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THE USE OF CONCRETE AGGREGATE IN THE PRODUCTION OF NEW CONCRETE

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ABSTRACT

As climate change proceeds, a frugal lifestyle becomes increasingly important for the wellbeing of the Earth’s ecosystems. The reasonable use of nature’s raw materials supports the circular economy, which lessens the environmental burden. Construction and demolition waste is a major waste source within cities, and therefore more valuable reuse of this waste is needed. Since the concrete industry is one of the most polluting industries globally, the reuse of raw materials in concrete production would not only diminish urban waste but also the emissions of the concrete industry itself.

The aim of the thesis was to find out how the compressive strength of concrete changes if quarried stone aggregate used in concrete production is replaced by concrete aggregate. For the study, leftover concrete aggregate from concrete production was prepared by sieving, and particle size distribution was calculated. Concrete test pieces were then made in a laboratory. Finally, compressive strength tests were conducted on concrete test pieces to gain quantitative data about the potential change in compressive strength when using recycled concrete aggregate.

The results of the compressive strength tests show that the compressive strength of concrete decreases by 6–7.3 MPa when using concrete aggregate instead of natural aggregate in the production of new concrete. It has been estimated that this difference in strength can be compensated by using a plasticizer. Therefore, the use of concrete aggregate in the production of new concrete is possible. To improve the reuse of concrete aggregate, the standard SFS-EN 206 (2014) should be updated to allow the use of concrete aggregate with a 100 % replacement ratio. Mikkeli Development Miksei Ltd. can utilise the results of this study to advance the use of concrete aggregate in the production of new concrete. Further research is needed to find ways to improve the technical properties of recycled concrete aggregate and to examine the effect of fine recycled concrete aggregate on the quality of new concrete.

Keywords: recycled aggregate, standard, compressive strength, workability, circular economy, sustainability

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Appendix 1. Particle size distribution data

ACRONYMS

C&D – Construction and demolition

EoW – End of Waste

GGBS – Granulated blast furnace slag

NA – Natural aggregate

RCA – Recycled concrete aggregate

1 INTRODUCTION

Construction and Demolition (C&D) waste is the largest waste stream in the EU, representing about one-third of all waste produced (European Commission 2016). Concrete aggregate results in demolition activity and as excess in the concrete production industry. It is the biggest construction waste fraction with approximately two million tons of it created in Finland per annum (Ministry of Environment 2018). Reusing this waste would therefore support the circular economy, where the amount of waste is kept minimal and materials retain their value through continuous reuse and recycling for as long as possible.

A large part of the concrete industry's emissions comes from cement production, which consumes a massive amount of energy and natural resources, constituting 7 % of global CO_2 emissions (Aitcin & Mindess 2011, 3). Therefore, it is important to find ways to lessen the environmental burden created by the concrete industry.

Economically, mining virgin quarried stone is still in some cases cheaper than using recycled concrete aggregate (RCA) in concrete production. However, as natural resources are depleted, the transportation distances of virgin quarried stone will grow. Therefore using RCA may well become more economical (Aitcin & Mindess 2011, 161).

There are also other economic benefits to reducing the emissions of the concrete industry. Finland is aiming to be climate neutral by 2035, which means that industries need to decrease their emissions rapidly. The methods of achieving the goal include diminishing the carbon footprint of the construction industry and enhancing the circular economy. Taxation will concentrate heavily on environmental disadvantages, and the sustainable use of natural resources will be worked for to maintain biodiversity in nature. For companies, this means that it is economically safer to be more sustainable than wasteful and energy-consuming. There may come specific limitations which affect the concrete industry, as well as possible financial support for companies who invest in clean technologies. (Ministry of the Environment n.d.b.)

This thesis was undertaken in cooperation with Mikkeli Development Miksei Ltd., and as a part of their City Loops project, which aims to diminish waste in the city of Mikkeli and to find ways to promote higher quality reuse of waste material.

Concrete aggregate generally comes from two sources, as a result of demolition work and as leftover excess from concrete production. Aggregate which is a result of demolition and has previously been used in construction is called “Recycled aggregate” (SFS-EN 206, 2014). In this thesis, such aggregate derived from hardened concrete will be referred to as “Recycled concrete aggerate” (RCA). Concrete aggregate which is crushed from leftover concrete from manufacturing and has not been used in construction is called ”Reclaimed crushed aggregate” (SFS-EN 206, 2014). These are the definitions that will be used throughout the rest of the thesis.

The aim of the study was to define how the compressive strength of concrete changes if instead of using natural aggregate (NA), reclaimed crushed aggregate is used in concrete production. The study is especially focused on the use of reclaimed crushed aggregate in Finland. To investigate how the quality of concrete changes when reclaimed crushed aggregate is used in the production of new concrete, an experiment was undertaken. The experiment consisted of sieving reclaimed crushed aggregate into a suitable diameter range and then using it instead of natural aggregate when making test samples. The samples were then tested for their compressive strength, which is a common practice for ensuring good concrete quality. The concrete reuse experiment took place at Semtu Oy’s laboratory, where the concrete test pieces were produced and tested. The reclaimed crushed aggregate and its sieving facilities were provided by concrete producer SBS Betoni Oy. The results were expected to give positive affirmation for the reuse of concrete aggregate and provide important information for further research on the topic.

2 THEORETICAL BACKGROUND

2.1 Concrete reuse in Finland

Finland had an objective to recycle 70 % of all construction waste by 2020. The goal was not met as still by 2020, less than 60 % of the total construction waste was recycled. A major part of the C&D waste material is stone material including concrete. C&D waste is the second biggest waste source in Finland. (Tolpo 2020; Ministry of the Environment 2022, 66.)

The amount of construction waste in Finland in 2019 was over 13.6 million tonnes (Figure 1). That is approximately 12 % of the total waste generated. (Statistics Finland 2021.)

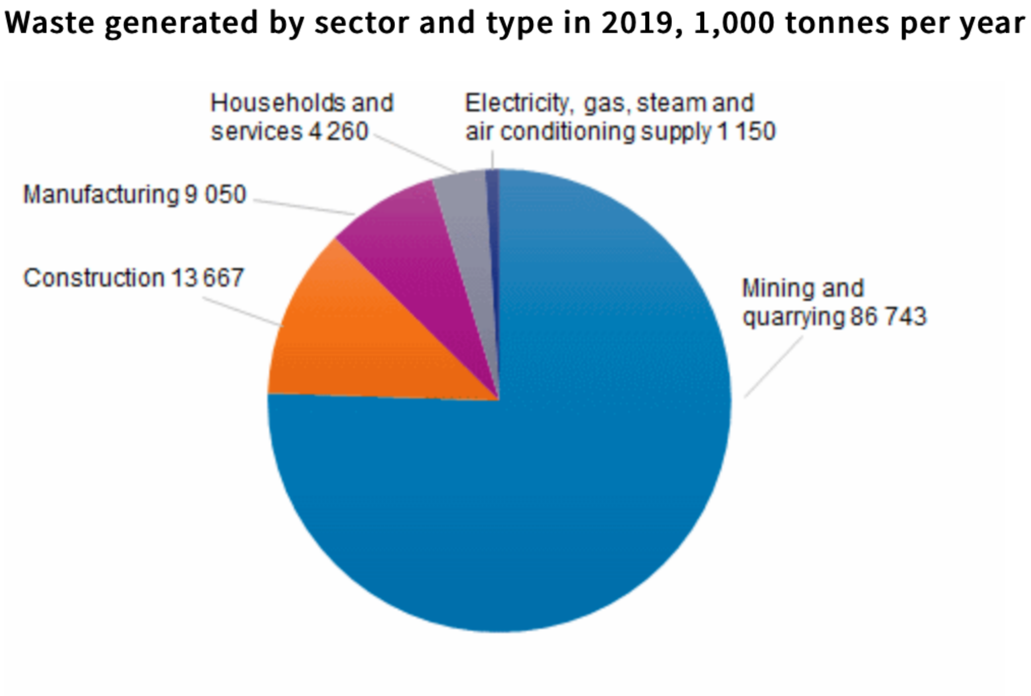

Figure 1. The amount of waste by sector in Finland in 2019 (Statistics Finland 2021)

In Finland, RCA is commonly reused in earth construction. The process for its use in earth construction became more viable in 2017, as the Government Decree on the Recovery of Certain Wastes in Earth Construction 843/2017 was approved. The decree supports circular economy as it makes the reuse of RCA cheaper and easier. After the decree passed into law, RCA with a maximum diameter of 90 mm could be utilised in earth construction if it fills the environmental requirements. (Lehtonen 2018.)

