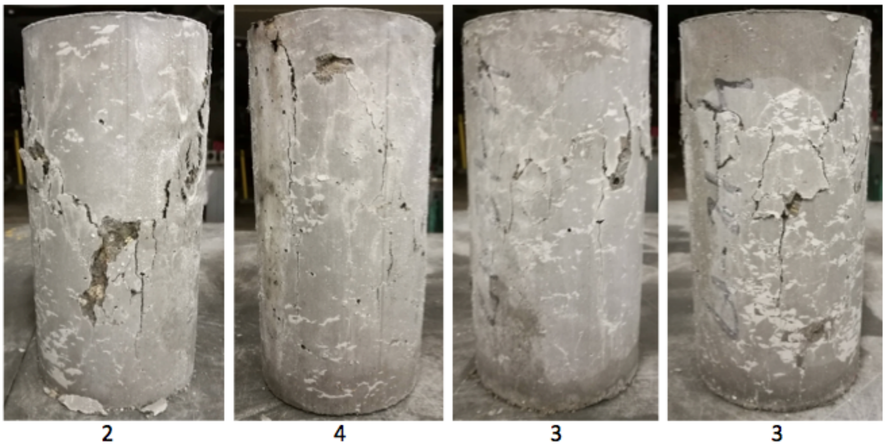


Figure 2.17: RCA50%, 7 days

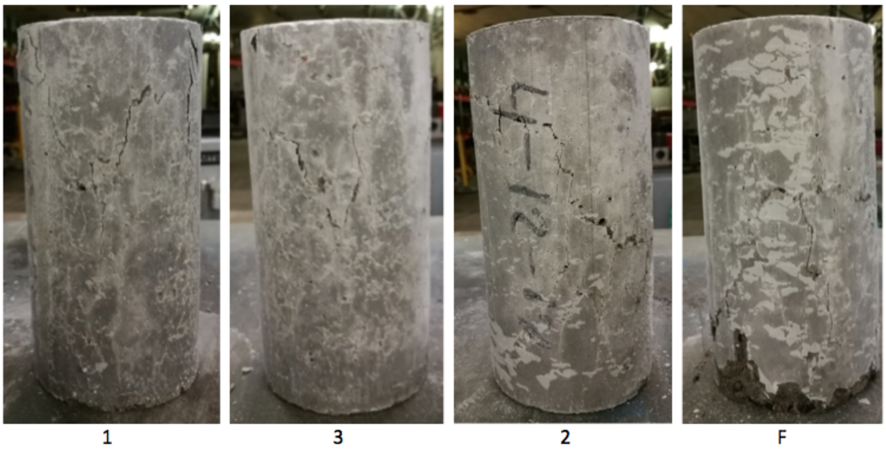


Figure 2.18: RCA50%, 28 days

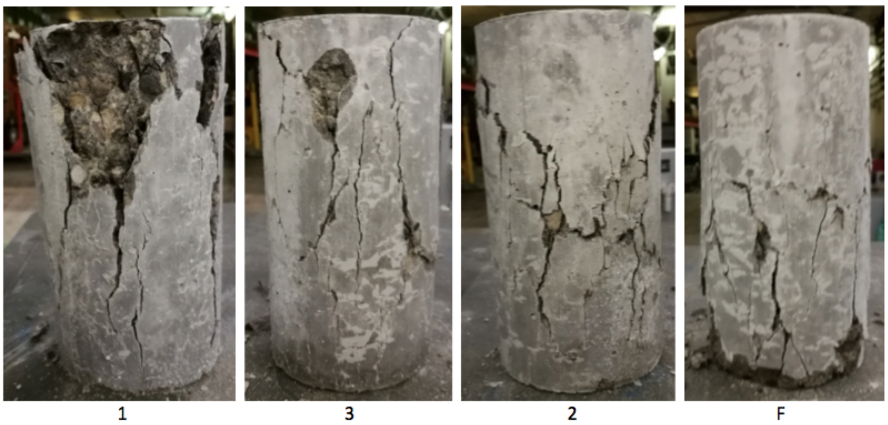


Figure 2.19: RCA50%, 28 days, X

2.8 RCA20%10%

4 4 1 4

Figure 2.20: RCA20%10%, 7 days

2 K 3 4

Figure 2.21: RCA20%10%, 28 days

2 K 3 4

Figure 2.22: RCA20%10%, 28 days, X

2.9 RCA20% (4-8mm)

Figure 2.23: RCA20% (4-8mm), 7 days

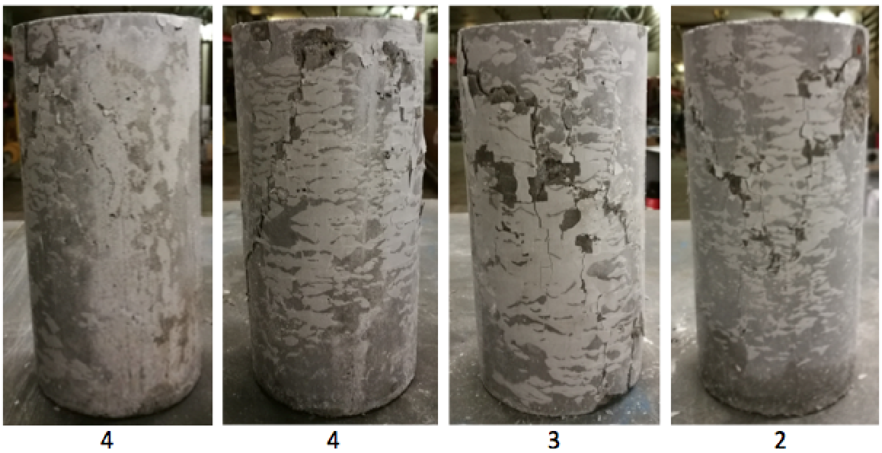


Figure 2.24: RCA20% (4-8mm), 28 days

2.9 RCA20% (4-8mm)

Figure 2.25: RCA20% (4-8mm), 28 days, X

2.10 RCA20% (8-16mm)

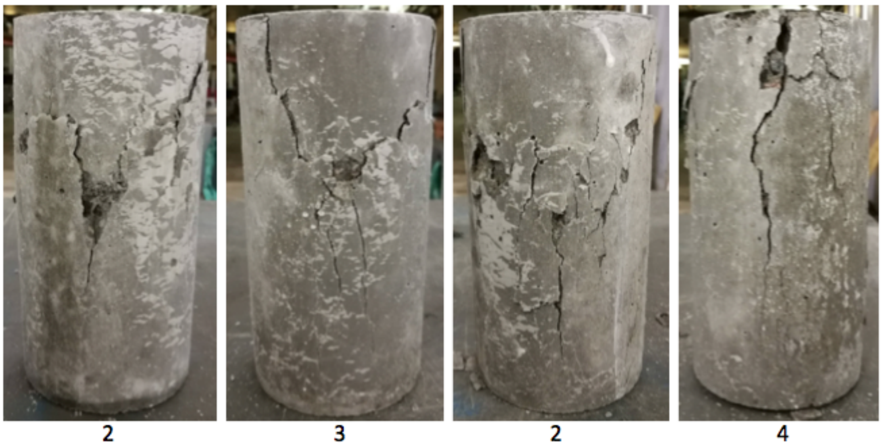


Figure 2.26: RCA20% (8-16mm), 7 days

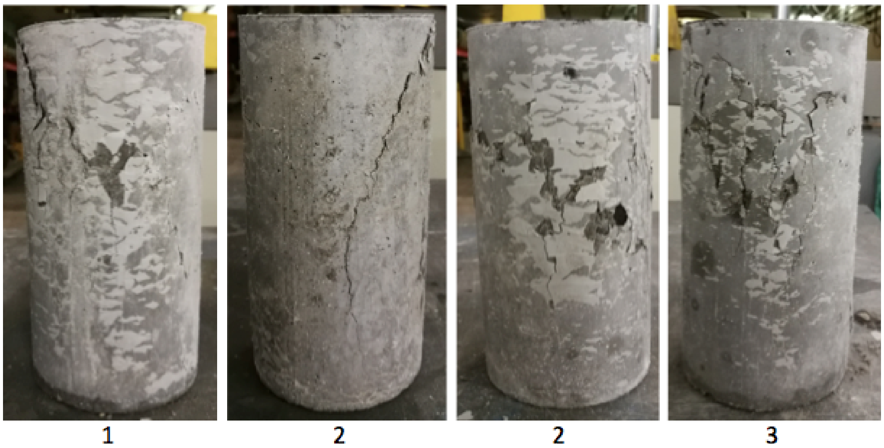


Figure 2.27: RCA20% (8-16mm), 28 days

2.10 RCA20% (8-16mm)

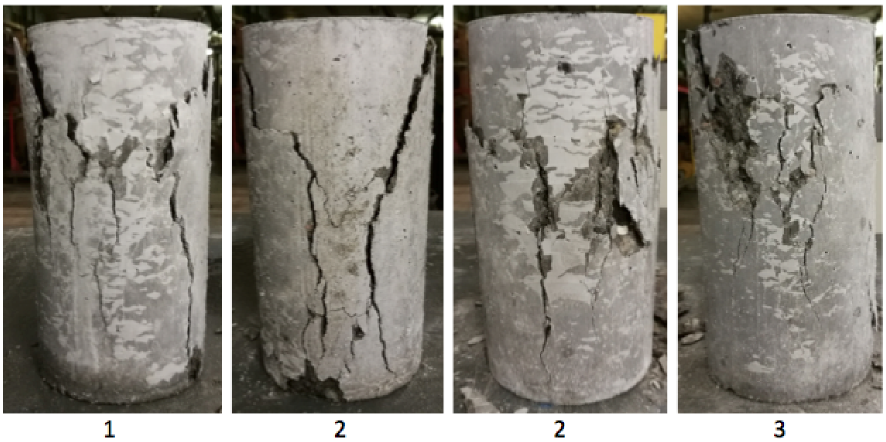


