Thesis for the Degree of Doctor of Philosophy

Recycling of concrete in new structural concrete

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ABSTRACT

Concrete waste as crushed concrete aggregates (CCA) in structural concrete gives a new purpose and prolongs the technical life of the reference concrete accomplishing closed loop recycling. This research investigates CCA as aggregate replacement in an industrial reference concrete recipe as fine aggregate fractions and overall aggregate replacement. Experimental study of CCA concrete is conducted by testing compressive strength and workability. Results show that CCA concrete has inferior compressive strength and workability than reference concrete due to the adhered mortar and flakiness index of CCA, properties which differentiate CCA from reference concrete aggregates. These properties influence the aggregate packing density and water absorption properties of CCA, crucial to concrete workability and compressive strength.

To overcome the challenges with determining water absorption of fine CCA, the standard pycnometer method is modified in an innovative way to test a combined fine and coarse aggregate fraction. The water absorption is measured at 15 minutes to estimate the water absorbed by CCA during the concrete mixing. Workability corresponding to reference is achieved when CCA fractions are momentarily pre-soaked with water corresponding to 50% of the 15-minute water absorption value just before concrete mixing.

To improve concrete properties, this research investigates two modifications: enhancing aggregate quality by adhered mortar removal and enhancing cement paste quality by adding secondary cementitious materials (SCM). Firstly, CCA is modified by a fraction-wise mechanical pre-processing in a horizontal rotating drum for 15 minutes to abrade adhered mortar which is then removed by washing. The abrasive nature of pre-processing results in the loss of aggregate material along with the adhered mortar accounted for by a mass-balance; resolved by adjustments in CCA particle grading. The loss of adhered mortar leads to reduction of CCA water absorption, influencing pre-soaking water content. Pre-processing also influences properties such as flakiness index, void-content, unit-weight and density, jointly seen as an increase in CCA packing density. After pre-processing, mixes with CCA as fine aggregates (CCA50) show mean compressive strength exceeding reference concrete. Mixes with overall CCA replacement (CCA100) show same compressive strength as reference concrete. The flow diameters of both mixes correspond to the same flow class F2 as reference concrete.

Secondly, modifications of cement paste are investigated by replacing 30% of the reference cement, CEM II/A-LL with granulated blast furnace slag (GGBS). Mixes investigated are CCA with/without mechanical pre-processing at both 50% and 100% replacements. Among the GGBS mixes, CCA100 achieves reference concrete compressive strength while CCA50 reaches the reference concrete strength only when combined with mechanically pre-processing. Addressing early-age strength, an improved mixing method with pre-soaked GGBS is investigated on CCA100 mix. The resulting mean compressive strength at seven days fulfils 93% of the corresponding reference concrete strength. Addition of GGBS causes the concrete workability to resemble a mix with increased mixing water content. Therefore, CCA flow diameter values of reference concrete flow class are achieved at a lower water/binder ratio.

The results are investigated with regard to statistical significance and sustainability. For concrete CCA100, GGBS addition results in statistically significant improvements of the compressive strength and a nearly 30% reduction of carbon dioxide-related emissions implying a green concrete. For CCA50 statistically significant improvements in compressive strength are realized for the combination of mechanical pre-processing and GGBS addition.

Key words: concrete recycling; sustainability; closed-loop recycling; recycled aggregates; compressive strength; workability mechanical pre-processing; secondary cementitious materials; green concrete; climate-optimized concrete

Every act of creation is first an act of destruction

Pablo Picasso

Dedicated to my dearest Yatin

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“If I have seen a little further, it is by standing on the shoulders of giants”.

Immensely humbled,

Madumita Sadagopan

Borås, January 2021

PUBLICATIONS INCLUDED IN THE THESIS

1. **RE:Concrete - Study on recycling of concrete in Sweden** *(Paper 1)*

   Sadagopan, M., Malaga, K. & Nagy, A. (2017). Nordic Concrete Research, 56(1), pp. 83-99.

2. **Modified pycnometer method to measure the water absorption of crushed concrete aggregates** *(Paper 2)*

   Sadagopan, M., Malaga, K. & Nagy, A. (2020).. Journal of Sustainable Cement-Based Materials, pp. 1-11

3. **Improving recycled aggregate quality by mechanical pre-processing** *(Paper 3)*

   Sadagopan, M., Malaga, K. & Nagy, A. (2020). Materials, 13(19), 4342 pp.1-16

4. **Effects of slag addition and mechanical pre-processing on the properties of recycled concrete in terms of compressive strength and workability** *(Paper 4)*

   Sadagopan, M., Malaga, K. & Nagy, A. (2020). Nordic Concrete Research *(submitted)*

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2. **RE:Concrete - Study on recycling of concrete in Sweden**

   Sadagopan, M., Nagy, A. & Malaga, K. (2017). XXIII Nordic Concrete Research Symposium 2017, Denmark, Norsk Betongforening, pp. 193-196.

ABBREVIATIONS

CCA	Crushed Concrete Aggregates
CCA100	Overall replacement of coarse, fine aggregates with CCA
CCA50	Replacement of fine aggregates with CCA
BREEAM	Building Research Establishment Environmental Assessment Method
LEED	Leadership in Energy and Environmental Design
CDW	Construction and Demolition waste
SSD	Saturated Surface Dry
MP	Mechanical Pre-processing
SCM	Secondary Cementitious Materials
ITZ	Interfacial Transition Zone
GGBS	Granulated Blast furnace Slag
GP	Glass Powder

CONTENTS

Appended articles:

Article 1: RE:Concrete study on recycling of concrete in Sweden

Article 2: Modified pycnometer method to measure the water absorption of crushed concrete aggregates

Article 3: Improving recycled aggregate quality by mechanical pre-processing

Article 4: Effects of slag inclusion and mechanical pre-processing on the properties of recycled concrete in terms of compressive strength and workability

1 INTRODUCTION

This chapter explains the importance of concrete recycling, concrete waste statistics related to Sweden, the current challenges and incitements regarding the commercial implementation of concrete recycling in Sweden, also presented in article 1. The thesis objective to show the use of concrete waste as aggregates in structural concrete. The concrete recycling procedure for obtaining crushed concrete aggregates is shown.

1.1 Background

Due to the urbanization, the construction and infrastructure sectors are growing at an accelerated rate. This leads to increased production of concrete and related waste at the same time. A recent European report shows a total of 2.8 billion ton of aggregates consumed yearly in the EU28 out of which about 40% is used in the production of structural concrete [1]. The construction and demolition waste accounts for 41% of the mineral waste generated in the EU, amounting to approximately 900 million ton [2].

Recycling concrete maybe modelled as the prolonging of the parent concrete technical life to a second life in new applications, shown in figure 1.1.

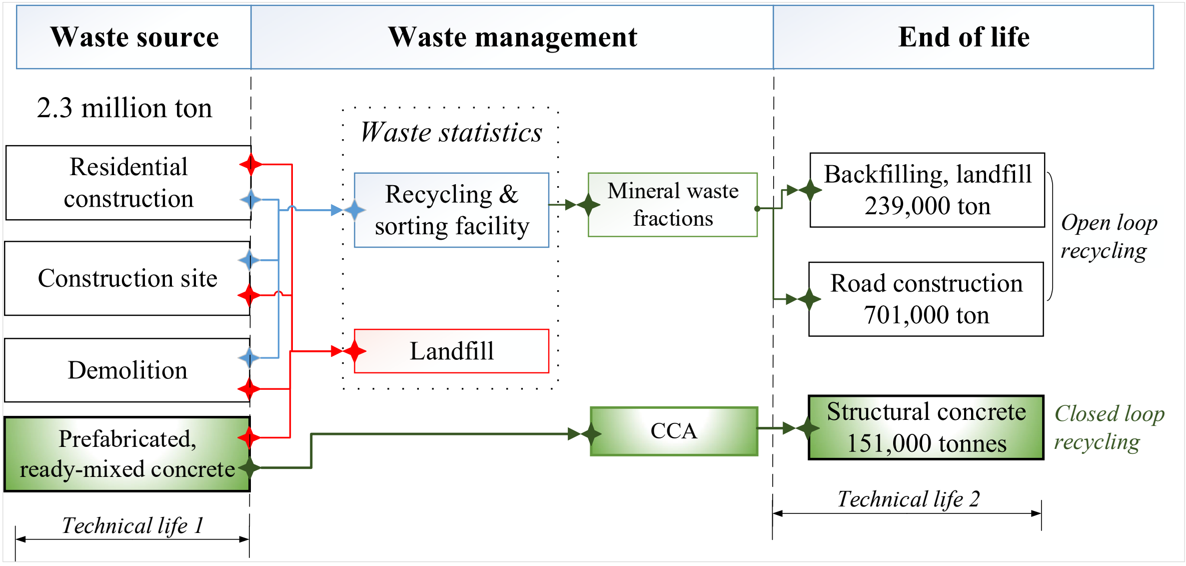

Figure 1.1 Concrete waste material flows in Sweden, 2018 [4]

In Sweden, the waste from construction and demolition relate to 2.3 million ton in 2018, originating from load-bearing structures and building foundations [3]. This waste is in its second technical life used for backfilling amounting to 239,000 ton and in road construction 701,000 ton according to statistics from the Swedish Environmental Protection Agency and Statistics Sweden [4]. Road construction is the major application field for concrete recycling in Sweden but realizes an open loop recycling in an un-bound form as an aggregate layer in road sections.