The use of waste concrete as a material source in new concrete production has previously been studied in Finland. However, there are always more factors to be considered. Although several studies have been carried out in Finland (Nieminen 2015; Rudus Oy 2021), the more data that is available about the behaviour of concrete aggregate in the production of new concrete, the faster it can be effectively utilized on a larger scale in Finland.

2.2 Legislation and standards

2.2.1 Building, environmental, and waste legislation

There is plenty of legislation to be considered when using and planning to use recycled materials in construction products. Here the most important points of concrete aggregate are presented as for CE-marking, environmental requirements, and waste handling.

The construction products which have a harmonised product standard, need to be labelled with a CE marking. This includes concrete aggregate. The CE marking in a construction product means that the product in question has been tested according to the harmonized European product standard, and it verifies that the product has achieved the stated performance characteristics. The CE marking, however, does not automatically mean that the construction product is suitable for all construction scenarios. Therefore, the product requirements of concrete aggregate for each building location should be checked separately from the relevant standards. (Ministry of the Environment n.d.a.)

The reuse of demolition waste concrete is expected to be facilitated by End of Waste (EoW) concrete regulation, which will come into effect in 2022. After the demolition waste concrete is no longer handled as waste, it can be sold forward as construction material. It would then follow the same regulations as those used for products, such as The Regulation (EC) No 1907/2006 of the European Parliament and of Council concerning the Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) and the regulation (EU) No 305/2011 of the European Parliament and of the Council laying down harmonized conditions for the marketing of construction products and repealing Council Directive 89/106/EEC. (Ministry of the Environment 2018; Ministry of the Environment 2021.)

As concrete aggregate is handled as waste, the following laws and regulations apply:

- Government Decree on Waste 179/2012
- Waste Act 646/2011
- Waste Tax Act 646/2011
- Valtioneuvoston asetus ympäristönsuojelusta 713/2014
- Government Decree on the Recovery of Certain Wastes in Earth Construction 843/2017

The owner of C&D waste needs to organize the concrete waste so that a major part of the waste can be reused or recycled in other ways. Possible asbestos waste needs to be collected and transported for further handling separately from the other types of waste. All the waste needs to be accounted for by detailed documentation of the operations. Concrete waste needs to be transported so that none of it is released into the environment. This is regulated in Government Decree on Waste (179/2012). If the waste ends up in a landfill, it needs to be taxed. The waste tax is €70 per ton of waste. Concrete waste with a diameter less than 15 cm is counted as tax-free waste if it is delivered to the landfill separate from other waste and is intended to be used in the essential builds of the landfill. (Waste Tax Act 1126/2010.)

It is stated in the Waste Act (646/2011) that waste that has been recycled or reused is no longer waste if: it is meant to be used for special purposes, it has market and demand, it fills the technical requirements of its intended use, and fulfils the standard requirements set for comparable products. Therefore, it could be argued that if concrete aggregate fulfils the standard requirements and it has a buyer who has intended to use it for a specific purpose, it would be considered material instead of waste. However, as defined in Valtioneuvoston asetus ympäristönsuojelusta (713/2014), handling annually anything less than 50 000 tons of concrete waste in any other way than by putting it in a landfill needs to go through an authorisation process by the city's environmental protection authority.

If the concrete aggregate is used in earth construction, the Government Decree on the Recovery of Certain Wastes in Earth Construction 843/2017 is applied. The decree defines the requirements that the concrete aggregate needs to fulfil in order to be utilised in earth construction without the application of an environmental permit.

2.2.2 SFS Standards

Standards are publications which include requirements and recommendations for products, their testing, and production methods that have been universally agreed upon (SFS ry n.d.). There are various standards for each type of concrete element and structure. The general requirements for concrete production in Finland can be found in two standards: SFS-EN 12620 (2008) and SFS-EN 206 (2014). It is important to follow the requirements of these standards when recycled aggregate is used to replace natural aggregates in concrete production.

The standard SFS-EN 12620 (2008) sets physical and chemical requirements for concrete aggregate used in new concrete. The standard defines which technical and chemical tests should be performed on recycled aggregate before its use in construction. The upper limits of contaminants and minimum test frequencies for recycled aggregate are defined in this standard. The standard also contains information about the requirements for CE-marking and how to use the label to mark products. The necessity of the mentioned requirements depends on the origin or application of the aggregate. The relevant physical requirements listed in the standard are resistance to fragmentation of coarse aggregate, resistance to wear of coarse aggregate, resistance to polishing and abrasion of coarse aggregate to be used for surface courses, particle density, water absorption, bulk density, freeze-thaw resistance, volume stability – drying shrinkage, and alkali-silica reactivity. In addition, the classification of the constituents of coarse recycled aggregates needs to be performed in accordance with prEN 933-11: Tests for geometrical properties of aggregates – Part 11: Classification test for the constituents of coarse recycled aggregate. The chemical requirements for the concrete aggregate used in new concrete are set in the standard SFS-EN 12620 (2008) to be water-soluble chloride ion content, acid-soluble chloride ion content, acid-soluble sulfate, water-soluble sulfate content, total sulfur, and constituents that alter the rate of setting and hardening of concrete. Authorities of the city of Copenhagen suggest that some of the properties of recycled aggregate such as density, absorption, frost resistance, and alkali-silica reactivity could be tested with modified test methods to obtain a better determination of the concrete properties (Kobenhavns kommune 2020). Based on the standard SFS-EN 12620 (2008), it is also required to check the aggregate for constituents that affect the volume stability of air-cooled blast furnace slag. This requirement should be considered when using RCA along with cement that contains blast furnace slag.

The other important standard is SFS-EN 206 “Concrete” (2014). It includes detailed requirements regarding the quality control systems of concrete production. The standard includes definitions of reclaimed crushed aggregate and RCA and information about their usage in concrete production. The limits for the usage of RCA have been defined in this standard.

2.3 Physical, chemical, and mechanical properties of recycled concrete aggregate

2.3.1 Coarse concrete aggregate

Coarse concrete aggregate has been defined in the standard SFS-EN 12620 (2008) to be of grade size bigger or equal to 4 mm. Concrete primarily consists of cement and coarse and fine aggregates (PCA 2022a). Cement paste contains calcium carbonate ($CaCO_3$), silicon oxide (SiO_2), iron oxide (Fe_2O_3), aluminium oxide (Al_2O_3), fillers, and plaster. (Finnsementti n.d.)

C&D waste concrete consists of the same ingredients as the parent concrete and the cement used in its initial production. Depending on its origin, it may also include contaminants such as asbestos, polychlorinated biphenyl (PCB), polycyclic aromatic hydrocarbons (PAH), and heavy metals. Newer buildings contain fewer contaminants as the use of contaminants such as heavy metals and PAH in construction products has lessened after the 20th century. There has been a total ban on PCB and asbestos use in construction for several years. (Komulainen et al. 2011.)

Due to its porosity, RCA has a higher water absorbance and lower density than NA. The porosity is due to adhered mortar which is attached to the aggregate, and which is a remnant from the previous concrete build. (Sadagopan 2021, 17) According to Rasiah and Tam (1985, 32) by volume, RCA contains on average 50 % adhered mortar depending on the grain size. To enhance the strength of the concrete, aggregate can be pre-processed before use to de-attach dried cement mortar.

Before using RCA to substitute NA, its water absorbance should be tested. The tests should be conducted according to the standard EN 1097-6: Tests for mechanical and physical properties of aggregates Part 6: Determination of particle density and water absorption. A study by Brito et al. (2014, 17–22) shows that RCA has a water absorbance of 4.7 % whereas the water absorbance of NA varies between 0.5 % and 1.5 %.

Based on several studies, the density of NA is on average 2548 kg/m^3, whereas the density of coarse RCA is 2477 kg/m^3 (Rahal 2005; Lima et al. 2013; Nieminen 2015; Sadagopan 2021). Concrete aggregate's bulk density directly correlates with the compressive strength of the new concrete. The lower the density, the more porous the aggregate is. The lower density of aggregate results in lower compressive strength of concrete. (Sadagopan 2021, 27–46.)

By the standard SFS-EN 206 (2014), concrete aggregate needs to be separated into coarse concrete aggregate and fine concrete aggregate. If the fine material is not separated from the aggregate, it falls under the term of all-in aggregate. The standard SFS-EN 206 (2014) limits the use of all-in aggregate so that it should only be used in concrete which has a strength class ≤ C12/15. The standard also states that if the coarse and fine reclaimed aggregates are not divided, the mixture can only make up 5 % of the total mass of the aggregate used. When the quantity of reclaimed aggregate is more than 5 % of the total mass of the aggregate, it follows the same regulations that have been set for recycled aggregate.