Figure 2.28: RCA20% (8-16mm), 28 days, X

2.11 RCA30% (Absorption)

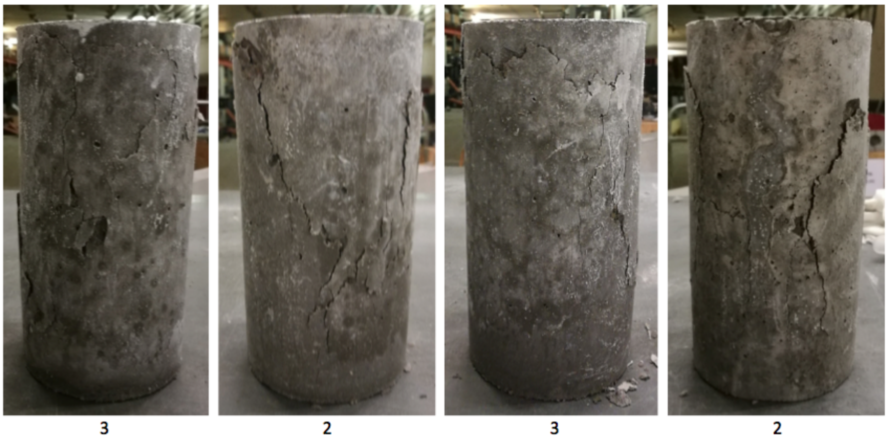


Figure 2.29: RCA30% (Absorption), 7 days

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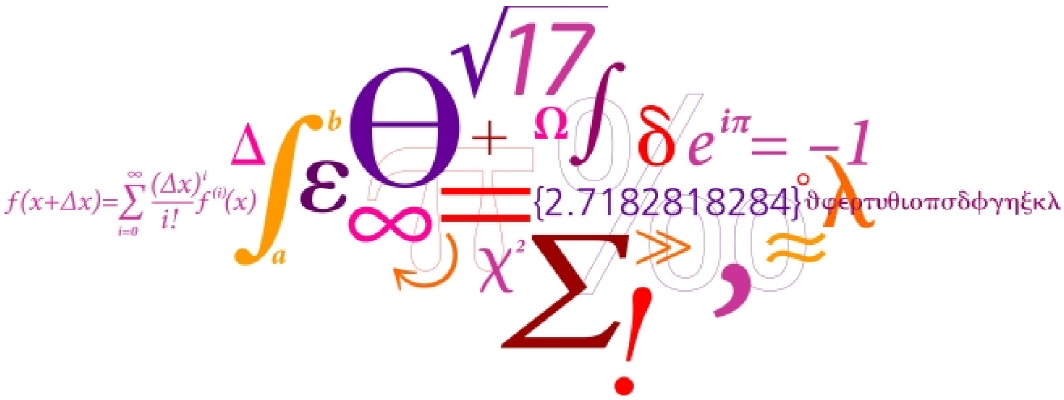
Appendix D
Modulus of elasticity

Nanna Johnsøn, s123837

28-01-2018



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Contents

1 Modulus of elasticity

The stress strain curve for the the specimens on which the modulus of elasticity was examined are presented in this appendix.

1.1 Ref-B (2)

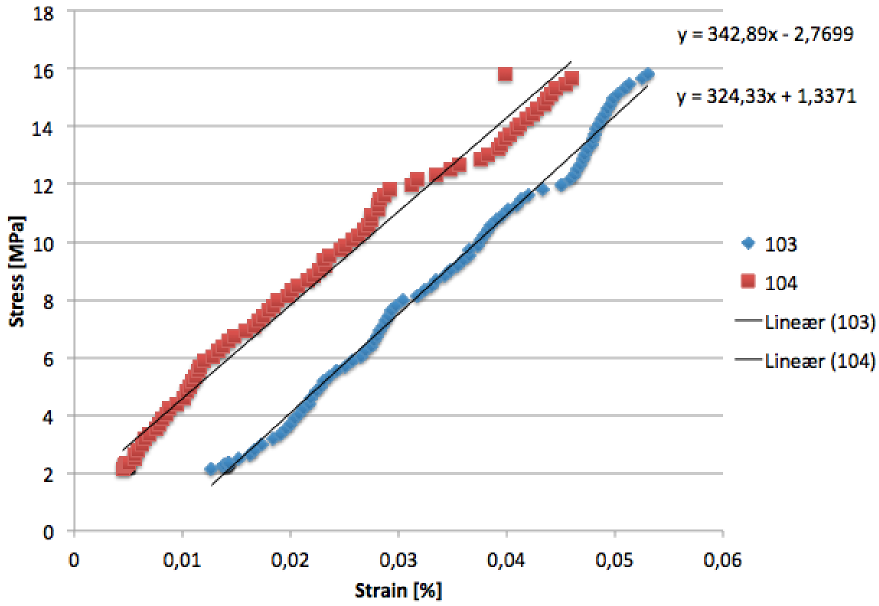

Figure 1.1: Ref-B (2)

For the Ref-B (2) was a clear change in the stress-strain curve noticed for both displacement gauges at 12 MPa. Therefore it was decided not to include the data above 12 MPa stresses, this is seen in Figure 1.2.