A second biggest waste source is the prefabricated and ready mix concrete giving a concrete waste of high quality with no contaminants such as bricks, tiles or other construction waste. Thus fulfilling the performance checks directly for structural applications. In this way, a closed loop recycling is realized and the concrete waste is introduced as crushed concrete aggregates (CCA) in structural concrete to an amount of 151,000 ton corresponding to only 6.3% of the concrete waste. The amount of concrete waste undergoing such closed loop recycling corresponds to the application of SS EN 206 in Sweden allowing 5% recyclable fine and coarse fractions from own production [5].

Mineral waste material from demolition has different characteristics compared to CCA from prefabricated concrete. Mineral waste quality is assessed according to specified environmental requirements and mechanical performance in un-bound applications. The CCA fractions from prefabricated concrete needs to undergo an evaluation of physical, mechanical and durability properties in order to fit structural concrete applications in a certain exposure class. Thus, CCA need to be assessed according to the aggregate standard SS EN 12620.

According to Swedish environmental goals, natural aggregates need to be preserved and replaced due to their importance in preserving drinking water resources; a common replacement at present is crushed rock aggregates [6, 7]. However, the crushed rock aggregate reserves around metropolitan regions are depleting due to major ongoing construction projects for instance, regions around Stockholm and Uppsala [8]. This requires concrete producers to source aggregates from longer distances, which increases the amount of transport related to material destinations, as reported in the study [8]. Thus, CCA become a more suitable alternative from environmental and technical standpoint compared to natural and crushed rock aggregates.

The availability of CCA of uniform quality is challenging in Sweden because source sorting is not mandatory. But even when such sorting is implemented, the Swedish branch-normative guidelines recommend concrete waste to be sorted as a mineral fraction combined with bricks, stones and asphalt which only increases the chances of CCA of varying quality [9]. The implementation of regulatory measures such as selective demolition would provide sorted CCA of uniform quality for use in structural concrete. This is challenging to implement due to the need of extra space for on-site sorting; thus severely increasing the total cost of processing construction and demolition waste [9, 10].

Control plans in the Planning and Building Act (PBL) in Sweden are focused on the reuse and recycling of non-hazardous construction and demolition waste/ products [11]. To ensure such reusability and recycling, source sorting of construction waste is necessary. Other examples of Swedish regulations improving the rate of concrete recycling are the taxation on landfill and taxation on the extraction of natural aggregates [12].

Concrete recycling is also encouraged by certification systems BREEAM (Building Research Establishment Environmental Assessment Method) and LEED (Leadership in Energy and Environmental Design). BREEAM encourages the use of recycled stone and gravel (aggregates) to reduce use of virgin raw materials. LEED allocates points for the content of recycled material in the concrete [13].

Societal claims on recycling of concrete are also mirrored in the revision of technical standards such as:

- SS137003, application standard to SS EN 206 concrete properties standard, allows up to 5% of the reclaimed concrete waste from own production to be recycled in new concrete without any additional testing. In its new revised form, this standard will allow for increased use of materials with reduced climate impact, such as recycled aggregates and supplementary cementitious materials.
- SS EN 1992 Eurocode 2 Design of concrete structures is being revised with a new information chapter on designing concrete structures with recycled concrete aggregates. It is proposed that up to 20% of the reclaimed concrete waste can be used as fine and coarse aggregate in structural concrete if the new concrete confirms to the parent concrete exposure class. Even higher amounts of replacements are allowed if both mechanical and durability performance are tested.

1.2 Objective

The objective of this research is to produce CCA concrete fulfilling the compressive strength and workability requirements of a reference structural concrete. The structural concrete investigated is an industrially active recipe where CCA replaces:

- **Fine and coarse aggregates** – shows closed-loop recycling, practically feasible with sufficient waste supply for continuous production of CCA; denoted CCA100.
- **Fine aggregates** – showing environmental considerations regarding exploitation of natural aggregates, practically feasible for less availability of waste; denoted CCA50.

This study adopts two main modification tools, densifying two phases of the concrete: aggregate (CCA) and cement paste, to produce a concrete fulfilling compressive strength and workability claims of the reference concrete at both 50% and 100% replacement ratios, figure 1.2.

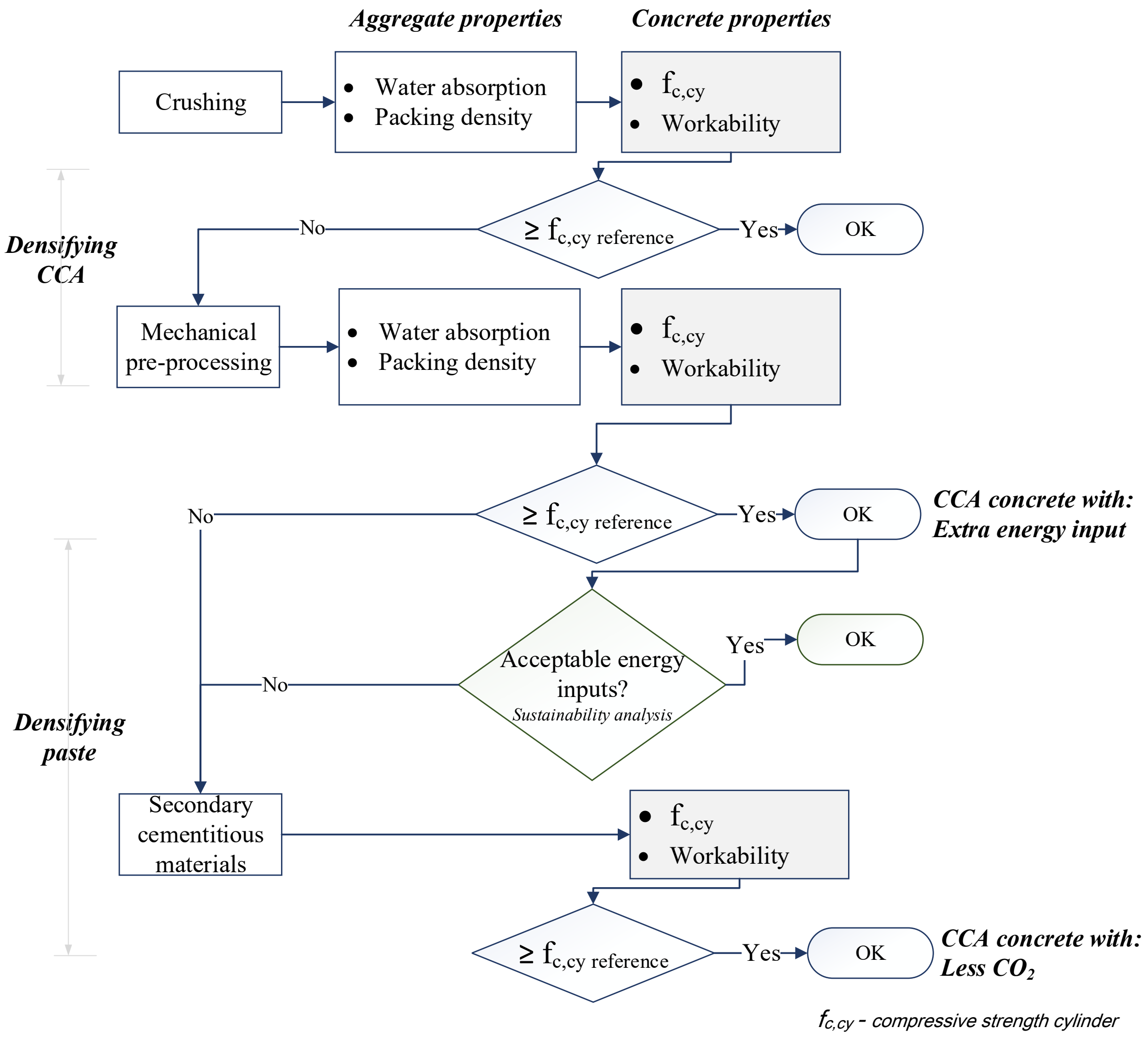

Figure 1.2 Study approach conceived for CCA50, CCA100

Minor objectives of this study are to illustrate the statistical significance of the improvements in CCA concrete compressive strength and briefly address the climate-related consequences arising from densification of CCA/paste.

Research questions

The main research question of this study is whether it is possible for CCA concrete to achieve the compressive strength and workability requirements of a reference structural concrete using test methods and infrastructure suitable for conventional concrete. This is to enable a smooth transition of replacing virgin aggregates (natural, crushed rock aggregates) with CCA in structural concrete, from a technical perspective. Related research questions to be answered in this study are:

1. Is it possible to reuse concrete waste from prefabricated elements in new structural concrete as a complete replacement of fine and coarse aggregate fractions?
2. Reference concrete demonstrates compatibility of natural aggregates as fine fraction with crushed stone as coarse fractions, can fine CCA produce a concrete similar to the reference when used in combination with coarse crushed stone fraction?
3. What techniques are needed for processing the CCA/ cement paste in order to achieve the required reference concrete strength and workability?
4. Identifying aggregate properties that are more significant for CCA compared to virgin aggregates and innovative techniques to measure such properties.