A problem arises when NA is replaced by RCA, as the standard SFS-EN 206 (2014) limits the use of RCA in concrete production. Concrete can be classified by its exposure class, depending on the conditions in which the concrete may corrode. It is stated in the standard that only 50 % of RCA can be used to replace coarse NA in the exposure class X0, in which concrete is at no risk of corrosion. In the rest of the exposure classes, the replacement percentages are even lower**,** down to 0–30 % depending on the origin of the RCA.

2.3.2 Fine concrete aggregate

Fine RCA has a particle size smaller or equal to 4 mm (SFS-EN 12620:2008). It has different particle size distribution, moisture states, and water absorption properties than natural sand. Its use in concrete production is challenging due to varying physical and chemical properties which depend on the quality of the parent concrete and the concrete crushing process. In 100-% replacement of fine NA by fine RCA, concrete’s compressive strength decreases by a maximum of 50 %. The decrease is due to increased water absorption of the fine RCA. To reach the same workability as normal concrete, the concrete mix with fine RCA needs more water, which leads to an increased water-cement (w/c) ratio. For the concrete workability, the optimal w/c ratio for concrete made with fine RCA is 0.6 (Yildimir 2015), but to be sufficiently hydrated, concrete only needs a w/c ratio of 0.42 (Chan et al. 2018). The increase in the w/c ratio causes the concrete strength to decrease (Chan et al. 2018).

The crushing of concrete aggregate creates more adhered cement mortar, which results in higher contents of soluble alkalis and sulfates in fine RCA than in coarse RCA. The properties of fine RCA can result in harsh and unworkable mixes. Therefore fine RCA should be used to replace a maximum of 10–20 % of the total fine aggregate. (Aitcin & Mindess 2011, 161.)

Authorities of the city of Roskilde have experimented with the 50-% replacement of fine NA by fine RCA in concrete production alongside the 100-% substitution of coarse RCA. Based on their report, the partial replacement of fine NA by fine RCA requires the use of an extra silo or for the two fine materials NA and RCA to be mixed beforehand. The problem arises as the fine RCA can form lumps at the high silos, which results in problems in production. The fine RCA that is a maximum 1-year-old causes more problems than older fine RCA, as it contains more unhydrated cement that can react with moisture in the silo. (Roskilde Kommune 2021.)

It would be environmentally more sustainable to substitute sand by fine RCA, as the extraction of river sand alters the course of water, causes shoreline erosion, and creates dead-end diversions and pits. However, cleaning the fine material for reuse purposes would be environmentally and economically more consuming than simply using NA. (Nedeljkovic 2021) Better techniques are needed for cleaning and sorting fine RCA to make its use more beneficial.

The permission to use fine RCA in concrete production is limited depending on the jurisdiction. The most significant hindrance to the use of fine RCA in Finland is that the Finnish concrete standards SFS-EN 12620 (2008) and SFS-EN 206 (2014) have no mention of the use of fine RCA in concrete production. Therefore, it can be challenging for the concrete industry to start reusing this material in concrete production.

2.4 Aggregate quality and compressive strength

2.4.1 Compressive strength

Concrete can be classified by its compressive strength. The compressive strength of concrete can be tested from a concrete cube or a concrete cylinder. For example, the classification C35/45 means that the strength of the concrete cylinder would be 35 MPa and the strength of the cube would be 45 MPa (SFS-EN 206:2014, 25).

The requirements for the compressive strength of concrete vary based on the application of the concrete. The classification is different for normal weight, heavy-weight, and light weight concrete, however, the results are acquired by the same method. The compressive strength of concrete is tested at the age of 28 days by using a 150 x 150 mm concrete cube or a 150 x 300 mm concrete cylinder. In some instances, such as with massive structural elements, the compressive strength of concrete is tested earlier or later than 28 days. (SFS-EN 206:2014, 24–36.)

The lower compressive strength of concrete made by using RCA is due to the lower density of the RCA which results from the aggregate’s high porosity. The high porosity means increased water absorbance of the aggregate. Extra water in the concrete mix weakens the concrete. Therefore, the lower the density, the lower the compressive strength. (Sadagopan 2021.)

2.4.2 Admixtures

Concrete is made by mixing coarse and fine aggregates with cement paste and water (Betonitieto n.d.a). Fresh concrete is concrete which has been fully mixed but is not yet hardened (SFS-EN 206:2014). During the mixing process of fresh concrete, admixtures can be added for altering the properties of concrete and maintaining a good concrete quality while mixing (PCA 2022b).

Water-reducing admixtures diminish the amount of water needed for the concrete. The admixture increases the workability without the need to increase the quantity of water, thereby leading to a lower w/c ratio and an increased strength of the concrete. (PCA 2022b.)

Plasticizers are admixtures that improve the workability of fresh concrete (Betonitieto n.d.a). They can be used to greatly diminish the amounts of water and cement needed in the concrete (PCA 2022b). Plasticizers are often used for producing high strength concrete. (Betonitieto n.d.b.)

2.4.3 Pre-treatment

Pre-processing is a way to enhance the quality of RCA, which can then improve the quality of the new concrete made by using it. In the study by Sadagopan (2021), RCA was pre-processed by rotating it in a horizontal rotating drum for 15 minutes and washing it afterward to remove adhered cement mortar. The pre-processing of RCA was shown to have a positive impact on the compressive strength of the concrete.

Several studies (Kobenhavns Kommune 2020; Sadagopan 2021) have shown that water saturating RCA before use is important for the workability and compressive strength of concrete. This is due to the high porosity of adhered cement mortar in RCA. RCA can be water saturated by submerging it in water or spraying water directly on the surface of the aggregate. Without proper water saturation prior to mixing, the aggregate will absorb water in the mixing process, thereby causing problems in the concrete workability and strength.

Another method of improving the quality of the new concrete is to reduce the water absorption of RCA by polymer treatments. In a polymer treatment, the polymer forms a film in the aggregate pores consequently preventing the water from penetrating the aggregate. The treatment has shown significant improvement in the RCA water resistance and reinforcement of the cement matrix in the aggregate. (Spaeth & Tegguer 2013.)

2.4.4 Workability

Workability or consistence refers to the fluidity and smoothness of fresh concrete (Concrete2you 2022). According to Boehme et al. (2015, 596) the overestimation in water absorbance leads to excess water in the fresh concrete, which causes increased workability of concrete. For the water content to remain within the limits required by workability, superplasticizers can be used to increase the workability of fresh concrete (Boehme et al. 2015). This should be considered, as a higher w/c ratio leads to a decreasing compressive strength of concrete (Chan et al. 2018).

The study by Boehme et al. (2015, 595) shows that the lack of water in the concrete mixture has the same decreasing effect on the compressive strength of the newly created concrete as overestimating the water content. The study shows that even a 1 % misjudgment of water absorption can lead to a 7 % decrease in the concrete compressive strength.

Table 1. Slump classifications (SFS-EN 206:2014)

Class	Slump tested in accordance with EN 12350-2 (mm)
S1	10-40
S2	50-90
S3	100-150
S4	160-210

The workability of fresh concrete is defined by the slump (Table 1). The number of the slump class rises when the depth of the slump increases. The slump should be tested according to the standard EN 12350-2:2019. (SFS-EN 206:2014)

2.5 Previous concrete reuse experiments

Denmark is a leader in waste concrete reuse. There have been several experiments where old buildings have been demolished and the crushed concrete has been used in building new infrastructure. One of these experiments (Kobenhavns kommune 2020) has been undertaken by the city of Copenhagen in collaboration with Amager Resource Center (ARC) and PELCON. In the project, the floors and walls of the Sydhavn Recycling Center were built from RCA which originated from an industrial plant chimney and T-beams. The project aimed to get an overview of the demolition concrete's value chain and material flow all the way from demolition to construction. The study helped to provide critical information about the technical details of RCA suitable for concrete production. It also provided comparable results for further studies on the subject.

In the experiment, the parent concrete originating from the chimney and T-beams had a compressive strength of 50–55 MPa, which is more than in the final recycled product, and the w/c ratio of the concrete didn't exceed 0.40. It was estimated that there was a maximum of 2 % of alkali-reactive sand per unit volume in the concrete. The chloride content of the parent concrete was 0.020 % of the concrete weight. However, it was estimated to be much lower because the majority of the chloride content was bound to the adhered cement mortar, which in the crushing process became mostly 0–4 mm fine material that was not used in the experiment. The concrete used in the experiment had a grain size of 4–25 mm. After crushing, 43.3 % of all the crushed concrete became fine material of 0–4 mm diameter. The amount of cement was optimised for the project and was, therefore, lower than what is normally used in concrete production with natural aggregates. The new concrete was designed to consist of 100 % recycled aggregate of diameter 4–25 mm. This required a dispensation from the City of Copenhagen. However, the Danish standards were later updated to allow the use of concrete aggregate in a 100-% replacement ratio. The water absorbance of the recycled aggregate of fraction 4–25 mm was relatively high: 3.6–5.1 %. (Kobenhavns kommune 2020.)