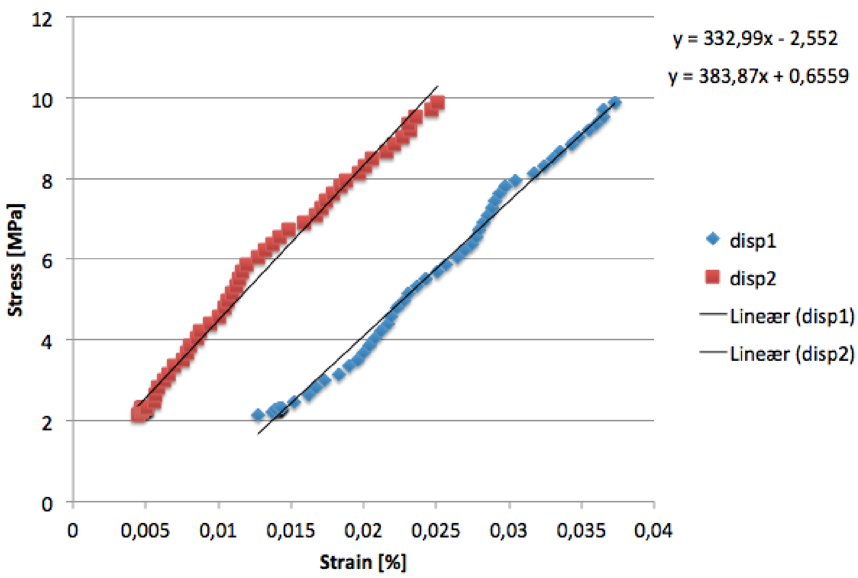

Figure 1.2: Ref-B (2), modified

1.2 RCA30% (1)

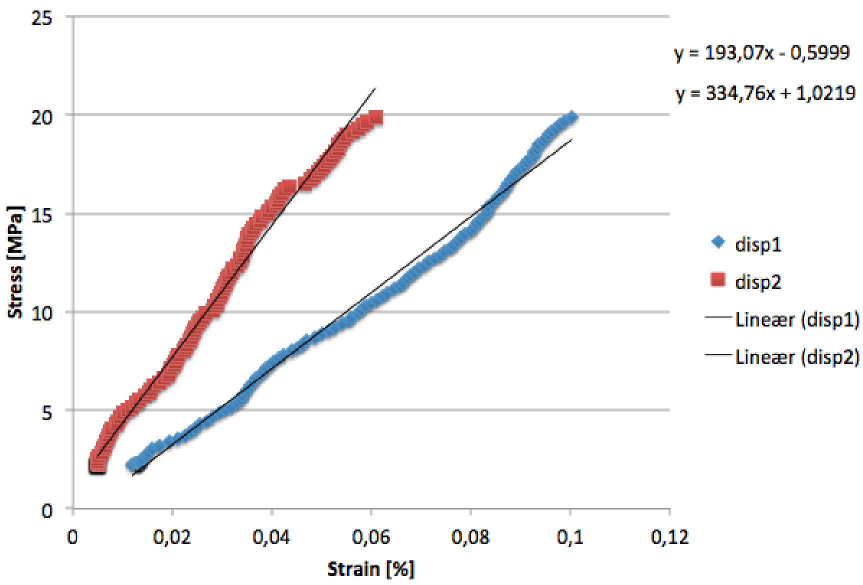

Figure 1.3: RCA30% (1)

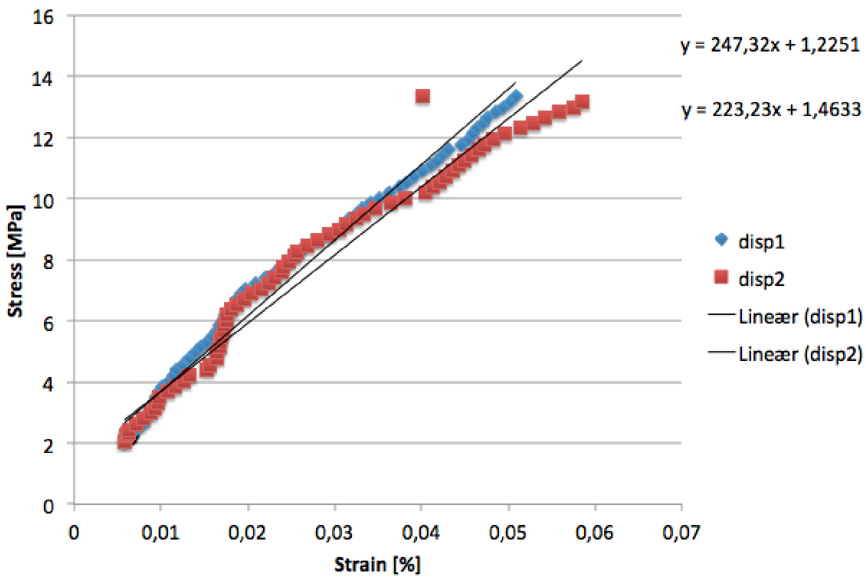

Figure 1.4: RCA30% (1)

1.3 RCA30% (2)

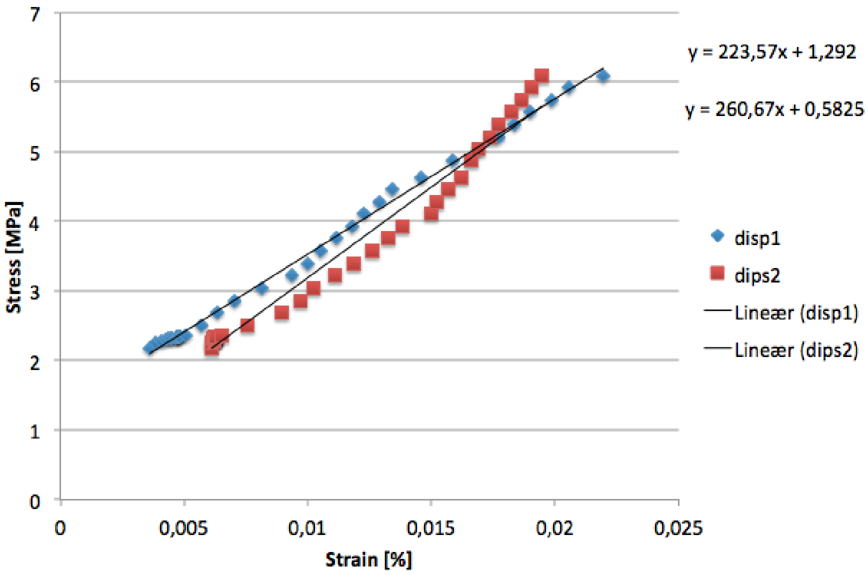

Figure 1.5: RCA30% (2)