1.3 Concrete mechanical crushing towards CCA

Aggregates are crushed from parent rocks or excavated from gravel pits followed by sieving to classify the aggregates into specific size ranges or fractions based on their application requirements [14]. Commercial aggregate production follows a combination of primary, secondary and tertiary crushing stages included with sieving. With each stage there is a gradual size reduction, improvements in aggregate shape and removal of organic matter and other contaminants [15]. Generally, the primary crushing uses a jaw crusher for size reduction and particle size distribution; gyratory or impact crushers are used in the secondary and tertiary stages to resolve the aggregate shape to spherical and cubic forms especially in the case of crushed rock aggregates [7, 14, 15]. Aggregates suitable for concrete production are outputs from secondary and tertiary crushing with fine aggregates sieved out in the last stage [16].

The production of CCA for concrete application is similar to aggregate production concerning sequential crushing and sieving; differences are the complexity of separation and screening processes depending on whether the parent waste is solely hardened concrete or mixed construction and demolition waste (CDW). [17, 18]. The separation processes range from basic reinforcement separation in the case of concrete waste to the separation of materials such as wood, plastic, paper and gypsum found usually in mixed CDW which negatively influence concrete properties [19].

In this research, the prefabricated concrete is crushed in two stages to reduce to CCA fractions for substitution in the reference concrete recipe. Reinforcement separation occurs during primary crushing itself. A mobile crusher is used for the primary crushing to reduce the prefabricated concrete to rubble, which is capable of fitting into a lab-scale jaw crusher for secondary crushing. The coarse fractions are prepared first followed by a second stage of crushing to produce fine fractions. The CCA fractions are subsequently sieved suiting reference concrete aggregate fraction sizes. A comparison of workflows of CCA production in this research and the commercial production of aggregates from [16] are shown in figure 1.3.

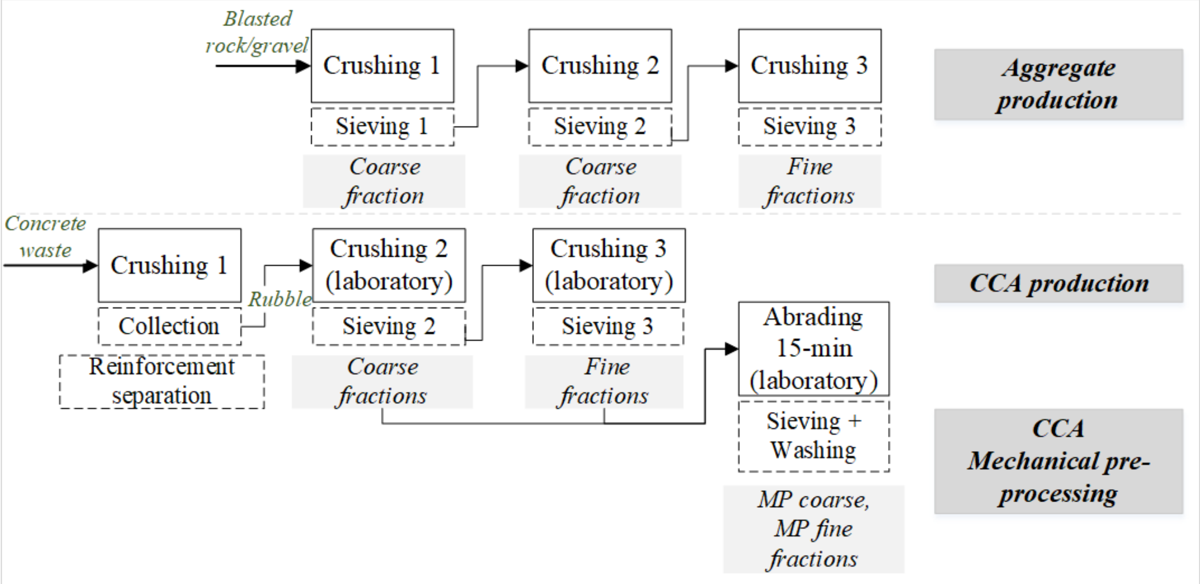

Figure 1.3 Production of aggregates [16], CCA

The crushing process influences CCA particle grading and water absorption [20], which are investigated and adjusted for before concrete mixing, measurements and methods in article 2. Similar to an additional step of crushing, a mechanical pre-processing on the CCA is performed in this study to densify the CCA, figure 1.3. This process is carried out by abrading coarse and fine CCA fractions separately in horizontal rotating drum for 15 minutes followed by washing on sieves, details in article 3. A mass balance of the pre-processed CCA indicates loss of aggregate material along with adhered mortar; requiring therefore adjustments in particle grading and water absorption measurements. Transport is not addressed in the figure 1.3 but is a process that has a considerably large carbon footprint, to be analyzed on an industrial scale using life cycle assessment tools.

1.4 Crushed concrete aggregates, CCA

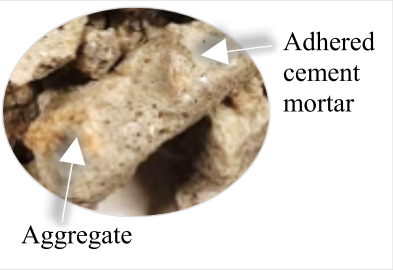

Figure 1.4
Adhered mortar on CCA

The CCA comprises of original aggregate surrounded by cement mortar physically attached to the surface of the aggregate [21-24], seen in figure 1.4. The adhered mortar is a remnant from the parent concrete that has undergone crushing. This contributes to CCA porosity, showing as lower density and higher water absorption than natural and crushed rock aggregates [25, 26]. The density of the adhered mortar depends on the strength of the parent concrete, CCA sourced from stronger concrete shows higher density [25, 27]. The adhered mortar content is seen to vary with CCA size; fines are shown to contain more adhered mortar than coarse fractions [21, 25].

Due to the negative effects on the fresh and hardened properties on the resulting concrete, the adhered mortar becomes the factor limiting the extent of CCA replacements in structural concrete [19, 28, 29]. For example, the Swedish standard SS 137003 limits the replacement of coarse CCA originating from concrete -type A to a maximum of 50% in structural concrete with exposure class X0, replacement percentages reducing further for more severe exposure conditions. Fine CCA fractions have the highest adhered mortar content, agreed upon by previous research [30-32], verified in article 3 of this research. Therefore standards limit the inclusion of fine CCA up to 5% in combination with coarse CCA, possible when the CCA belongs to the same concrete when acquired as spill or reclaimed from production [5].

1.5 Mechanical and durability aspects of CCA concrete

In this study, the concrete waste is used as aggregates in a new concrete, thus the standard requirements of SS EN 12620 have to be fulfilled just as for all other types of aggregates in concrete. Besides the physical and shape related properties of aggregate two mechanical properties of the fresh and hardened concrete are investigated workability and compressive strength respectively.

Investigated here is the feasibility for recycled concrete replacing 100% of all aggregates or as replacing the naturally graded aggregates in the reference concrete as fine recycled aggregates. In order to meet reference concrete strength and workability, a mechanical pre-processing is performed on CCA fractions and the secondary cementitious materials

(SCM) introduced in the recipe. Effectiveness of such modifications are assessed on resulting compressive strength and workability.

The starting point for the study is that the exposure class of the parent concrete is maintained through the waste management process into the new structural concrete. For an indoor concrete as in this study, the X0 exposure class - means that it is necessary to assess the durability aspects which are specifically related to recycled aggregates such as drying shrinkage due to aggregate porosity [33] and alkali-silica reaction (ASR) due to the alkalinity of the adhered mortar [34]. For higher exposure classes one may have to investigate carbonation, chloride and freeze-thaw resistance depending on the intended exposure class of the concrete. The durability aspects of CCA concrete are addressed by a literature study presented in article 4 of this thesis.

1.6 Limitations and disposition of the thesis

The results of this study are based on CCA acquired entirely from concrete waste fitting indoor application (X0). The parent concrete originates from an industrially produced prefabricated element, having undergone quality assessment routine after production and is therefore a more superior quality than concrete waste from demolition. The new concrete based on CCA is made to suit exposure class to X0.

This research is a feasibility study of using recycled aggregates in a structural concrete. The two main properties from structural concrete perspective are compressive strength and workability investigated in this study. Additional properties of interest are ASR and drying shrinkage relating specially to the alkalinity of adhered mortar and porosity of the CCA respectively. Possible changes in the physical properties of CCA are not investigated after the addition of SCM in the concrete.

Disposition of this thesis

- Chapter 2 addresses aggregate properties related to moisture and relates it to the properties of the CCA- addressed in article 2
- Chapter 3 addresses physical properties of the aggregate mostly influenced by the crushing process and is related to CCA properties , addressed in article 2;3
- Chapter 4 addresses properties of the concrete in relation to the replacement of CCA and improvements to CCA and cement paste; this is addressed in articles 2;3;4
- Chapter 5 addresses statistical analysis of compressive strength and sustainability analysis of SCM addition in concrete and mechanical pre-processing of CCA, seen in article 4

2 AGGREGATE PROPERTIES RELATED TO MOISTURE

Porous aggregates such as CCA have a high water absorption capacity compared to natural and crushed rock aggregates leading to inferior fresh and hardened properties of CCA concrete. The standard method for water absorption of aggregates is well suited for natural aggregates; however, it requires procedural modifications for a reliable water absorption measurement of crushed aggregates like CCA. This chapter discusses the modified pycnometer method and the water absorption results, based on article 2 and 3.