The concrete recipe used by Kobenhavns kommune (2020) consists of 300 kg/m^3 Rapid cement, 697 kg/m^3 fine material, 983 kg/m^3 coarse aggregate, 141 kg/m^3 water, 75 kg/m^3 fly ash, and several other filler materials. Fly ash was added to reduce the risk of alkali-silica damage. Replacing cement with fly ash has a positive effect on the quality of the concrete. Nevertheless, using fly ash, a byproduct of the coal industry, is not very feasible in concrete production in Finland due to the phasing out of coal (Corrosionpedia 2019; Ministry of Economic Affairs and Employment 2020).

The strength class of the new concrete in the Danish project was C35/45, reaching a compressive strength of 40 MPa after 28 days. The new recycled concrete did not need a higher cement content than traditional concrete in the same compressive strength class. The study showed that CO_2 emission reduction and economic savings were possible by using recycled aggregate in the production of new concrete. According to the calculations presented in the study, a 17-percent reduction of CO_2 emissions was achieved solely by reducing the cement content of the concrete by approximately 15 %. (Kobenhavns commune 2020.)

The study by Sadagopan (2021) studied the partial replacement of cement (CEM II/A-LL) with granulated blast furnace slag (GGBS) in the production of recycled concrete. The new concrete was tested for its compressive strength, and RCA used was tested for its water absorbance. The RCA was pre-processed to see how adhered mortar removal would affect the aggregate quality. The pre-processing involved adding the RCA into a horizontal rotating drum for 15 minutes and washing it afterward to remove the mortar. Secondary cementitious materials were added to the cement paste to improve its quality; 30 % of the cement was replaced by GGBS. It was found that pre-processing reduced the water absorption of the coarse RCA due to the loss of adhered mortar. It also affected the flakiness index, void-content, unit weight, and density. However, the mechanical pre-processing was estimated to cause 100 g worth of CO_2 emissions per m^3. The mean compressive strength for concrete that had been produced by using RCA which had been through mechanical pre-processing reached the compressive strength of 46.6 MPa regardless of the RCA replacement ratio. It was found that there was an increase in the compressive strength of GGBS-infused concrete only when 100 % of the natural aggregate was replaced by concrete aggregate.

One of the biggest concrete producers in Finland, Rudus Oy, has previously experimented with the use of RCA in their own concrete. In their UUMA-concrete, 30 % of coarse NA has been substituted by RCA. The study found that a substitution rate of 30 % does not cause any changes to concrete and its workability in the exposure class XC. Based on the study, 70-% substitution stiffens the concrete, but keeps it still fully workable. (Rudus Oy 2021.)

Similar results were achieved in a study by Ayub et al. (2021), where it was discovered that a 30-% replacement of natural aggregate by RCA had a less than 5-MPa decrease in the compressive strength and could therefore be used for structural concrete. The water absorbance of the coarse concrete aggregate in the study was 3.25 %, which is important to note since it has a major effect on the quality of concrete. The study by Ayub et al. (2021) is not fully comparable with this study because plasticizers were used in the concrete samples in the study by Ayub et al. (2021).

Nieminen (2015) studied the effect that replacing NA with RCA has on the compressive strength of concrete. The compressive strength of the parent concrete used in the study depending on its origin, had on average compressive strength of 39.1 MPa and 38.9 MPa. In the study, the RCA was separated into different grades of 16–32 mm, 8–16 mm, and 0.125–8 mm, after which water absorbance and density tests were performed separately for the different grades. The fine material size 0.125–4 mm used in this study would be classified as fine RCA. The water absorbance of the RCA size 0.125–32 mm varied between 6.0 % and 7.8 %. The cement used in the study by Nieminen (2015) is Plus cement CEM II/B-M (S-LL) 42.5N which is also used in this study. In the study by Nieminen (2015), NA was replaced by RCA by 5.1–13.8 % depending on the sample. The compressive strengths of all the samples were a little lower than that of the control sample but still exceeded 30 MPa. The results of the study by Nieminen (2015) are not fully comparable with this study, since the fine material 0–4 mm used in this study is NA. The aggregate replacement ratios in the study by Nieminen (2015) are also significantly lower than the ones in this study.

2.6 Environmental benefits

The concrete industry is fairly unsustainable, mainly due to the consumption of cement in concrete production. As mentioned in the introduction, cement production consumes a massive amount of energy and natural resources, constituting 7 % of global CO_2 emissions. Portland cement production requires 4900 MJ of energy per tonne of cement, which results in 900 MJ energy consumption per tonne of concrete. As of CO_2 emission, cement production releases on average a tonne of CO_2 emissions per tonne of cement. The concrete industry also consumes a lot of natural resources: 10 billion tonnes of sand, gravel, and crushed rock, and more than 1 trillion litres of fresh water per year of concrete production. From this, it can be concluded that replacing NA with RCA can have a marked positive impact on the sustainability of the concrete industry. (Aitcin & Mindess 2011, 1–4.)

There have been several studies on alternative materials for replacing cement in concrete production. Based on a study by Sadagopan (2021, 56), it is possible to produce strong and more sustainable concrete by replacing cement alone. By replacing 30 % of the cement content (CEM II/A-LL) with GGBS, a 28-% reduction in concrete production's CO_2 emissions can be achieved. Portland cement can be replaced by GGBS in varying proportions of 25–85 % (Aitcin & Mindess 2011, 6).

One study by Malhotra (2000, 231), concluded that when the w/c ratio of concrete is ≤ 0.30, fly ash can be used to replace 60 % of Portland cement to create strong and durable concrete. Silica fume, which is a byproduct of silicon and ferrosilicon industries, can be used to replace cement to create high-strength concrete with a compressive strength of over 100 MPa. Due to its negative effect on concrete workability and high cost, substitution usually varies between 5 % and 10 %. (Aitcin & Mindess 2011, 7.)

In the study by Kobenhavns kommune (2020, 37), the amount of cement in concrete production could be reduced by 10–15 % when replacing NA with RCA. Based on the study, the lower density and cubicle-like shape of the RCA makes it possible to diminish the amount of cement needed.

Detailed examination of carbon dioxide uptake of crushed concrete by Kikuchi and Kuroda (2011, 123) showed that the CO_2 uptake of crushed RCA increases significantly the smaller its particle size is. The study mentions that alternately wetting and drying the RCA also increases the CO_2 uptake. Based on a survey presented in the study, the CO_2 uptake of one ton of crusher-run concrete aggregate of size 0–40 mm is 11 kg. The CO_2 emissions of mining 1000 kg of quarried stone have been estimated to be 2.76 kg CO_2 (Ramboll 2019). This would mean saving 13.76 kg of CO_2 emissions for each 1000 kg of RCA used to replace NA in concrete production. The problem with these kinds of calculations is that the numbers rely heavily on varying transportation emissions, and the kind of energy used. To minimise the emissions created in the process, the distance between the place of demolition, concrete crushing, and concrete production should be minimal.

It can be gathered that carbonation would occur with crushed RCA even if it was not used in new concrete production. However, since the size of the RCA is important for carbon uptake, there can be benefits in using RCA in the production of new concrete since it causes a lot of fine RCA to form. Nevertheless, the fine RCA also has disadvantages. The highly carbon absorbent fine RCA can make up almost half of the total concrete material crushed (Kobenhavns kommune 2020, 47). The current Finnish concrete standard SFS-EN 206 (2014) has no mention of the use of fine RCA in concrete production. Therefore, leftover fine material from concrete crushing is not yet widely used and can become waste. It is important to find a way to reuse this material to increase material reuse efficiency and reduce the environmental impact of future concrete production. There are, as of now, some ways to deal with fine RCA. In the study by Kobenhavens kommune (2020), the leftover fine material 0–4 mm was sold to another company, which then used it as filling material. Roskilde Kommune (2021) calculated that replacing 50 % of fine NA by fine RCA alongside with 100 % replacement of coarse NA by coarse RCA in concrete production leads to 14 kg CO_2 savings, which equals 3 % of CO_2 savings as the total CO_2 consumption was estimated to be 457 kg.