1.4 RCA20%

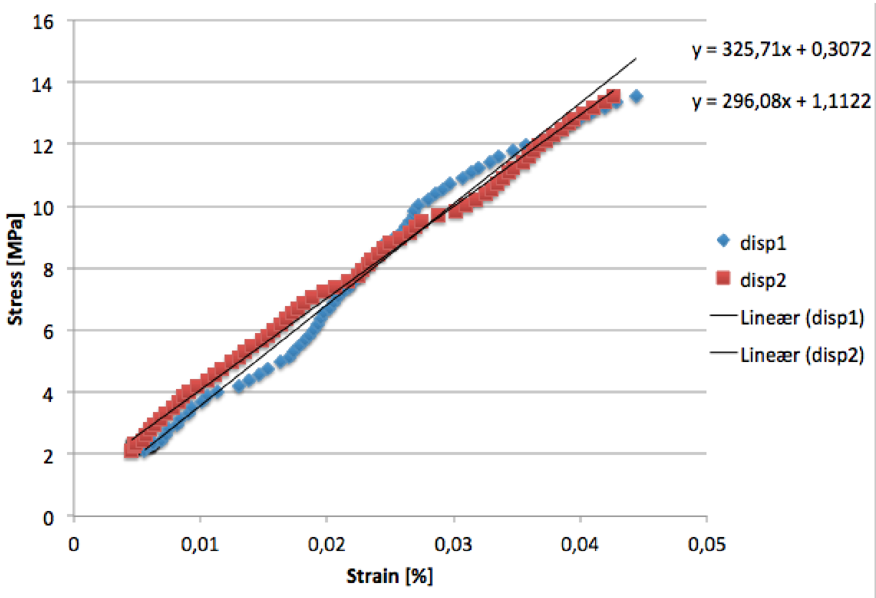

Figure 1.6: RCA20%

1.5 RCA50%

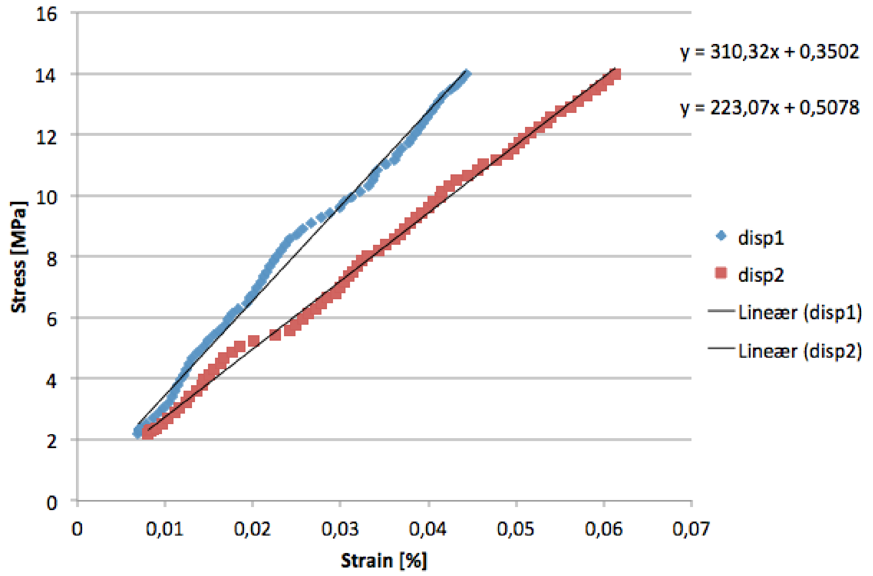

Figure 1.7: RCA50%

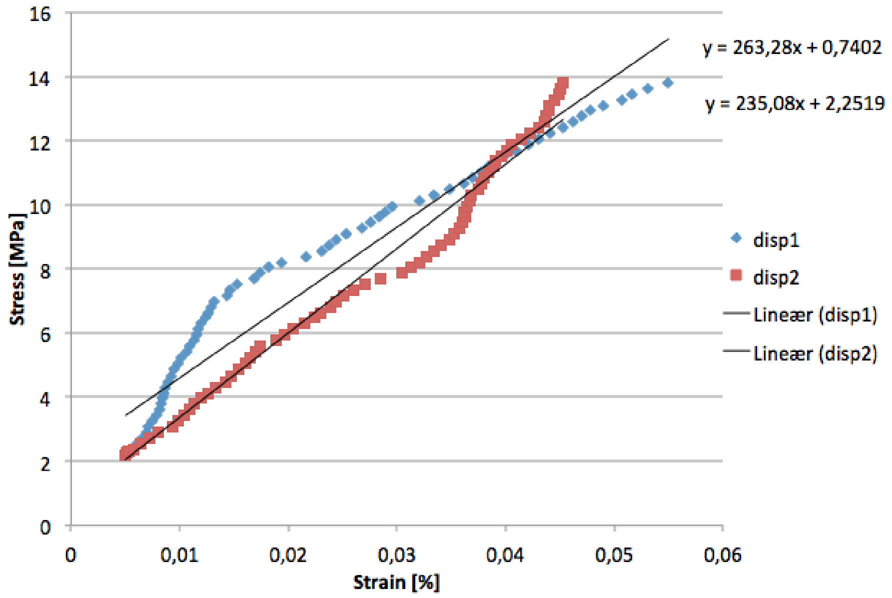

Figure 1.8: RCA50%

1.6 RCA20%+FCA10%

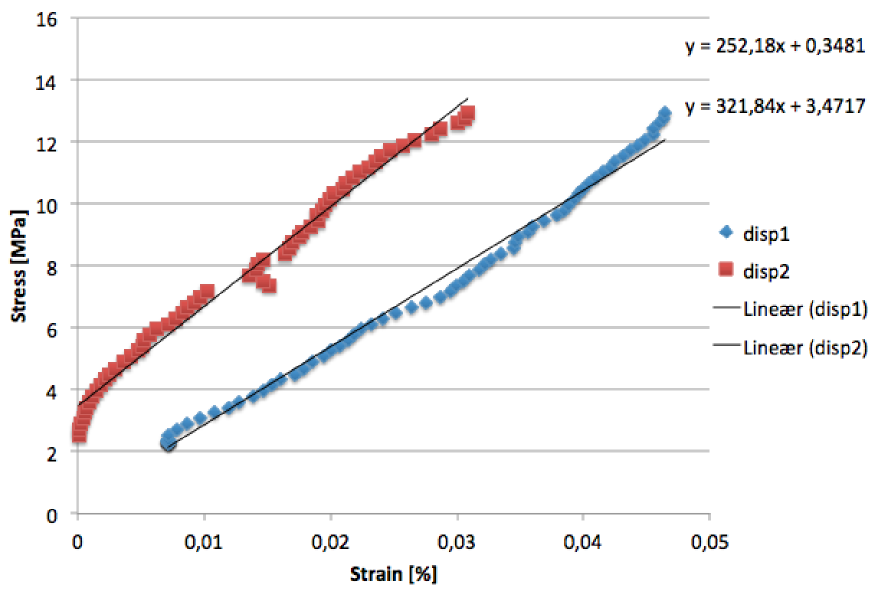

Figure 1.9: RCA20%+10%

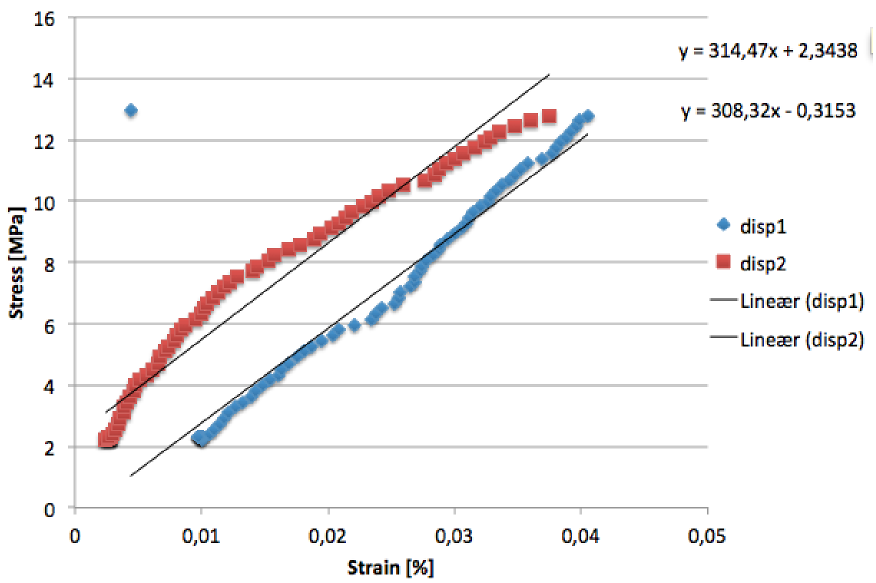

Figure 1.10: RCA20%+10%

1.7 RCA20% (4-8mm)

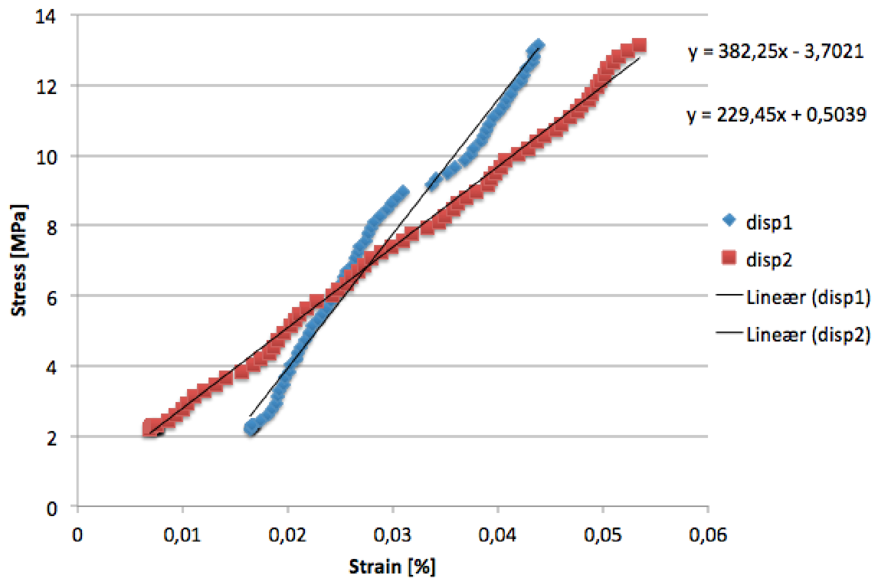

Figure 1.11: RCA20% (4-8mm)