2.1 Moisture transport

Aggregates absorb moisture from the surroundings, influencing practical aspects related to concrete mixing such as the mixing water content. For example, moisture absorbed by aggregates when stored outdoors if not deducted from the mixing water content could lead to excess water in the concrete mix [14]. Similarly, when CCA encounters mixing water in an un-saturated condition it absorbs a part of the mixing water required for concrete workability [35].

Aggregate porosity

The porosity of the aggregate is the ratio of the added volume of the closed (V_c) and inter-connected pores (V_{ip}) to the total aggregate volume (V) shown in figure 2.1.

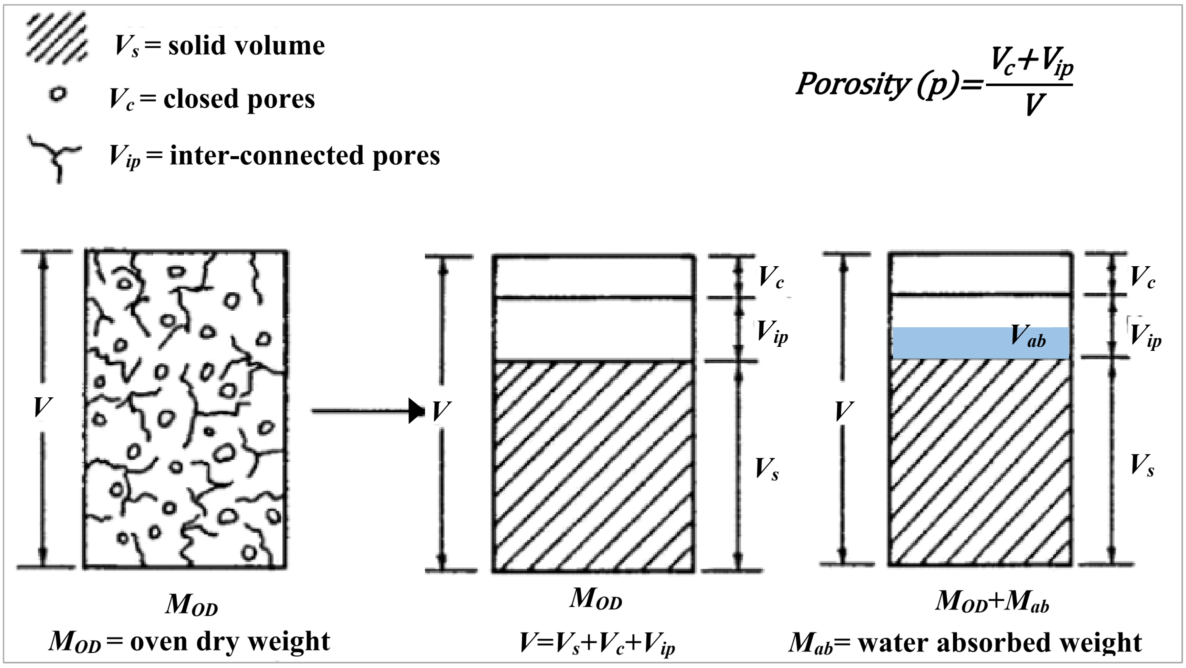

Figure 2.1 Schematic representation of aggregate porosity, according to [58]

When the aggregate contacts water, it is the inter-connected pores also called capillary pores, responsible for absorption and storing of the water occupying volume (V_{ab}) of capillary pores. The absorption of water brings an increase in aggregate weight by M_{ab}. Aggregates based on limestone and carbonates show a higher porosity in the range of 5-30% compared to denser granite based aggregates having 0.5-3.8% porosity; measured by the volume of inter-connected pores [14]. The solid volume in such natural and crushed rock aggregates is usually composed of a single material, the pores just being an absence of that material. The CCA originating from concrete is a composite consisting of an aggregate part and adhered mortar part, the latter usually more porous than the former resulting in CCA having higher porosity than natural aggregates or crushed rock [36].

Previous research claims that the density of the adhered mortar is dependent on the water/cement ratio of the parent concrete such that a stronger parent concrete leads to denser adhered mortar [21, 27, 37]. Such that the difference between reference aggregate and CCA density is not so significant [25]. Similarly seen in this research where the coarse CCA shows density of 2640 kg/m^3 whereas the reference crushed stone shows 2720 kg/m^3 respectively. CCA originating from demolition waste containing combination of different construction materials show higher porosity and lower density especially when larger share of ceramic materials such as tiles or bricks are included [36, 38].

Moisture transport mechanisms

The movement of moisture in a porous material happens by three main mechanisms, capillary absorption, diffusion and convection which are driven by differences in pore pressure, relative humidity, air pressure and temperature respectively [39]. Since CCA is enclosed by hardened cement mortar capillary absorption is more prevalent such that moisture is absorbed and transported through open and inter-connected pores within the aggregate [14, 40, 41]. This shows as high water absorption measurements of CCA leading to durability issues such as higher drying shrinkage than conventional concrete [42].

Moisture states in aggregate

Depending on the amount of moisture absorbed, the aggregates are characterized into four moisture states as shown in figure 2.2. By losing all evaporable water, aggregates reach oven dry state. Air dry when they are in equilibrium with the ambient moisture condition. Completely saturated aggregates dried on the surface are in saturated surface dry (SSD), moist on surface in addition to SSD implies wet aggregate [14, 43]. The inter-connected pores are filled with water in the last two states however; the closed pores are impermeable in all four moisture states.

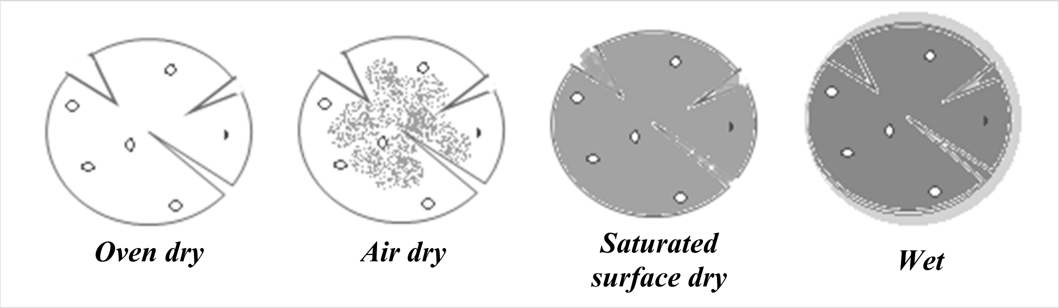

Figure 2.2 Common moisture states of aggregate

Aggregate density slightly changes corresponding to the moisture content. This influences the weighing of aggregates during concrete mixing and proportioning of concrete in cases where aggregates are to be mixed in at a certain moisture condition in the concrete [14].

2.2 Water absorption of aggregate

Aggregates are expected to be in SSD condition within the concrete to maintain a moisture equilibrium with the paste, this is important in the case of porous aggregates such as CCA, observed to destabilize this equilibrium unless they are saturated [44]. The amount of water required to bring an aggregate to SSD is shown by the water absorption of the aggregate calculated according to equation 2.1.

$$\text{Water absorption} = \frac{\text{Mass}_{\text{SSD}}-\text{Mass}_{\text{oven dry}}}{\text{Mass}_{\text{oven dry}}} \tag{2.1}$$

The mass at oven dry condition is a starting point from which the moisture absorbed by the aggregate to reach the SSD condition signifies termination of water absorption. This property is denoted as a ratio of aggregate masses at these different moisture states. By replacing SSD mass with mass values at other moisture conditions, one could determine the moisture content of the aggregate with reference to a known water absorption value. This is a common practice by industrial concrete producers to determine the excess water present in aggregates stored outdoors to be deducted from the mixing water content [14, 44]. Previous research on CCA shows it is sufficient to partly saturate the CCA to have a better control on CCA concrete workability [17, 45] by dosing this water as a pre-soaking process just before concrete mixing, results in better compressive strength especially for semi-saturated aggregates [46].

Pycnometer method

Water absorption of coarse and fine fractions are tested individually by immersing aggregates in a pycnometer containing distilled water for 24 hours to attain complete saturation. Aggregates are then wiped/dried down to SSD state; the water absorption is determined by the pycnometer method in SS-EN 1097-6, ASTM C128-15 [43, 47], pycnometer with aggregate samples, figure 2.3.

Figure 2.3 Aggregate water absorption using pycnometer

The SSD state for coarse aggregates is determined by wiping the surface of saturated aggregates with a semi-dry cloth until their surface appears dry. The procedure for fine aggregates requires oven drying for the particles to lose water held between each other. They are then pushed through a cone to form a slump. A collapsing slump with a definite peak and angular slopes indicate that aggregates have reached SSD, figure 2.4. This assessment criteria shows consistent results for natural aggregates due to their favourable shape and surface. The implementation of this criteria on crushed rock fines and CCA, which have a more angular shape and surface roughness, is highly operator dependent and shows inconsistent results [41, 48, 49]. SSD assessment of CCA shown in comparison to standard criteria, natural aggregate in figure 2.4.