3 MATERIALS AND METHODS

3.1 Preparation of the reclaimed crushed aggregate

A quantitative lab experiment was used as a method to answer the lack of data on the 100-% replacement of NA with reclaimed crushed aggregate. Reclaimed crushed aggregate was used in the experiment instead of RCA for practical reasons, as the cooperative company SBS Betoni Oy had it available. The experiment began by preparing reclaimed crushed aggregate for producing concrete test pieces, which were tested for their compressive strength.

The reclaimed crushed aggregate used in the experiment was left over from SBS Betoni Oy's concrete production. The strength class of the parent concrete varied mostly between K30 and K45, which is comparable to 30–45 MPa. The reclaimed crushed aggregate had a seemingly good flakiness index, as it was quite round. The aggregate was also cleaner than RCA as it did not contain any contaminants from demolition. There was very little visible trash, mainly asphalt, plastic, and styrofoam remnants in the aggregate. The impurities supposedly came with the reclaimed crushed aggregate from the area where the aggregate had been stored and during transportation.

The aggregate was taken by a front-end loader from a 6-meter-tall aggregate pile which was stored outside and was under a thick snow cover at the time of sample taking. The frozen aggregate was taken from the pile and put on a floor of a hall to be thawed out. The temperature in the hall was 15–20 °C. The concrete aggregate which was prepared for the sieving was size 0–32 mm (Figure 2).

After the aggregate had stayed in the hall for a few days, it was carried to a laboratory in four 45-litre plastic buckets. The concrete aggregate size needed for the experiment was 4–32 mm. This meant that the fine material ≤ 4 mm needed to be sieved out manually. The fine material was not used in the experiment, because its usage potential within the limitations of the current standards was small, and it was important to know the effect that coarse concrete aggregate alone had on the compressive strength of the concrete.

Figure 2. Concrete aggregate before sieving (left) and laboratory sieve set used in the experiment (right)

Before sieving, the concrete aggregate needed to be dried in an oven. Two ovens were used in the drying. The ovens were set to a temperature of 150±5 °C and could take approximately 2.5–10 kg of concrete aggregate at a time. The aggregate was added into the oven in five 0.5–2 kg batches. It took approximately 1 h for each patch to dry. To increase the drying speed, the aggregate patches were periodically stirred. The biggest visible trash particles were taken out by hand before letting the aggregate into the sieve, to prevent clogging the sieve. About 0.5–1 kg of concrete aggregate was put into the sieve at a time (Figure 2). The sieve was then put on a sieve shaker for

5–10 minutes. During the sieving process, the laboratory sieve set had sieves of 1 mm, 2 mm, 4 mm, 8 mm, 16 mm, and 31.5 mm. The 1 mm and 2 mm sieves were left in the set to allow the 0–4 mm material to have more room and therefore to create less dust.

Figure 3. 4–32 mm concrete aggregate after sieving

Figure 4. Fine material 0–4 mm after sieving

The sieved aggregates of 0–4 mm and 4–32 mm were stored separately into six plywood boxes (Figure 3). The coarse concrete aggregate of 4–32 mm was sent to Semtu Oy for producing test concrete pieces and to Mitta Oy for particle density and water absorption tests. Since the fine material could not be further utilised in the experiment, it was left at the factory to be restored (Figure 4).

3.2 Preparation of concrete test pieces

Concrete test pieces were made by following a recipe provided by Semtu Oy (Table 2). Their aim was to create a recipe that follows the guidelines given to concrete proportioning and gives an estimate of what kind of recipes concrete manufacturers could potentially use. The numbers were slightly different for each batch due to the humidity percentage of sand and water optimisation. The amount of cement stayed the same in each experiment. The cement used was Finnsementti Oy's Plus cement CEM II/B-M (S-LL) 42.5 N. No fillers or admixtures were added to the concrete mixture so that the expected decline in the concrete's compressive strength could be properly observed. In the recipe, the sand content was estimated to be 20.5 kg for a 20-litre batch. The water content was optimised separately for each batch depending on the visible absorbance of the fresh concrete. The desired workability of the fresh concrete was S3, which can be achieved when the slump is 10–15 cm. The w/c ratio in this recipe varied between 0.5 and 0.8.

Table 2. Concrete recipe for a 20-litre batch of concrete

	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	Cement (kg/m^3)	Additional water (kg/m^3)
Control sample	20.5	17.3	3.0	5.6	-
30 % replacement	20.5	17.3	3.5	5.6	0.5
50 % replacement	20.5	17.3	3.7	5.6	0.7
100 % replacement	20.5	17.4	3.9	5.6	0.9

For the comparability of the results, a modified version of the two-step mixing process as in the study by Nieminen (2015, 53) was applied. First, the concrete mixer was lightly sprayed with water to make the cleaning of the mill easier. Then the aggregates were weighed and added into the concrete mixer from heaviest to lightest. The aggregates were mixed for about 30 seconds, after which half of the total amount of water was added to the mix. The aggregates and water were mixed for another 30 seconds before they were left to steady for 4 minutes. After this, cement was added to the mix and the mix was mixed for approximately 10–20 seconds. The rest of the water was added, and it was mixed for a few seconds to see if the mix needed more water. In all the batches, some additional water was added at this point while the mixer was on, after which the mixing continued for a minute. The water was added for achieving a concrete workability class S3. The temperature was measured from the fresh concrete after mixing.

Each batch was tested for its consistence after mixing. The consistence test was done according to the standard SFS-EN 12350-2:2019. One-third of a cone was filled with concrete mix and stroked by a compacting rod 25 times. The same was repeated when the cone was two-thirds full, and finally for a fully filled cone. The cone was raised and the slump was measured from the top of the cone to the highest point in the concrete heap (Figure 5).

Figure 5. Fresh concrete and a successful 11 cm slump

The cube moulds were coated with a thin layer of oil to prevent the pieces from getting attached to the edges or bottom of the mould. The mould was half-filled with fresh concrete, then put on a vibrating table. The mould was vibrated for about 10 seconds to make the surface of the concrete even. The rest of the mould was then filled and vibrated for another 10 seconds to make the surface even. A trowel was used to wipe the surface of the cube flat (Figure 6). The finished cubes were left drying on a shelf in a hall at 18 °C temperature. The cubes were all covered by plastic sheets to retain moisture. The cube molds were removed 2–3 days later, after which the cubes were put into a water bath at 20 °C for 25 days. The samples were taken off the bath to dry on a floor drain for 1–2 h before testing compressive strength.

Figure 6. Concrete test cubes drying before water bath

The amount of additional water added to the concrete mix was calculated by formula 1. The following notations are only applicable to this study.

$$(W - W_c) - (CCA \ x \ A_{cca}) = W_{add} \quad (1)$$

W = Total water added (g)
W_c = Water in the control sample (g)
CCA = Amount of coarse concrete aggregate (kg)
A_{cca} = Absorbance of Coarse Concrete Aggregate (%)
W_{add} = Additional water (g)

3.3 Tests on the reclaimed crushed aggregate

To have a better idea of the quality and properties of the aggregate used in the production of the test cubes, the aggregate was tested for its particle density and water absorption according to the standard SFS-EN 1097-6 (2022). The particle size distribution of the aggregate was also tested according to the standard SFS-EN 933-1 (2012).

While sieving the concrete aggregate, the particle size distribution was measured to a suitable size. For this test, the sieves of sizes 0.125 mm, 0.25 mm, 0.5 mm, 1 mm, 2 mm, 4 mm, 8 mm, 16 mm, and 31.5 mm were used. Approximately 1 kg of aggregate was put into the sieves for this measurement. The sieve was then put on a sieve shaker for 5–10 minutes. The content of each sieve was weighed separately on a laboratory scale. The results were rounded by one decimal place. The measurement was then repeated with aggregate from another one of the buckets. After the measurements, the passing percentages were calculated for each sieve, and particle size distribution curves were drawn from them.

The aggregate in this experiment was not water saturated or pre-processed. Instead, to avoid workability and strength issues with the concrete, water was added to the fresh concrete mix based on the workability of the concrete. The additional amount of water in the mixing process was calculated afterwards. In this experiment, particle density and water absorbance of the concrete aggregate were measured by Mitta Oy. This was to determine the average water absorbance percentage of the concrete, as the results can tell a lot about the quality of the concrete. Approximately 20 kg of 4–32 mm concrete aggregate was sent for the tests.