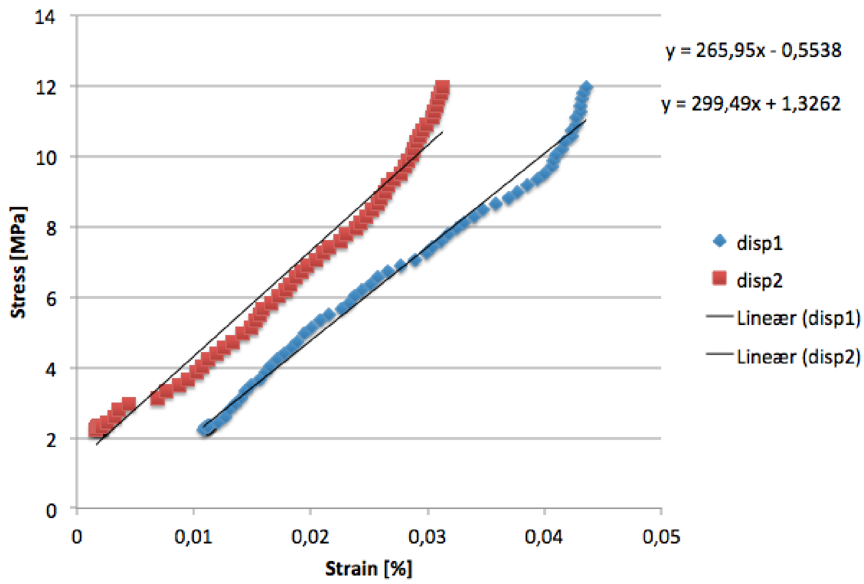

Figure 1.12: RCA20% (4-8mm)

1.8 RCA20% (8-16mm)

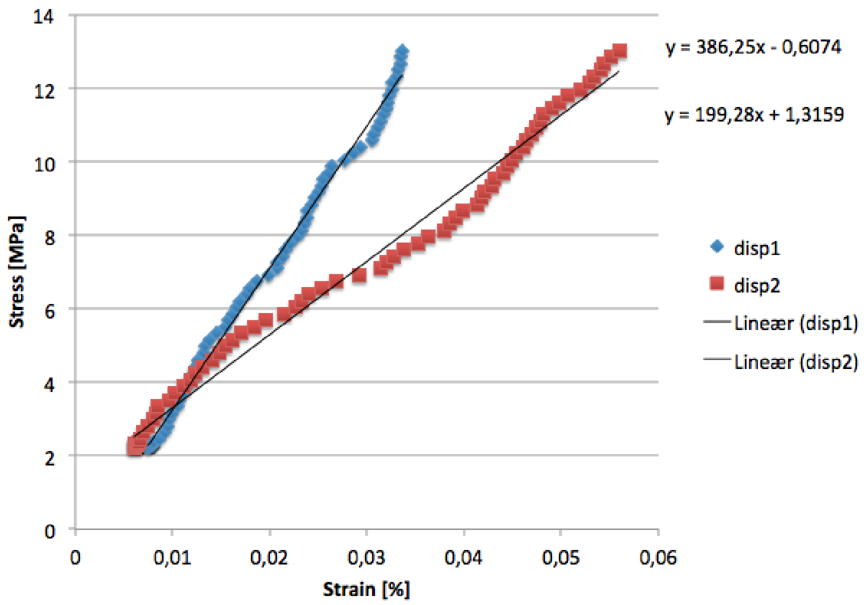

Figure 1.13: RCA20% (8-16mm)

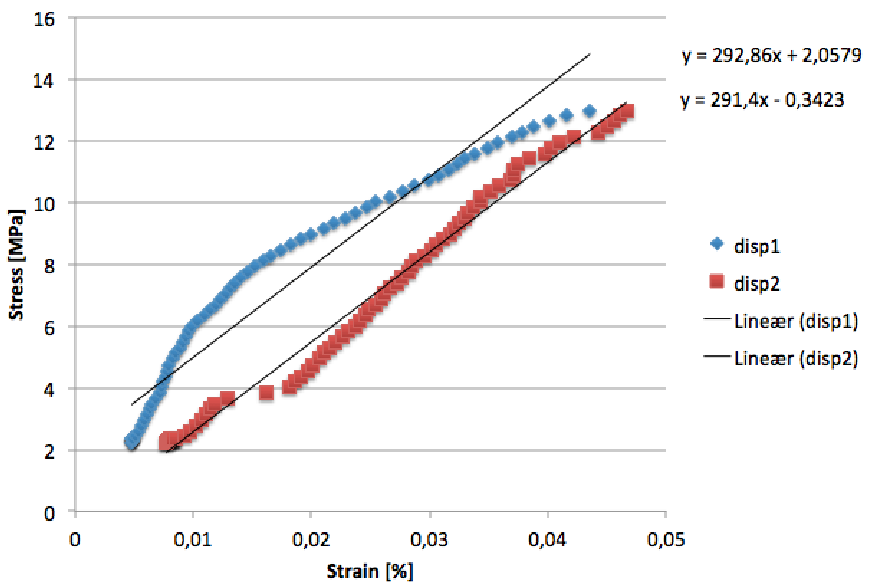

Figure 1.14: RCA20% (8-16mm)

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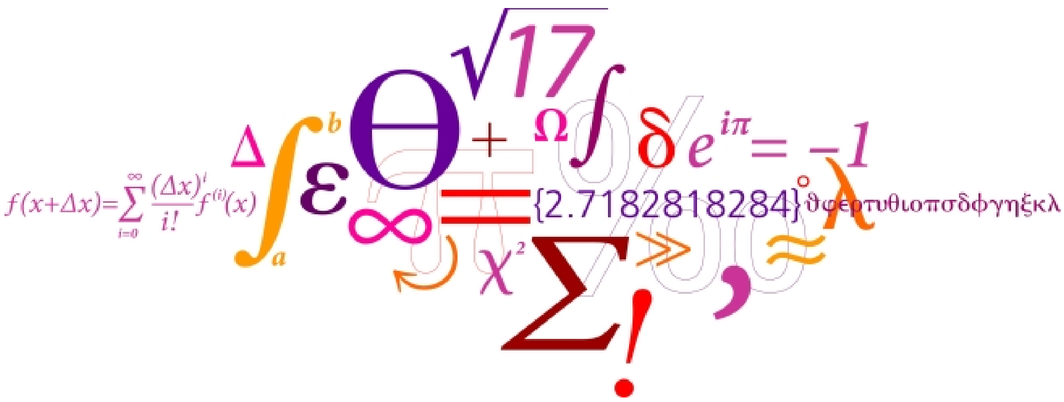
Appendix E
Porosity & Density

Nanna Johnsøn, s123837

28-01-2018



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Contents

1 Porosity & Density

The porosity and density is found by using the LBM-standard. This method is descrided on the following two pages.

Porøsitet og densitet (LBM-standard)

A **Princip**

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

B **Specielt apparatur**

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

C **Analysens udførelse**

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

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

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

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

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

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

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

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

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

D **Beregning af resultat**

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

1.1 Cut discs

A circular cut with a height of approximate 15mm was needed for this test. this cut was taken in the top, middle and bottom for each cylinder, this is illustrated in Figure 1.1.