Guidance on the SSD assessment of fine aggregates (SS EN 1097-6)

SSD assessment natural aggregate

SSD assessment CCA

Figure 2.4 SSD assessment criteria for fine aggregates

An imprecise measurement of water absorption for fine crushed rock ensuing such SSD assessment does not drastically affect the fresh properties of crushed rock concrete due to the low porosity. Especially in the case of granite-based crushed rock aggregates, used in Sweden [14, 50, 51]. In comparison to crushed rock, the water absorption of CCA can range between 0-12% depending on the adhered mortar content [21]. Therefore, a more reliable measure of water absorption is required so that the moisture equilibrium is maintained during concrete mixing. It is for this reason that alternative SSD assessment techniques are investigated in literature. Examples are evaporometry methods where the

CCA mass is continuously measured during the drying period, SSD is observed to occur with the flattening of the rate of drying [48, 49, 52]; centrifuging to release water from CCA surface [46] and drying coupled with centrifuging [53].

Another challenge with executing pycnometer test for fine CCA is when the fine particles settle down causing sedimentation of CCA due to the shape or potential hydration capacity of cement paste adhered to the fine CCA particles [54]. Previous research shows that this can be counteracted by pre-soaking CCA in particle dispersant solutions. For example, sodium hexa-metaphosphate [55] or by replacing the absorption medium being water, with a solution of sodium diphosphate [56].

2.3 Modified pycnometer method

This research carries out a modification of the pycnometer method in order to address the challenges for assessing the water absorption of CCA investigated at two replacement percentages CCA50, CCA100. The primary aim is to have a robust method, which is reliable, less operator sensitive and bridges the problems with assessment of water absorption of fine CCA, see workflow in figure 2.5.

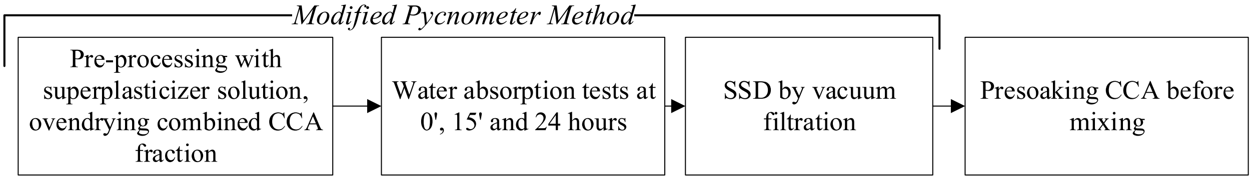

Figure 2.5 Workflow of modified pycnometer method

To identify the amount of water CCA absorbs during concrete mixing, this method tests a combined CCA fraction consisting of fine and coarse aggregates based on the adjusted grading after crushing or mechanical pre-processing of CCA. Combined fractions are prepared based on the CCA replacement scenario investigated, CCA50 combined crushed rock and fine CCA whereas CCA100 brings together both fine and coarse CCA fractions.

Testing combined fractions for the determination of apparent density and water absorption shows acceptable correlation of results with fractions tested separately, according to previous research [57]. This research validates the combined fraction by comparing the apparent densities of individual, combined CCA and reference aggregate fractions, results showing correlation, article 2.

Sedimentation of CCA particles observed while measuring water absorption in distilled water is mitigated by chemically pre-processing CCA using a particle dispersant solution of polycarboxylate based superplasticizer with distilled water (concentration of 6.35 g/L). The superplasticizer is the same as in the reference concrete recipe. To facilitate faster removal of excess solution and to start the CCA water absorption at a uniform base level, the pre-processed CCA is oven-dried at 110 ± 5 ° C before it is introduced in the pycnometer containing the superplasticizer solution.

To determine the water absorption development with time, measurements are made at 0 minutes, 15 minutes and 24 hours. The results show that 90% of the 24-hour water absorption happens in 15 minutes. This is consistent with previous research, which shows the ratio between 15-minute and 24-hour absorption to be between 80-90% [35, 55].

SSD assessment by vacuum filtration

Just as the standard method prescribes wiping to dry coarse aggregate surface, this research uses a technique that focusses on the removal of water from CCA surface by draining instead of oven drying. A vacuum filtration setup conducts draining when the contents of a pycnometer after concluding water absorption are poured into a funnel containing a filter paper (retaining 10 μm). The excess water is drained into a flask by vacuum generated from flowing water, filtration setup shown in figure 2.6.

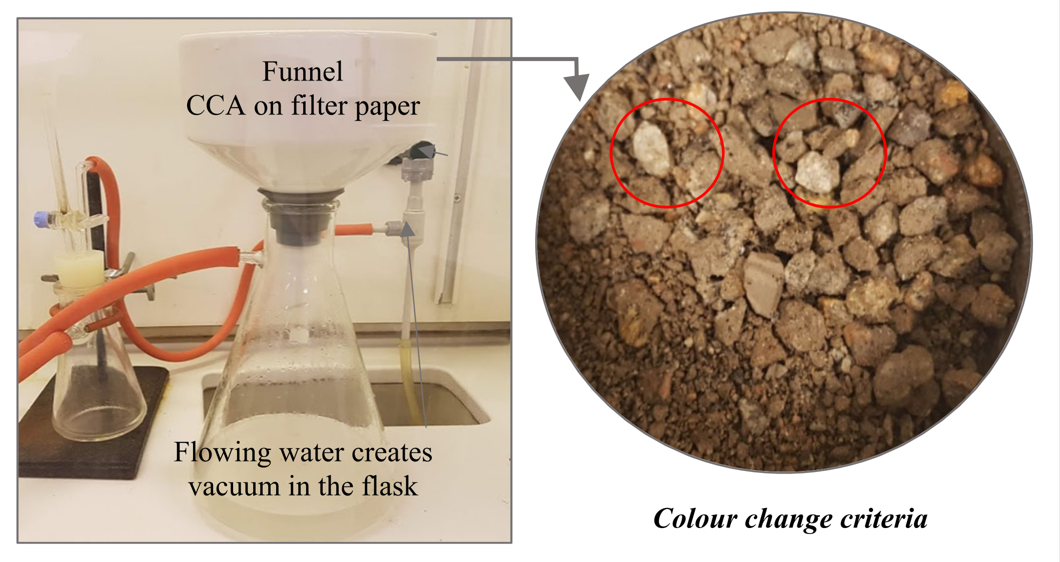

Figure 2.6 Vacuum filtration setup, Ocular assessment of SSD state for combined fraction – CCA100

This method gives ocular feedback in the critical moments when the coarse CCA loses surface water and starts changing colour on drying, seen in Figure 2.6. The sudden colour change in coarse aggregate is proposed as a criterion for SSD condition signifying termination of the filtration procedure and the end of the water absorption test. The colour change occurs repeatedly across different trials each made at 0 min, 15min and 24 hours; results are an average of three trials. The colour change criteria is a feature of the adhered mortar on CCA, in the case of CCA50 fractions containing crushed stone, a matte appearance similar to wiped saturated crushed stone is the SSD criteria. Therefore, the colour change criteria is objectively noticeable to the operator, and enhances the reliability compared to the standard method.

2.4 Pre-soaking water for CCA concrete

The water absorption development for combined fractions CCA50, CCA100 shows average of three specimens and standard deviations in the range 0.2-0.6% time durations 1min, 15 min and 24 h in figure 2.7. The general observation is that more than 90% of the 24-hour water absorption happens in 15 minutes. CCA50 shows lesser water absorption that CCA100 due to lesser over-all adhered mortar content since only the fine fractions are replaced with CCA.

Since it is known from literature that partially saturating the CCA by pre-soaking before mixing leads to better control on workability and increased compressive strength, the water absorption value at 15 minutes is used as a basis to presoak the CCA. Better control on workability and compressive strength is affirmed through casting trials when CCA is pre-soaked with 50% of the 15-min water absorption value for both CCA replacements. Since the pre-soaking is meant to saturate the aggregates, it is not accounted for in the water–cement ratio of the concrete mix.

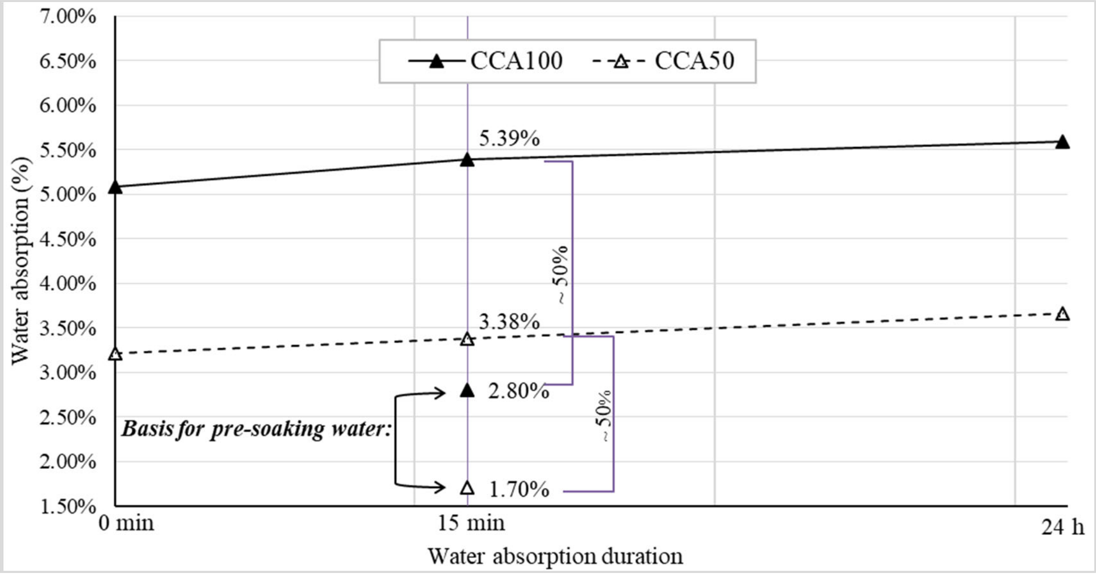

Figure 2.7 Water absorption development- CCA50, CCA100 combined fractions

Water absorption of mechanically pre-processed CCA

This study investigates CCA densification by mechanical pre-processing at durations 10 and 15 minutes, denoted MP10 and MP15 respectively. The adhered mortar content is shown to decrease with increasing pre-processing duration. The reduction in adhered mortar content reflects a general reduction in the 15-minute water absorption values of combined CCA fractions resulting from the pre-processing alternatives, seen in figure 2.8.