3.4 Tests on the new concrete

Concrete cubes were tested in the laboratory to find out how the new concrete's compressive strength has changed compared to ordinary concrete. The compressive strength test class of the control sample concrete was expected to be around C25/30. The test cubes were tested for their compressive strength according to the standard EN 12390-3. The size of the test cubes was 150 mm x 150 mm as defined in the standard SFS-EN 206

(2014). Normally the test cubes need to be tested for their compressive strength at the age of 28 days (SFS-EN 206:2014, 26). However, the test pieces in this study were tested at the age of 27 days, except for the control samples and the 30 % concrete aggregate replacement samples, which were all tested at the age of 28 days. This was because the NA of size 4–8 mm needed to be manually sieved out of NA of size 0–8 mm for every other batch except for the control sample. The manual sieving took longer than expected, resulting in some of the samples being produced only the next day. Trusting the Semtu Oy’s expertise, the concrete samples had already gained sufficient strength on day 27, and the difference of the last day on the compressive strength was estimated to be minuscule.

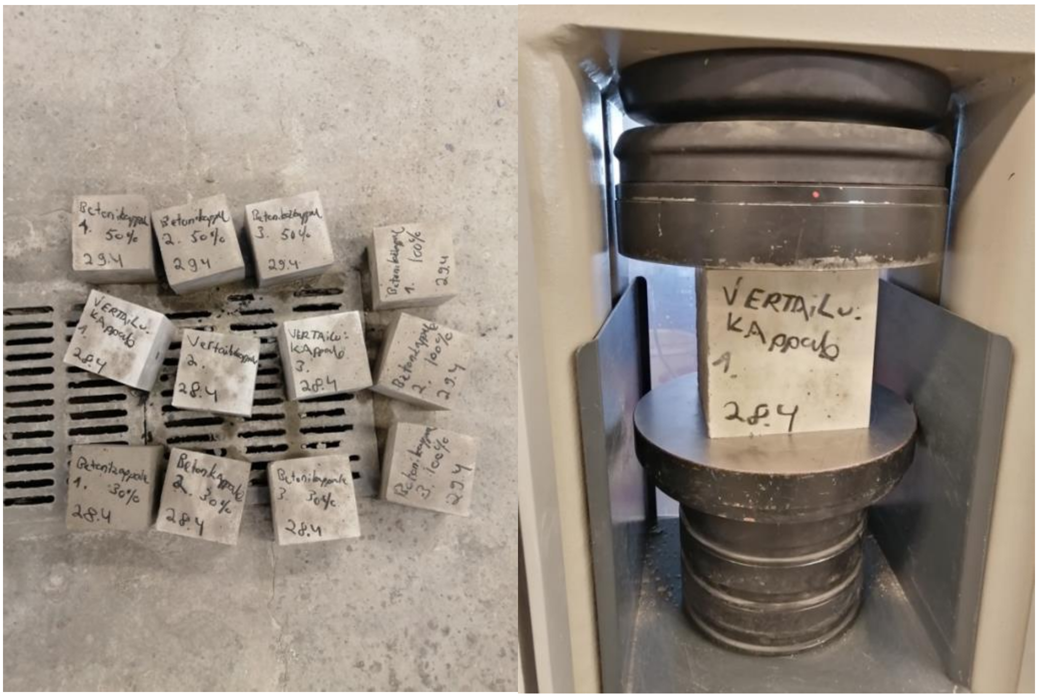

Figure 7. Concrete tests samples and measurement device

To measure the compressive strength of the samples, each one of them was put into a compressor. The device pressed the cube until it detected a crack, at which point the measurement ended (Figure 7).

4 RESULTS

4.1 Results of tests for concrete aggregate

After sieving 116.2 kg of concrete aggregate, there was 69.2 kg of 4–32 mm coarse concrete aggregate and 47 kg of fine material 0–4 mm. Therefore, the fine material accounted for 40.4 % of the total volume of the sieved material.

The laboratory test results of reclaimed crushed aggregate showed that the water absorbance was 1.66 % (Figure 8). This is over three times higher than the water absorbance of the natural aggregate used in the tests. The water absorbance of the NA used was 0.5 %. The particle density of the concrete aggregate of size 4–32 mm was 2550 kg/m^3, whereas the particle density of the NA size 8–32 mm was 2706 kg/m^3. The slump in each fresh concrete batch was measured to be 11 cm, making the concrete workability class S3 as desired.

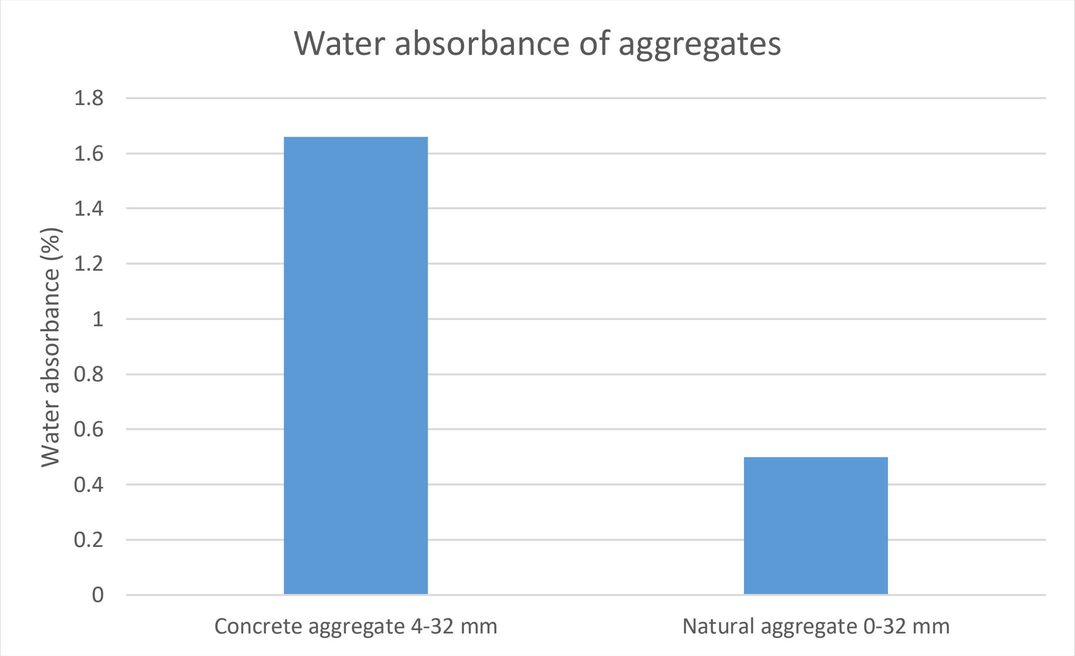

Figure 8. Water absorbance of aggregates

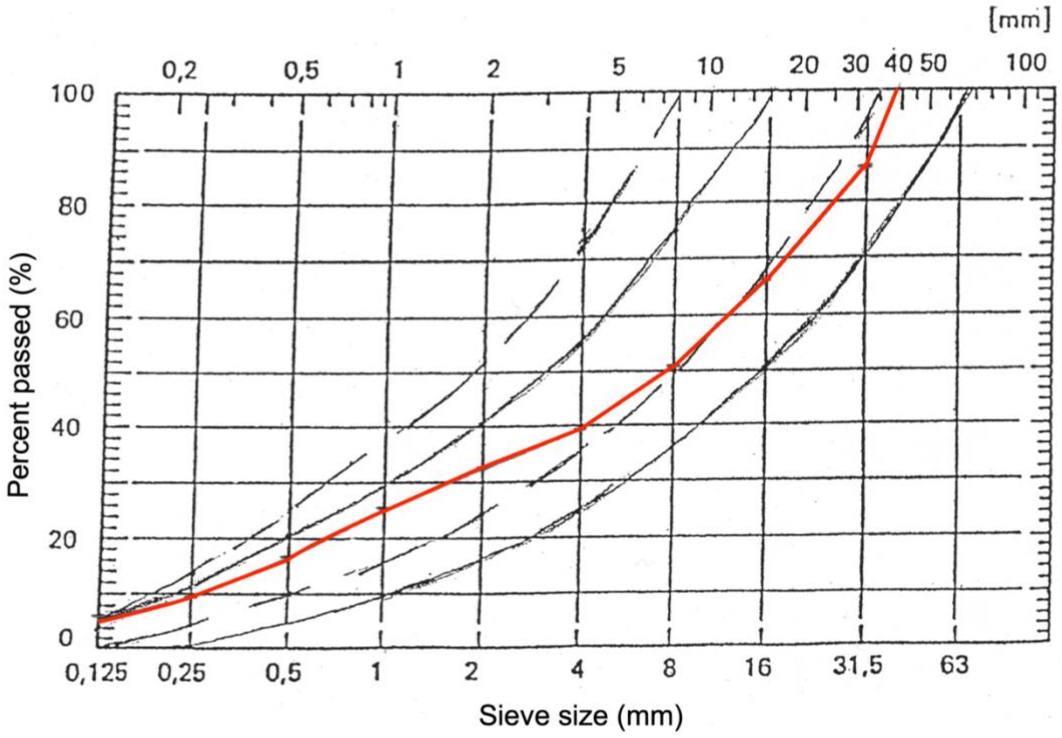

Figure 9. Particle size distribution curve of concrete aggregate (red)

The particle size distribution of concrete aggregate was steady, as the values maintained within the standard gradation zone (Figure 9). The more detailed grading data used for calculating the curve can be found in appendix 1.