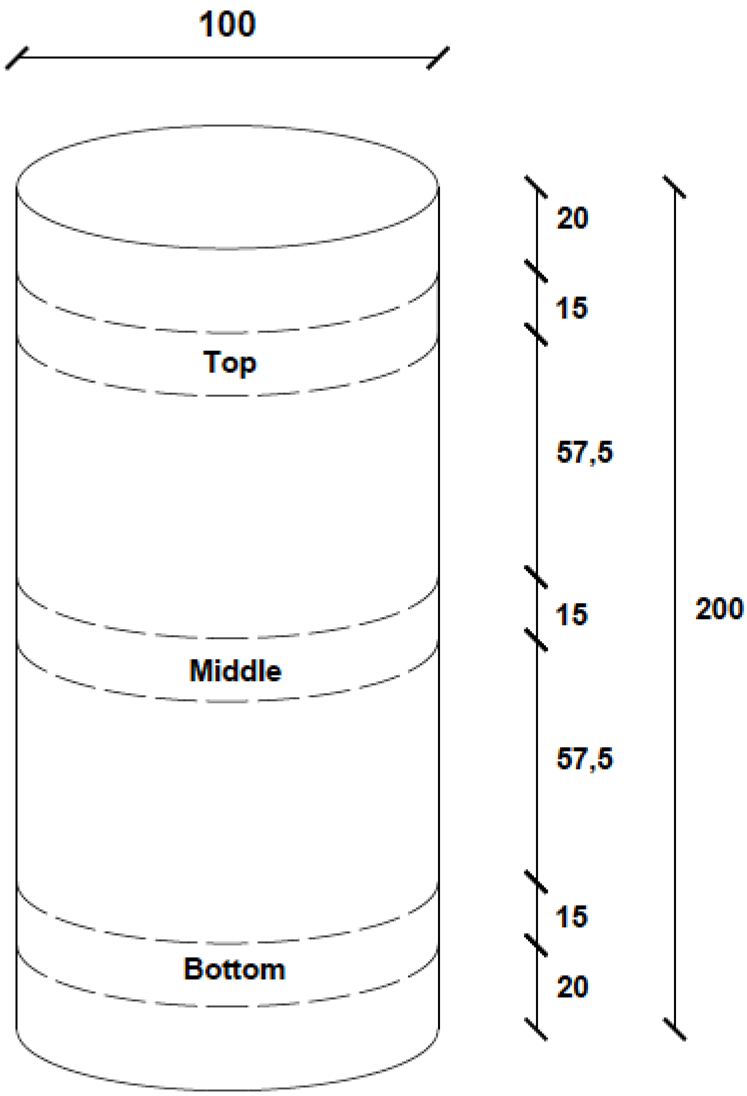
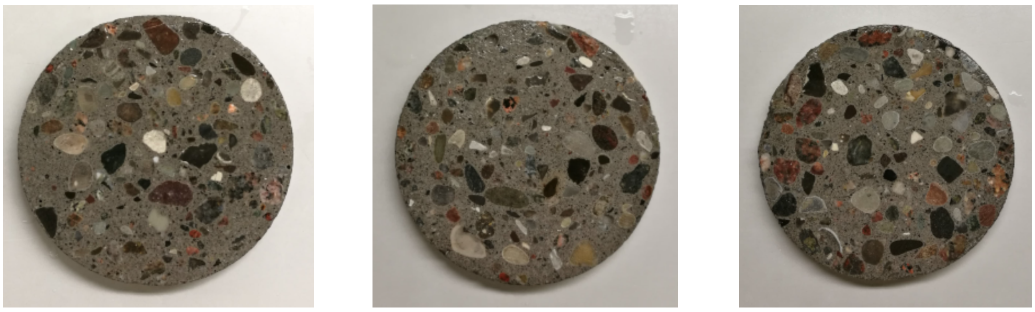


Figure 1.1: Illustration of the cut discs, all measurements in mm.

The cut discs from this experiment are seen on the following pages.

1.1 Cut discs

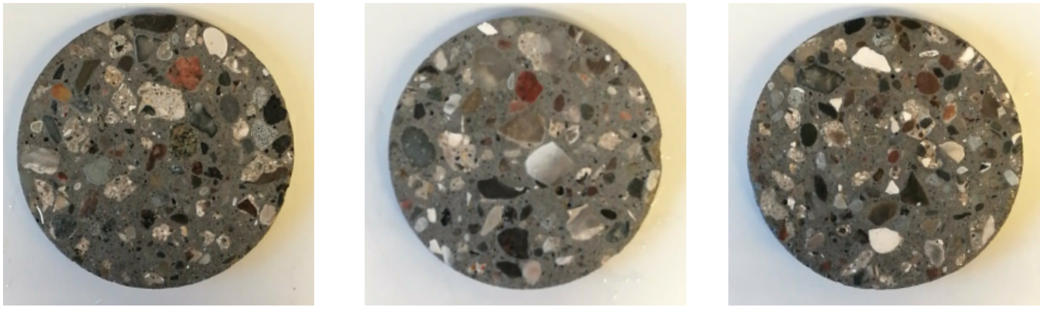
1.1.1 Ref-B (2)



(a) Top **(b)** Middle **(c)** Bottom

Figure 1.2

1.1.2 RCA50%



(a) Top **(b)** Middle **(c)** Bottom

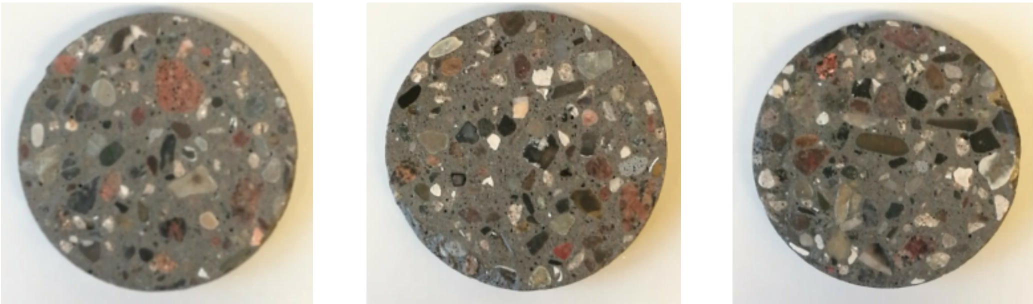
Figure 1.3

1.1.3 RCA20%+FCA10%

(a) Top **(b)** Middle **(c)** Bottom

Figure 1.4

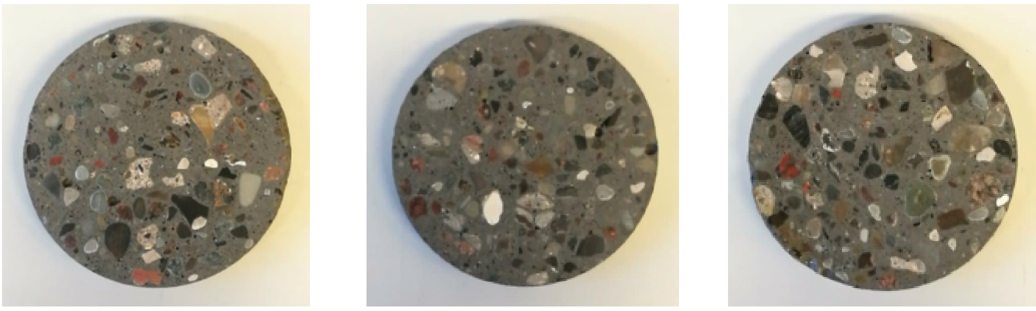
1.1.4 RCA20% (4-8mm)



(a) Top (b) Middle (c) Bottom

Figure 1.5

1.1.5 RCA20% (8-16mm)



(a) Top (b) Middle (c) Bottom

Figure 1.6

1.2 Raw data

All the raw data from this experiment are shown in tables for each concrete cylinder.