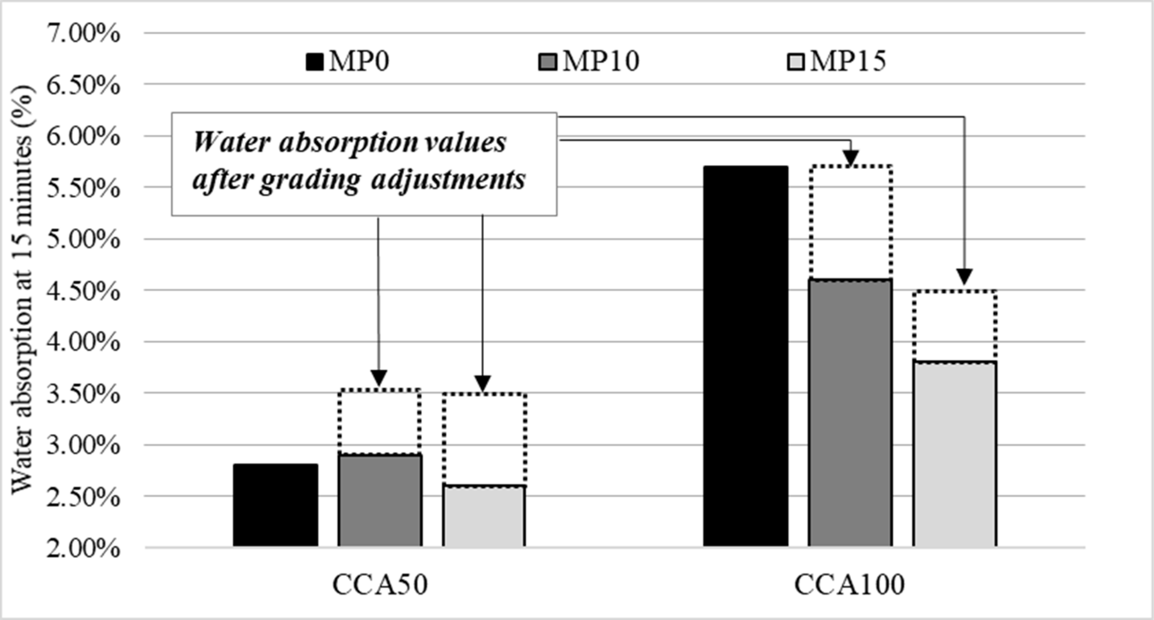

Figure 2.8 Water absorption at 15 minutes for mechanically pre-processed CCA

The CCA particle grading adjustments following pre-processing to match reference aggregate grading is achieved by increasing the proportions of fine CCA in the concrete mix. Increase in fine CCA proportion consequently increases the volume of adhered mortar in the combined CCA fraction, which is seen to counteract the reduction in water absorption from CCA densification, dotted lines in figure 2.8.

From casting trials it is seen that the pre-soaking water amount can still be controlled as the same as before mechanical pre-processing resulting in CCA concrete with workability and strength comparable to reference concrete.

3 PHYSICAL PROPERTIES OF AGGREGATES

This chapter highlights the physical properties of aggregate investigated in this research identified to be of importance to concrete compressive strength and workability. The improvements on these properties induced by mechanical pre-processing and by coating with cementitious materials, workflow in figure 3.1, are discussed in this chapter. The results are based on article 3 and partly article 4.

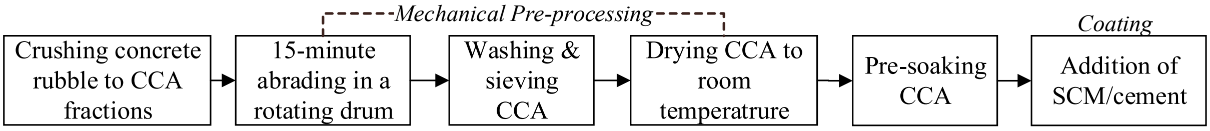

Figure 3.1 Workflow showing mechanical pre-processing and cementitious coating on CCA

3.1 Density and unit weight

The density also called particle density, describes the density of the aggregate material while unit weight is the aggregate density measured in bulk; both these properties are measured separately for coarse and fine aggregates [14]. Higher particle density results in higher unit-weight. These properties are of practical importance in the volumetric proportioning of concrete as they can indicate the weight of aggregates as particle or bulk for filling up a certain volume [58]. Based on the particle density, aggregates are classified as normal, light and heavy weight aggregates suiting concrete with different applications [14].

Aggregates from crushed rock usually have a higher density than gravel and natural aggregates obtained from glacial river sediments [6]. The density of CCA lies in between natural aggregate and crushed rock. For example in this research, the density of the coarse CCA fraction is 2640 kg/m^3, the reference coarse aggregate that is a crushed stone is 2720 kg/m^3 whereas a natural aggregate of limestone of the same fraction size is 2630 kg/m^3 [59].

Density investigated by pycnometer method

Aggregates being granular require indirect methods for volume assessment for the determination of density, for example liquid displacement methods [60]. The relevant standard SS-EN 1097-6 prescribes a hydrostatic weighing procedure for aggregates larger than 31.5 mm, where aggregate volume is determined from the volume of water displaced by immersion of aggregates in a water filled container. Since the maximum size of aggregates in this study is 11.2 mm, the pycnometer method prescribed by the standard is pursued [43].

The aggregate volume ($V_{aggregate}$) is determined by taking a sample weighed in air (M_{air}) and submerging it in a pycnometer filled with water for 24 hours, to ensure that water occupies all available volume. The mass of submerged aggregates ($M_{submerged}$) is the difference in mass of the pycnometer filled by aggregate and water from pycnometer filled only with water. The aggregate volume is determined from the mass of displaced water related to water density, shown by equation 3.1.

$$V_{\mathrm{aggregate}} = \frac{M_{\mathrm{air}} - M_{\mathrm{submerged}}}{\rho_{\mathrm{water}}} \tag{3.1}$$

Therefore, the density of aggregates from the pycnometer test is calculated by equation 3.2. The aggregate sample measured in air is usually in oven-dry condition for a mass unaffected by moisture content.

$$\rho_{\mathrm{apparent}} = \frac{M_{\mathrm{oven-dried\ aggregate}}}{M_{\mathrm{oven-dried\ aggregate}} - (M_{\mathrm{pycnometer+water+aggregate}} - M_{\mathrm{pycnometer+water}})} * \rho_{\mathrm{water}} \tag{3.2}$$

The apparent density measures aggregate volume excluding capillary pores and is not related to a specific moisture condition of the aggregate [14]. Apparent density is seen to be used as a proxy for aggregate strength to calculate aggregate elastic modulus [61] and is used in this research to evaluate CCA densification by mechanical pre-processing.

Besides apparent density, the aggregate density is measured at saturated-surface dry (SSD) condition firstly because this reflects the moisture condition of aggregates in fresh concrete. The second reason involves practical considerations such as the outdoor stockpiling of aggregates causing them to accumulate moisture. The SSD density in this case takes into consideration the density of such aggregates saturated with water; also determined by the pycnometer method calculated by equation 3.3.

$$\rho_{\mathrm{SSD}} = \frac{M_{\mathrm{SSD}}}{M_{\mathrm{SSD}} - (M_{\mathrm{pycnometer+water+aggregate}} - M_{\mathrm{pycnometer+water}})} * \rho_{\mathrm{water}} \tag{3.3}$$

This study investigates the apparent density of CCA even though the SSD density is most suitable as it more closely represents the partly saturated condition of CCA just before concrete mixing brought about by pre-soaking. However not pursued due to the challenges in achieving SSD state for fine CCA. The outdoor accumulated moisture is accounted by testing and adjusting the mixing water for this extra amount of water.

The density is an important property for CCA as it denotes CCA quality in comparison to the reference therefore influencing aggregate strength and consequently the compressive strength of concrete. The CCA density changes with adhered mortar content. For example the adhered mortar content on CCA after crushing is removed with mechanical pre-processing [38] leading to an increase in CCA density. This difference is seen distinctly for low-density aggregates <2000 kg/m^3. On the contrary, coarse CCA in this study has comparatively higher density, 2640 kg/m^3 and on pre-processing shows slight decrease to 2621 kg/m^3. This indicates that along with loss of adhered mortar pre-processing also leads to a loss of aggregate material.