4.2 Results of tests for concrete test pieces

The results of the compressive strength tests showed that when using reclaimed crushed aggregate in concrete production, the compressive strength decreases by 6–7.3 MPa depending on the NA replacement ratio.

Table 3. Compressive strengths of test samples. Sample 1 of the 30-% replacement batch has been marked in brackets because due to a testing error the result was significantly different from the rest of the batch and therefore will not be analysed further

Sample	**Compressive strength sample 1 (MPa)**	**Compressive strength sample 2 (MPa)**	**Compressive strength sample 3 (MPa)**
Control sample	27.3	25.9	26.0
30 % replacement	(18.4)	20.8	21.0
50 % replacement	20.7	20.5	20.0
100 % replacement	18.9	19.1	19.3

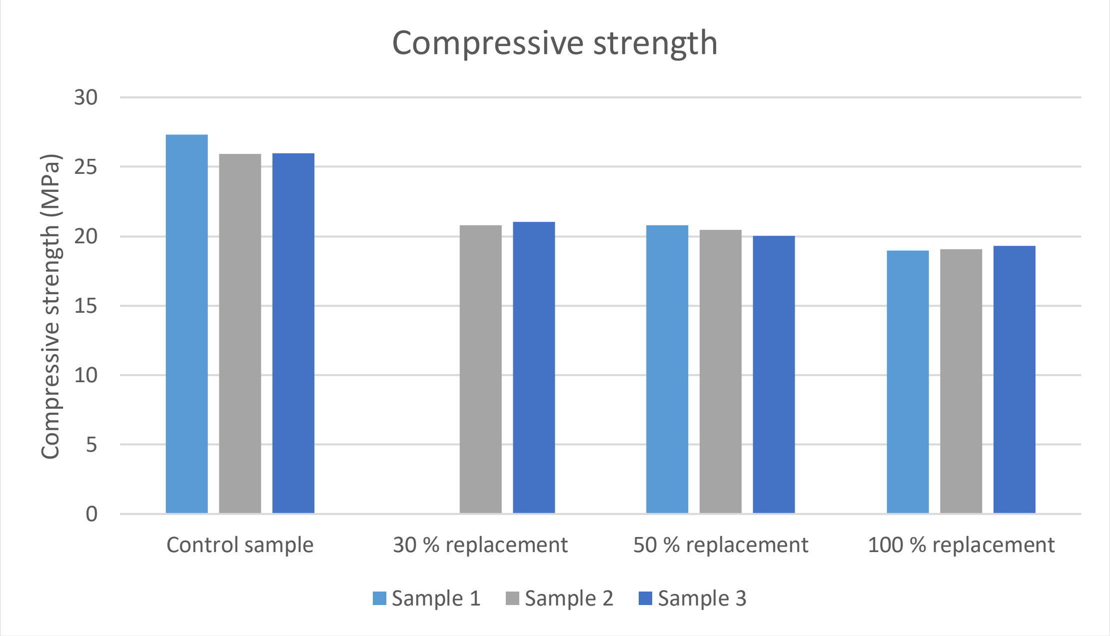

Figure 10. Compressive strengths of test samples as a graph

The result of the first sample in the 30-% replacement was ignored for all the calculations as the sample was in poor condition at the time of testing. The variation in the compressive strength between the different replacement ratios was 0.1–2.1 MPa, which is 0.5–10 % (Table 3, Figure 10).

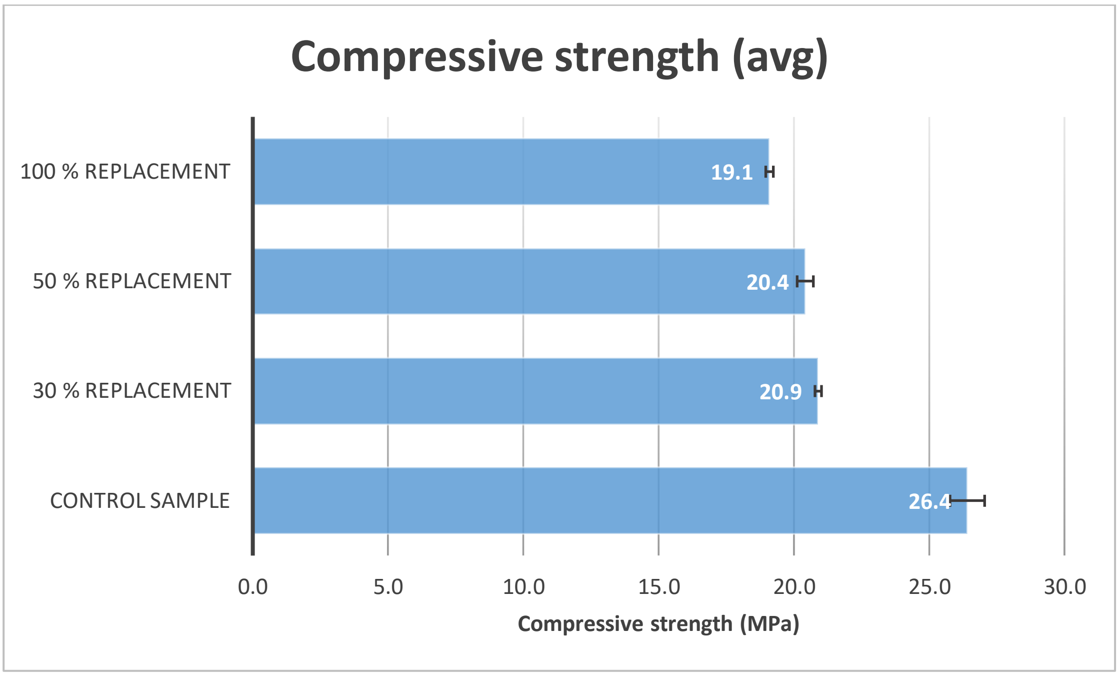

Figure 11. Average compressive strength of samples with standard deviation

The compressive strength of concrete decreases on average by 21–28 % when substituting natural aggregate with reclaimed crushed aggregate (Figure 11). The average variation between the 30-% and 100-% replacement ratios was 8.6 %.

The control sample concrete achieved the strength class C20/25. The 30-% and 50-% replacement samples achieved the strength class C16/20.
The 100-% replacement reached an average compressive strength of 19.1 MPa, falling into the strength class C12/15.

5 DISCUSSION

5.1 Concrete aggregate analysis

The volume of fine material (40.4 %) was similar to that used in a study by Kobenhavns kommune (2020), where the volume of fine material from all crushed material was 43.3 %. This would imply that the aggregate material behaves in a uniform way in crushing regardless of its origin. The effect of the crushing method used is not known.

Particle size distribution measurements are important because they define the constitution of the aggregate. When aggregate is well graded, the concrete is dense and requires less fine material and cement (Haque & Tuhin 2012). Particle size distribution curves need to stay within the standard gradation zone for the aggregate to be suitable to use in concrete production. The particle size distribution curve of the aggregate used in the experiment showed that the constitution of the concrete aggregate remained well within the set limit values and was suitable for this experiment. The concrete aggregate overall seemed to be of very good quality, as it was quite round unlike NA, which can often be flaky. This may have had a positive effect on the concrete’s compressive strength.

The average density of the reclaimed crushed aggregate of 2550 kg/m^3 was slightly higher than in previous studies (Rahal 2005; Lima et al. 2013; Nieminen 2015; Sadagopan 2021) in which the average density of RCA has been 2477 kg/m^3. The density of the reclaimed crushed aggregate is close to the average bulk density of NA, which according to the same studies is 2548 kg/m^3. However, the density of the reclaimed crushed aggregate differed remarkably from the NA used in this study. The difference between the reclaimed crushed aggregate density and the NA density was bigger than the comparable difference in previous studies (Rahal 2005; Lima et al. 2013; Nieminen 2015; Sadagopan 2021). This could be one of the reasons for the lower compressive strength of the concrete.