1.2.1 Ref-B (2)

Samples		Top	Middle	Bottom
m_50	[Kg]	0,17143	0,18004	0,16523
m_ssd	[Kg]	0,181	0,191	0,17427
m_sw	[Kg]	0,106	0,111	0,10219
V	[m^3]	7,56E-05	8,01E-05	7,21E-05
V_p	[m^3]	9,98E-06	1,13E-05	9,04E-06
P_open	[m^3/m^3]	0,132	0,141	0,125
p_d	[Kg/m^3]	2267,293	2247,129	2292,314
p_f	[Kg/m^3]	2612,068	2614,580	2621,034
p_ssd	[Kg/m^3]	2399,286	2387,668	2417,730
u_ssd	[Kg/Kg]	0,058	0,063	0,055

1.2.2 RCA50%

Samples		Top	Middle	Bottom
m_50	[Kg]	0,19161	0,18951	0,22733
m_ssd	[Kg]	0,20663	0,20559	0,24458
m_sw	[Kg]	0,11749	0,11571	0,13945
V	[m^3]	8,91E-05	8,99E-05	1,05E-04
V_p	[m^3]	1,50E-05	1,61E-05	1,73E-05
P_open	[m^3/m^3]	0,168	0,179	0,164
p_d	[Kg/m^3]	2149,540	2108,478	2162,370
p_f	[Kg/m^3]	2585,132	2567,886	2586,823
p_ssd	[Kg/m^3]	2318,039	2287,383	2326,453
u_ssd	[Kg/Kg]	0,078	0,085	0,076

1.2.3 RCA20%+FCA10%

Samples		Top	Middle	Bottom
m_50	[Kg]	0,20864	0,21924	0,20645
m_ssd	[Kg]	0,22488	0,23478	0,21934
m_sw	[Kg]	0,12835	0,13499	0,12774
V	[m^3]	9,65E-05	9,98E-05	9,16E-05
V_p	[m^3]	1,62E-05	1,55E-05	1,29E-05
P_open	[m^3/m^3]	0,168	0,156	0,141
p_d	[Kg/m^3]	2161,401	2197,014	2253,821
p_f	[Kg/m^3]	2598,580	2602,255	2622,920
p_ssd	[Kg/m^3]	2329,638	2352,741	2394,541
u_ssd	[Kg/Kg]	0,078	0,071	0,062

1.2.4 RCA20% (4-8mm)

Samples		Top	Middle	Bottom
m_50	[Kg]	0,23669	0,22306	0,29197
m_ssd	[Kg]	0,25244	0,23878	0,30882
m_sw	[Kg]	0,14567	0,13758	0,18045
V	[m^3]	1,07E-04	1,01E-04	1,28E-04
V_p	[m^3]	1,58E-05	1,57E-05	1,69E-05
P_open	[m^3/m^3]	0,148	0,155	0,131
p_d	[Kg/m^3]	2216,821	2204,150	2274,441
p_f	[Kg/m^3]	2600,417	2609,499	2618,095
p_ssd	[Kg/m^3]	2364,335	2359,486	2405,702
u_ssd	[Kg/Kg]	0,067	0,070	0,058

1.2.5 RCA20% (8-16mm)

Samples		Top	Middle	Bottom
m_50	[Kg]	0,26675	0,26125	0,26107
m_ssd	[Kg]	0,28545	0,27955	0,27777
m_sw	[Kg]	0,16442	0,16111	0,16130
V	[m^3]	1,21E-04	1,18E-04	1,16E-04
V_p	[m^3]	1,87E-05	1,83E-05	1,67E-05
P_open	[m^3/m^3]	0,155	0,155	0,143
p_d	[Kg/m^3]	2203,999	2205,758	2241,521
p_f	[Kg/m^3]	2606,762	2608,848	2616,718
p_ssd	[Kg/m^3]	2358,506	2360,267	2384,906
u_ssd	[Kg/Kg]	0,070	0,070	0,064

Midtterm - poster presentation

Recycled aggregates in new concrete

Nanna Johnsøn

Introduction

The amount of waste and waste management is a major present concern. In Denmark the construction sector is accountable for 1/3 of the general waste per year. In 2015 the accumulated amount of waste from the construction sector was 4.2 million tons according to "Miljøstyrelsen"

The demand for natural aggregates (NA) has increased with an alarming rate in some countries, and it is therefore necessary to use an alternative to NA. This can be achieved by replacing a percentage of the NA with recycled concrete aggregates (RCA). RCA are aggregates which has previously been used in a concrete based construction. When demolishing an old concrete building the concrete is crushed, and the aggregates are deprived. Normally the crushed concrete is used as road fill, but when reusing the RCA as a supplement in the concrete mix the demand for NA will decrease. This concept can in the future result in a more sustainable development of new buildings and cities.

Objective

The purpose of this thesis is to investigate the possibilities and limits of using RCA in new concrete. In this project both the fractions 4-8mm and 8-16mm RCA will be replaced with the NA.

The new cast concrete with the RCA will harden for either 7 or 28 days, afterwards the compressive strength will be tested.

The properties, such as attached mortar, particle size distribution, density and porosity of the RCA will also be investigated.

Materials and Method

The RCA used in this project were collected from Islevgaard allé 5 in Rødovre. The crushed concrete is taken from a demolished building, which used to be a school.

In total 24 buckets of approximate 20kg were collected, the pile itself is seen on Figure 1a below. In order to get the desired fractions of RCA it was necessary to sieve all the collected material, afterwards the RCA was kept in buckets with a lid on.

Apart from the sieving process the RCA were not pretreated, others have experimented with washing of the aggregates.

A visible difference between the RCA and NA was very clear, for example the RCA were more angular than the NA due to the old attached mortar. Furthermore since the RCA were not washed, some dust and grit was present on the RCA, the visible difference is shown on Figure 1b and 1c below.

a b c

Figure 1

Mix design

The first concrete mixture in this project is identical to the one presented in [Pepe et al. 2016], see Figure 2a. Due to a low slump value a second recipe was developed, which is shown on Figure 2b

- Cement: 287 $\frac{kg}{m^3}$ for w/c 0.6
- Water: 172 $\frac{kg}{m^3}$
- Sand (0-4 mm): 762 $\frac{kg}{m^3}$
- Fine aggregates (4-8 mm): 554 $\frac{kg}{m^3}$
- Coarse aggregates (8-16 mm): 554 $\frac{kg}{m^3}$

a

- Cement: 346 $\frac{kg}{m^3}$ for w/c 0.6
- Water: 208 $\frac{kg}{m^3}$
- Sand (0-4 mm): 872 $\frac{kg}{m^3}$
- Fine aggregates (4-8 mm): 486 $\frac{kg}{m^3}$
- Coarse aggregates (8-16 mm): 486 $\frac{kg}{m^3}$

b

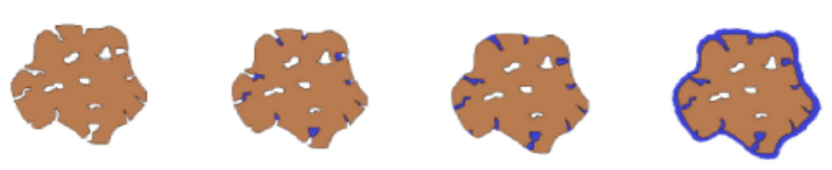
Figure 2

A survey of the cast concrete specimens is presented in Table 1.

Table 1: Survey of the cast concrete specimens

Name	w/c – ratio	4-8mm	8-16mm	Sætmål
REF-A1 (mix 2a)	0,6	-	-	20mm
REF-A2 (mix 2a)	0,6	-	-	20mm
REF-B (mix 2b)	0,53	-	-	70mm
RCA30% (1)	0,53 < w/c	30%	30%	120mm
RCA30% (2)	0,53 > w/c	30%	30%	15mm
RCA20%	0,53 > w/c	20%	20%	45mm

It is difficult to control the w/c – ratio because the exact water absorption of the RCA is unknown at the moment. When casting the concrete it would be optimal if the aggregates were in their saturated-surface-dry (SSD) state.