Unit weight

Unit weight or bulk density, determines the density of aggregates in a bulk form occupying a certain volume; measured both in compacted and loose condition. Unit weight increases with a denser packing of aggregates which is a combined outcome of shape, grading and surface texture [14]. Natural aggregates such as gravel having rounder shapes despite lower particle density always show higher unit weight than crushed rock aggregate, due to better packing consequent of shape and texture [62]. However, the unit weight of crushed rocks is more influenced by the particle density than aggregate packing. This is because crushed aggregates have a rougher texture and more irregular shape than natural aggregates, which influences aggregate packing.

The apparent densities of the reference coarse aggregate of crushed stone and coarse CCA are 2720, 2640 kg/m^3 respectively. The corresponding unit weights are 1486 kg/m^3 for crushed stone compared to coarse CCA - 1249 kg/m^3 even if CCA has lower flakiness index than crushed stone.

In this study unit weight is measured in loose condition in order to assess improvement in CCA shape and grading due to mechanical pre-processing which results in an increase in unit weight. The unit weight of the coarse CCA after mechanical pre-processing increases to 1336 kg/m^3 also shown for other CCA fractions in table 3.1. Increase in unit weight signifies improvements in shape, grading and density of CCA fraction as additionally confirmed by tests on flakiness index, particle grading, reported in article 3.

Table 3.1 Unit weight of reference aggregate and CCA fractions for different processing alternatives (kg/m³)

Aggregate fractions (mm) / Processing alternatives	0/8	8/11.2	0/4	0.5/4	8/11.2
Reference	*1837*	*1486*	-	-	-
Crushing	-	-	1475	1263	1249
Crushing, mechanical pre-processing	-	-	1464	1299	1336

The un-compacted unit weight of aggregate fractions is the basis for evaluating the packing density of aggregates. It is used to assess improvements in the physical and geometric properties of crushed rock aggregates to optimize concrete strength and workability [63, 64]. Similarly, this research uses the packing density calculated from unit weight as a bridging property connecting the collective aggregate strength with concrete compressive strength.

3.2 Adhered mortar content

The cement mortar belonging to parent concrete still adhered to CCA after crushing, is the most porous part of the CCA lowering density and increasing water absorption of CCA. Thus negatively influencing the mechanical properties and workability of CCA concrete [19, 29]. Previous research shows abrasive methods for adhered mortar removal using mechanical [38, 65], thermo-mechanical [66], and chemical treatments by acid dissolution [67] resulting in a densified CCA. This results in compressive strength improvements in the range of 6-15% in CCA concrete [20, 38]. Besides the removal of adhered mortar, these methods have an abrading effect on the aggregate part of CCA leading to a loss of aggregate/material [20, 62].

The thermal shock experiment is used to determine the adhered mortar content on aggregates. This is done by heating up aggregates pre-soaked in water to 500 °C and inducing a thermal shock by instantaneously immersing it in 20°C water to displace the adhered mortar. The aggregate sample is weighed before and after the experiment to determine the loss percentage [21].

Since this study finalizes the 15-minute mechanical pre-processing of CCA fractions followed by washing on sieves, there occurs a loss of both material and mortar, assessed in this research by material mass balance. As the mechanical pre-processing of reference aggregates leads only to material loss, the actual amount of adhered mortar removed from CCA by mechanical pre-processing is the material loss in reference aggregates deducted from the CCA loss, shown in equation 3.4.

$$adhered\ mortar\ loss_{fraction} = \frac{CCA_{loss\%} - reference\ concrete\ aggregate_{loss\%}}{reference\ concrete\ aggregate_{loss\%}} \tag{3.4}$$

Mass-balance checks that the adhered mortar losses are occurring mainly from mechanical pre-processing and just marginally from washing and sieving processes. Mass balance is made individually for each CCA and reference aggregate fraction in three stages:

1. Thermal shock before pre-processing to assess the potential loss of material and adhered mortar.
2. Losses by mechanical pre-processing to assess the actual material and/or adhered mortar loss
3. Thermal shock after pre-processing to determine the remaining material and adhered mortar left on the aggregate.

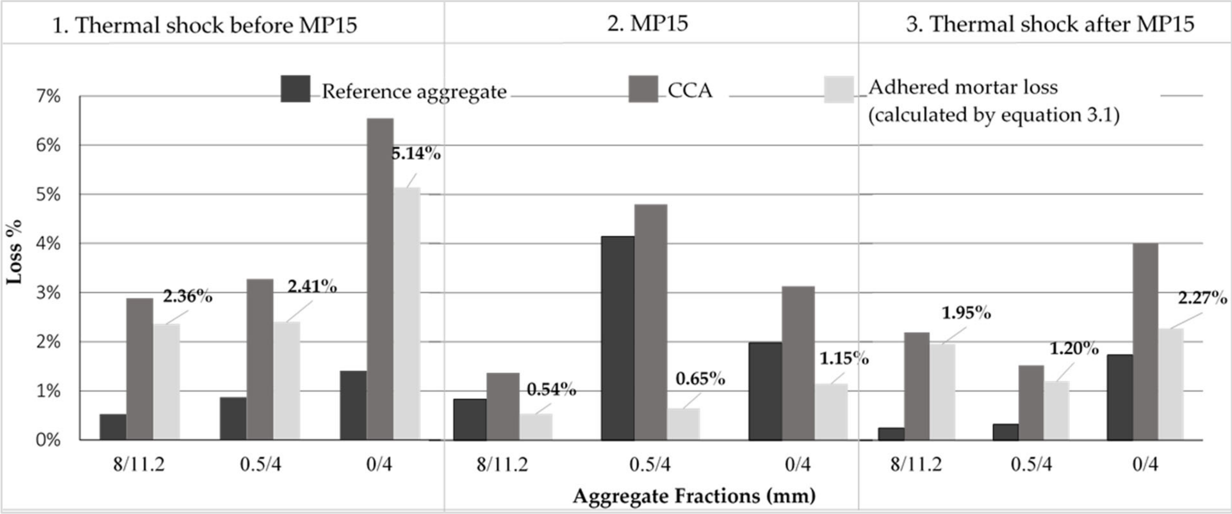

Figure 3.2 Adhered mortar loss by mechanical pre-processing

Mass balance for a coarse aggregate fraction 8/11.2 mm shows 2.36% actual adhered mortar loss given by thermal shock before pre-processing, Figure 3.2. With mechanical pre-processing of 15 minutes, MP15 including washing and sieving operations, a loss of 0.54% is measured. The final thermal shock shows 1.95% loss of mortar, which is the remaining adhered mortar on the CCA after pre-processing. The total mass balance for fraction 8/11.2 occurring in these three stages has an error of 0.13%, arising mostly from washing and sieving. The mass balance errors for fractions 0.5/4 and 0/4 mm are 0.5% and 1.7% respectively. The sum of the loss from mechanical pre-processing and thermal shock from stage 3 exceed by small margins the losses from thermal shock before pre-processing thus validating mechanical pre-processing and related processes to give reliable results on the adhered mortar loss.

The 0/4, 0.5/4 mm CCA fractions have higher adhered mortar content compared to coarse fraction, as shown in literature [30] and result in the most adhered mortar loss by mechanical pre-processing. The reduction in adhered mortar content is seen as improvements in the water absorption and density of CCA, resulting in compressive strength and workability comparable to reference concrete.

3.3 Properties related to aggregate shape

This sub-chapter discusses aggregate shape assessment by flakiness index and its influence on volume of voids when the aggregates are packed in an un-compacted condition. Flakier aggregates show higher void content, therefore require a larger volume of cement paste to show similar workability like rounded aggregates [62, 64].

There are very few instances in literature related to concrete recycling, where characterization of CCA shape is undertaken. Investigations on aggregate shape and their influence on concrete properties are seen to be more prevalent in the case of crushed rock aggregates. Investigation of aggregate shape improvements with different crushing methods is integrated in the production of structural concrete with crushed rock aggregates [64]. In the same way, this study assesses CCA shape improvements resulting from mechanical pre-processing, to make similar claims of shape properties on CCA as on crushed rock aggregates.

Flakiness index

Flakiness index (FI) is the proportion of flaky particles in an aggregate sample measured as a mass percentage of aggregates passing through harp sieves of specific sizes [14]. The standard methods such as SS-EN 933-3 [68] determines the FI solely for coarse aggregates, however, FI of fine crushed rock (till 1mm) is determined by a method with harp sieves of smaller slots following the standard method in principle, figure 3.3. This method was developed as a part of a project for proportioning concrete using crushed rock as aggregates as fine aggregates [69, 70]; used in this research to determine the FI of fine CCA.

Figure 3.3
Flakiness of fine aggregates

FI is seen to be the least in natural aggregates such as gravel and highest in crushed rock aggregates of granite; flakiness of CCA shows an in-between value [62]. Similar observation is made in this research where the coarse CCA shows lesser FI than reference crushed stone, 10.4% and 18.3% respectively. The FI of fine CCA fraction is 5.06%, which is more than the naturally graded aggregate, 4.7%.

Previous research shows that by subjecting CCA to multiple crushing stages it acquires an improved shape similar to reference aggregates [71, 72]. This study performs 15-minute mechanical pre-processing after crushing for both fine and coarse CCA separately. It is observed that the abrading effect of pre-processing modifies CCA shape in addition to dislodging adhered mortar; as a result, the FI of fine CCA gets closer to reference natural aggregate, table 3.2.