As concrete aggregate tends to be porous, water absorbance measurements for concrete aggregate should be taken to better estimate the amount of extra water needed for the fresh concrete. (Sadagopan 2021, 17–25). The amount of extra water varied between 0.5 kg and 0.9 kg per batch. The two-step mixing process might have helped to prevent a major decrease in the compressive strength, as the concrete aggregate had time to steady and absorb water from the mix. On the other hand, the increased water demand of the concrete aggregate most likely contributed to the decrease in the concrete’s compressive strength.

The water absorption value of the reclaimed crushed aggregate was low for concrete aggregate (Figure 8). This was most likely due to the visibly low amount of adhered cement mortar. The water absorption results were significantly lower than those in a similar study by Kobenhavns kommune (2020) where the water absorbance was 3.6–5.1 %. The water absorbance value was also smaller than in a study by Brito et al. (2014, 17-22) where the water absorbance of concrete aggregate was estimated to be 4.7 % and in a study by Ayub et al. (2021) where the water absorbance was 3.25 %. The lower water absorbance could have correlated positively with the compressive strength test results, although the compressive strength of the concrete in the aforementioned studies has been higher.

5.2 Compressive strength test analysis

The results of the compressive strength tests show that the decrease in the compressive strength of concrete is not grand. The decrease between the different replacement ratios is small, which was somewhat unexpected as a previous study by Ayub et al. (2021) showed that even when using a plasticizer, the replacement ratios higher than 30 % result in a much worse compressive strength for the concrete. The better compressive strength of the concrete between this and the previous study can be explained by the difference in the concrete’s water absorption. The water absorption of the aggregate was lower than in the previous study, implying that the concrete is less porous. The lower porosity of aggregate implies higher density, which has been connected to increased compressive strength (Sadagopan 2021, 46).

The difference between the bars in each sample series was 1–3 %, therefore it was assumed that the average values are accurate (Figure 10). The first sample of the 30-% replacement batch was left out of the average calculation, as the compressive strength of the sample was significantly lower than that of the other samples (Table 3). The reason for this is most likely because the mould was taken off too early and the edges of the sample cube were partially cracked when testing. The sample was also visibly darker than any of the other samples.

The concrete did not achieve the estimated compressive strength class C25/30. It also did not reach the same level as in the study by Kobenhavns kommune (2020), where the concrete strength reached the class C35/45. The difference in strength most likely results from the use of fly ash and other admixtures in the Danish study. The lower compressive strength of the concrete tested here was most likely a combined result of a high w/c ratio, lower bulk density in comparison with the NA used, increased porosity, and the lack of admixtures. As hard as it is to define the exact impact of the aggregate properties on the concrete's compressive strength without proper comparative data, the low water absorption, two-step mixing technique, and the seemingly round shape of the aggregate most likely had a very small but nonetheless beneficial effect on the concrete's compressive strength.

5.3 Final analysis of results

The results of this study can be helpful in the development of a more sustainable concrete industry in Finland. The achieved results prove that the use of reclaimed crushed aggregate in the production of new concrete is possible. The results of this study can be used by Mikkeli Development Miksei Ltd. to advance the use of concrete aggregate in the production of new concrete. Since reclaimed crushed aggregate can be concrete that a company has already paid for, utilizing it saves them money that would have otherwise been spent buying NA. Using aggregate which has already been paid for also ensures that the concrete's full value has been utilised. The lower compressive strength of concrete can be compensated for by using plasticizers (Salmimies 2022). Economically, using plasticizers to reach the required compressive strength of concrete is affordable. The estimated price of the plasticizer is significantly smaller than the savings that come from reusing reclaimed crushed aggregate (Salmimies 2022). This supports the initial hypothesis which claimed that the results would give positive affirmation to the use of reclaimed crushed aggregate to substitute NA in concrete production. Even though this study was done by using reclaimed crushed aggregate, compressive strength results for RCA could be similar.

The future of concrete reuse looks bright, but there are factors that need to change to make the process more beneficial for companies and for the environment. The upcoming EoW regulation for concrete is expected to facilitate the use of recycled aggregate in concrete production as it defines when concrete aggregate becomes a product and is no longer waste (Ministry of the Environment 2018). This is important not only for facilitating the legal processes of handling RCA but to help remove the waste status that this highly reusable material has in the minds of industrial operators.

Another challenge for higher utilisation of concrete aggregate is that currently the standard SFS-EN 206 (2014) recommends that a maximum of 50 % of the total aggregate should be replaced by RCA in the lowest exposure class X0. In the rest of the classes, the recommended proportions get progressively smaller. The standard should ideally be updated to accept the use of RCA with a 100-% replacement ratio as has been done in Denmark. In the Finnish standards, there are no mentions of usage limits, either, for fine material created in the concrete crushing process. This is problematic since crushing coarse concrete aggregate creates a lot of fine material. Better end-use for the fine material is needed to make using recycled concrete aggregate more sustainable.

It is of utmost importance that more tests on the properties of concrete aggregate and its effect on the properties of new concrete are taken. For further research, it would be advisable to test the effect of RCA use on the concrete’s freeze-thaw resistance because the water absorbance of concrete aggregate is higher than that of NA, which may result in insufficient properties for the concrete aggregate and hinder its reuse in the construction industry. More research should also be conducted to find the optimised amounts of plasticizer to go with RCA to attain a sufficient compressive strength for concrete. This research would be necessary for finding a balance between maintaining a high concrete quality and reducing the concrete’s environmental impact which mainly results from the use of cement. The fine RCA should be included in these tests to reach the optimal reuse potential of RCA as it may, due to its high water absorbance, reflect negatively on the compressive strength of concrete. The properties of fine RCA and limitations in its use in the production of new concrete should be thoroughly investigated. Finally, since Finnish C&D concrete is commonly utilised in earth construction, it would also be important to estimate how environmentally beneficial it is to use concrete aggregate in producing new concrete compared to using it in earth construction.

The results of this study can be interpreted as reliable because of the proximity of the adjacent results. To improve the reliability of the results, more test samples could have been taken to remove any potential outliers. To improve the organisation and flow of the project, the requirements for the tests on concrete quality should have been studied sooner. The freeze-thaw resistance tests would have required a waiting period of months, which in the current state of affairs was not doable. Overall, the project progressed smoothly after the project plan was agreed upon with the cooperative companies.

6 CONCLUSION

Although the reuse of demolition waste concrete has not yet become popular in Finland, it offers a multitude of opportunities. This study showed that the compressive strength of concrete decreases on average 21–28 % when substituting NA by reclaimed crushed aggregate. The compressive strength of the concrete did not reach the same level as in the previous studies recorded in previous papers. This was most likely because of the lack of plasticizers in this study in comparison with the previous studies. When admixtures are added, the compressive strength of concrete can reach the same strength as the control samples (Salmimies 2022). The results of this study provide important background information for further studies on concrete reuse in Finland, especially because a lot of the relevant research on the topic is not publicly available possibly as a means of competitive advantage by concrete companies. The results of this study can be used to prove the usability of reclaimed crushed aggregate in the production of new concrete to the concrete industry. Although the results were achieved by using reclaimed crushed aggregate, they could be directional to the effect that RCA has on new concrete. The reuse of RCA in the production of new concrete is important not only to diminish waste in cities but also because of the emission heavy concrete industry, which produces a considerable fraction of global CO_2 emissions. The reuse of RCA in concrete production would diminish the need for natural quarried stone in concrete production and therefore help to save natural raw materials and to support the circular economy.

The aims of the study have been achieved as planned and the process from the beginning to the end has been very educating. The knowledge gained on concrete properties and their effect on the concrete’s compressive strength alongside practical skills in producing concrete has been massively helpful. More research is needed to improve the usability of concrete aggregate in the production of new concrete. Concrete aggregate properties and the effect of RCA on the quality of new concrete should be studied further. It would be advisable to find the optimised use of plasticizer with RCA in concrete production and include fine RCA in these tests.

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PARTICLE SIZE DISTRIBUTION DATA OF CONCRETE AGGREGATE

sieve size (mm)	Concrete aggregate retained on sieve (g)	Concrete aggregate retained on sieve (%)	Percent passed (%)
bottom	95	5.1	-
0.125	83	4.5	5.1
0.25	142	7.7	9.6
0.5	148	8.0	17.3
1	137	7.4	25.3
2	129	7.0	32.7
4	223	12.0	39.7
8	268	14.5	51.7
16	376	20.3	66.2
31.5	244	13.5	86.5
63			100
Total	1845		434.1