Aggregates states	Notation	Description
Oven-dry	OD	Empty open pores will absorb water from the cement paste.
Air-dry	AD	Open pores are partly full, and will absorb some water from the cement paste.
Saturated-surface-dry	SSD	The pores are full, and water will therefor not be absorb from the cement paste.
Saturated aggregates	SAT	Water from the surface of the aggregate, will add water to the cement paste.

Results

The main results acquired so far in this project is the water and cement content of the RCA, and the compressive strength of the concrete cylinders.

Mortar content

A survey of the attached mortar for both fractions are seen in Table 2. From this it is noticed that a higher cement content is present for the fraction 4-8mm RCA.

Table 2: Survey of the attached mortar

Fractions	Weight before [g]	Weight after [g]	Difference [%]	Mean [%]
4-8mm	20.24	14.63	27.72	24.6
	20.02	15.73	21.43	
	20.26	15.27	24.63	
8-16mm	50.05	41.35	17.38	15.4
	50.23	43.31	13.78	
	50.16	42.56	15.15	

Water content

The results of the water content is shown in Table 3. It is noticed that the water content is higher for the fraction 4-8mm. This correlates well with the results from the mortar content survey, since it is mainly the attached mortar, which absorbs the water.

Table 3: Survey of the water content

Fractions	Weight before [g]	Weight after [g]	Water content [%]	Mean water content [%]
4-8mm	200	182	9.0	8.8
	200	182	9.0	
	200	183	8.5	
8-16mm	200	187	6.5	6.8
	200	186	7.0	
	200	186	7.0	

Compressive strength

The compressive strength of the concrete cylinders is tested in a Toni Technik 3000 machine, as described in DS/EN 12390-3 2009. The compressive strength depends on the weakest component in the concrete, i.e. either the w/c – ratio or the strength of the aggregates.

In Figure 3 is Bolomey's formula used to illustrate the effect of the w/c-ratio on the final compressive strength, these are the theoretical expected values, when using the Bacis Aalborg cement.

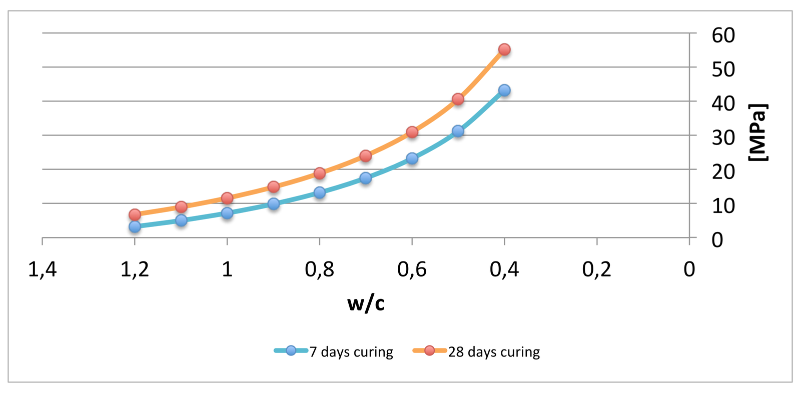


Figure 3: Theoretical expected values

The compressive strength of the tested cylinders are shown below. In Figure 4 the results are for the reference concrete cylinders, these has been curing for either 7 or 28 days. In Figure 5 REF-B is shown together with the RCA cylinders.

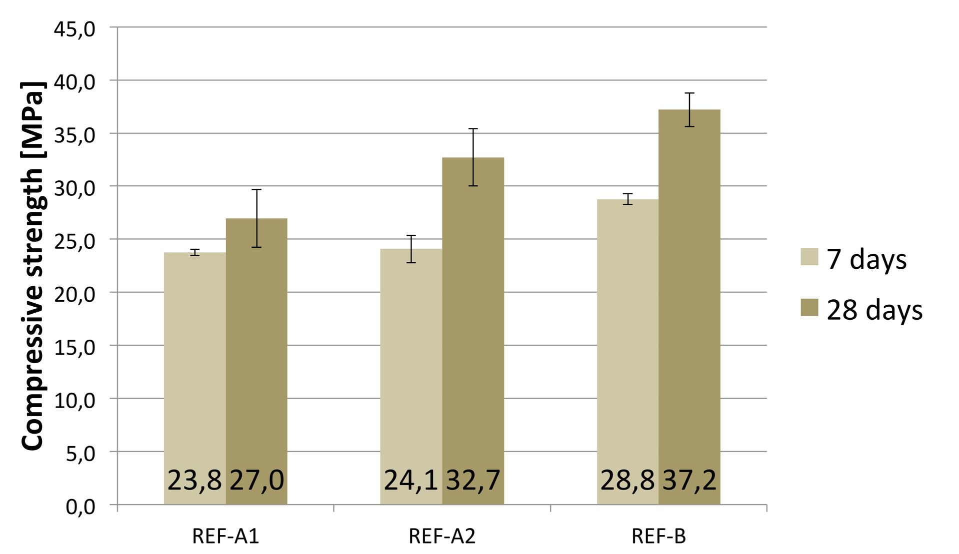


Figure 4: Reference specimens

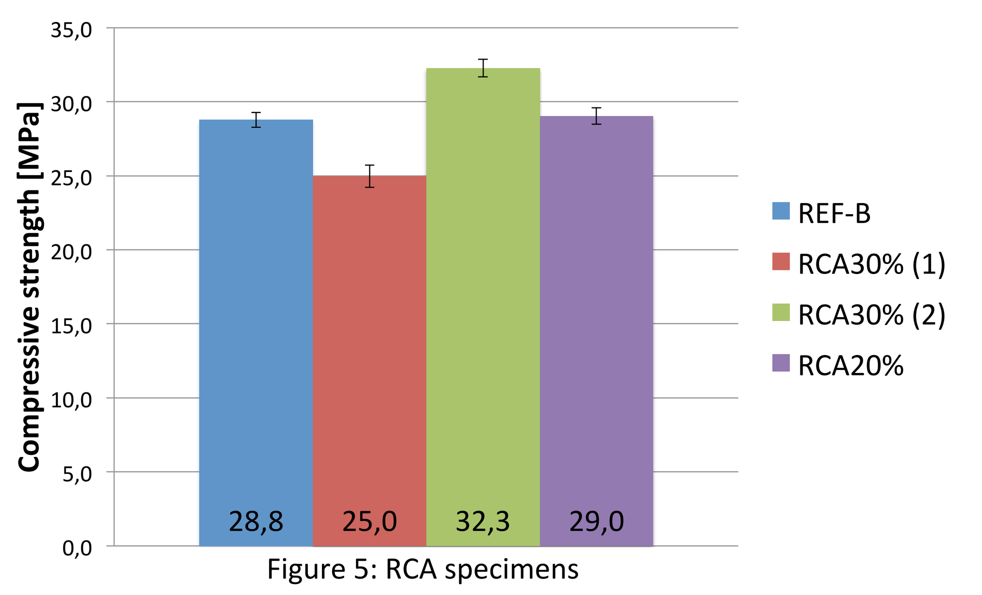


Figure 5: RCA specimens

The compressive strength for REF-B is very similar to the theoretical expected value in Figure 3. RCA30% (1) is significantly lower than REF-B, this can be explained by the fact, that there has been no correction for the water content. This correction was however done for the RCA30% (2), which resulted in a lower slump value and a stronger concrete, but the workability was very poor. The RCA20% had a good workability and the compressive strength is very similar to the REF-B.

Conclusion and Further work

From these results it can so far be concluded that both the water content and water absorption is two very essential parameters, since these both affect the final compressive strength and workability. Therefore the absorption of the RCA should be determined in order to be able to both correct for the water content and the absorption of the aggregates.

Further work suggestions:

Use the sand fraction (0-4mm)

Replace 50% NA with RCA

Test the E-module of the concrete cylinders