Table 3.2 Flakiness index and void content of aggregate fractions (mm)

Aggregate Fractions (mm) / Processing alternatives	Flakiness index (%)					Void content (%)				
	0/8	8/11.2	0/4	0.5/4	8/11.2	0/8	8/11.2	0/4	0.5/4	8/11.2
Reference	*4.7*	*18.3*	-	-	-	*32*	*44.4*	-	-	-
Crushing	-	-	5.06	3.4	10.4	-	-	45.6	53.6	52.7
Crushing, mechanical pre-processing	-	-	4.7	3.5	6.2	-	-	44.8	48.5	49

Void content

The void content is measured in un-compacted condition together with unit weight for the indirect assessment of aggregate shape. Previous research related to crushed rock aggregates use the void content to determine amount of rock filler required to fill in the voids formed between irregularly shaped rock aggregates to bring improvements in workability [64, 73]. This research uses void content to assess improved aggregate shape after mechanical pre-processing. The shape improvements are noticed indirectly as reductions in the void content due to improved aggregate packing in a unit volume, table 3.2.

Void content is the least when the flakiness index is exceptionally low as in the case of natural gravel. Despite CCA having lower FI than crushed rock/stone the void content is still larger than the latter [62]. Similar observations are made in this study that improvements in flakiness alone are not sufficient to bring same void content as reference aggregates, especially for the fine aggregate fraction. Differences in particle surface and grading of CCA may also lead to the creation of voids which if improved will increase the packing density of aggregates benefitting concrete strength and workability.

Reductions in FI and void content, by mechanical pre-processing, show increased aggregate packing density leading to better concrete compressive strength. The concrete with 100% CCA reaches reference compressive strength, while 50% CCA concrete exceeds reference strength. The workability of CCA concrete at both replacements is seen to be within the same flow class, F2 as the reference concrete.

3.4 Particle grading

The quantitative distribution of particles based on their size in an aggregate fraction is the particle size distribution of that fraction, represented graphically by a grading curve [14]. It is experimentally determined for fine and coarse fractions separately, by a sieve analysis. Aggregate samples are shaken on a sieve column arranged by descending size order and the quantity staying on each sieve is weighed as a percentage of the total quantity. The distribution of staying quantities is converted to a cumulative grading curve, showing the percentage of particles passing each sieve opening. This is followed by commercial concrete producers and used in this study [74-76].

The particle grading influences the void content formed between aggregates; a continuous grading with equal proportions of differently sized particles ensures dense packing as well as particle mobility required for workability [14, 76]. The reduced voids formed by such grading demands less cement paste to fill such voids resulting in an economized mix showing considerable workability [14, 63]. Therefore, every concrete recipe has a specific grading shown by a combined grading curve, by which the aggregates are controlled regularly to ensure consistent quality of commercially produced concrete [77].

The production process, crushing, influences the grading of aggregates as in the case of crushed aggregates, showing different grading from natural aggregates [50, 65, 78]. Thus, fine CCA shows different grading from reference natural aggregate, seen for 0/8 mm CCA fraction in this study, figure 3.4a.

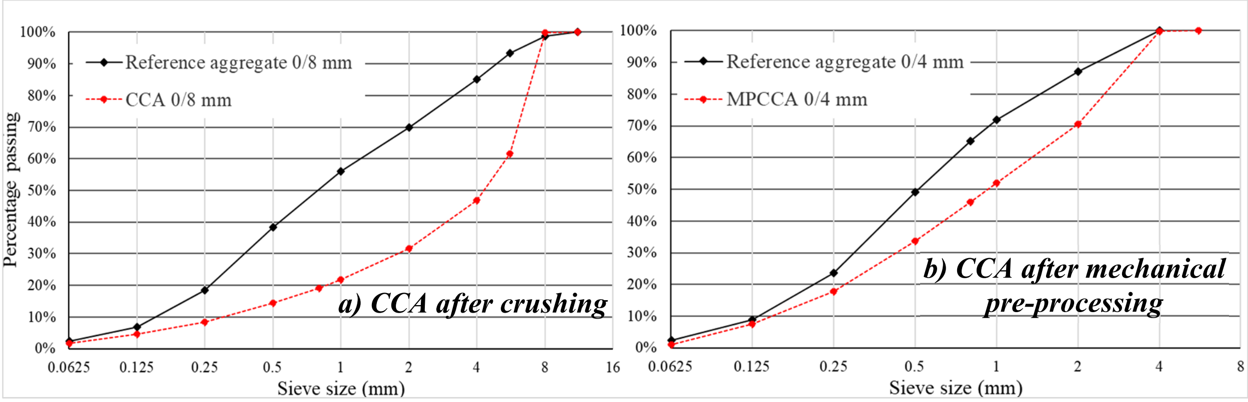

Figure 3.4 Particle grading from CCA production a) after crushing b) after mechanical pre-processing

The reference aggregate is a naturally graded aggregate of fluvial/glacial origin showing continuous and even grading resulting from weathering of rocks [14]. The CCA particle grading is adjusted to match the reference grading to achieve workability like the reference concrete by a gap-grading. Here the 0/8 mm CCA fraction is changed to 0/4 and 0.5/4 mm with proportions adjusted to match reference grading, CCA100 curve in figure 3.5.

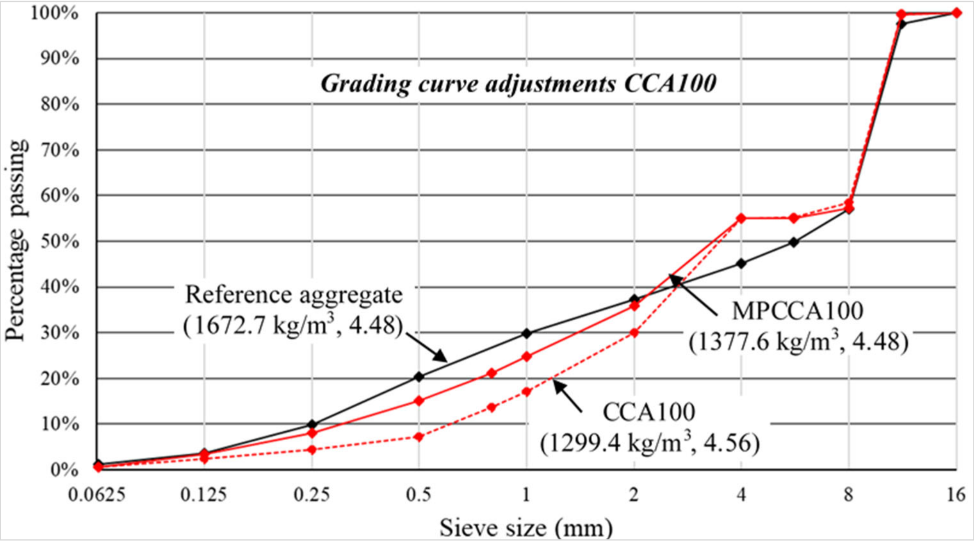

Figure 3.5 Combined grading curves CCA100 (packing density, fineness

Similar grading adjustments are required after mechanical pre-processing which results in the partial breaking down of particles causing the CCA grading curve to move away from the reference aggregate, shown for 0/4 mm fraction in figure 3.4b. The CCA grading curve is adjusted by increasing the proportion of the fine CCA fraction 0/4 mm; combined CCA grading curve MPCCA100 shown in figure 3.5.

The packing density is clearly influenced by particle grading and increases in magnitude as the CCA grading curve comes closer to the reference-grading curve, which has the highest packing density, see figure 3.5. This result is in accordance to the fundamental relationship by Fuller-Thompson, which shows that the ideal grading curve is the one with least void content, inversely highest packing density [79].

Fineness modulus (FM)

This study uses fineness modulus – a unit-less numerical parameter that characterizes a grading curve, to evaluate the CCA and reference aggregate grading curves [14, 80]. The fineness modulus is calculated by adding up the cumulative percentages of samples retained on each sieve up until sieve 125 µm and dividing the result by a 100 [14, 81]. Standard procedure recommends FM for fine aggregates; this research calculates FM for the combined coarse and fine CCA fraction to have control the combined grading.

In this study, the FM is seen to progress closer to reference aggregate value after every grading adjustment. The FM tested directly after crushing is 5.38; after first adjustment is seen to come closer to reference concrete with value 4.56, figure 3.5, article 2. The final grading adjustment after mechanical pre-processing leads to CCA100 aggregates showing FM 4.48, same as reference concrete.

Besides being a theoretical parameter the importance of FM is also noticed experimentally such that grading curves with similar FM require the same amount of water to produce mix of same workability [14, 44, 80]. The rule on FM and workability is actual in this study, where the CCA concrete mixes especially CCA100 after mechanical pre-processing results in flow diameter 377 mm, the reference concrete showing 380 mm with the same mixing water content, results in article 3.

3.5 Packing density

The aggregates cover a large volume among concrete mix constituents and contribute to concrete strength by the formation of a dense framework supporting the paste. For any composite material, this framework is a dense arrangement of differently sized aggregates enclosing an optimum void content to be filled by paste [63, 82, 83]. A higher packing density means a higher solid volume leading to higher compressive strengths [14, 84]; however, an optimum void content is required so that there is sufficient cement paste to cover all aggregate surfaces to ensure workability suitable to structural concrete [64]. Packing density is investigated as a weighed sum of the individual unit weight of fine and coarse fractions tested separately. In other words, unit weight is a similar property to packing density except it measures aggregate fractions separately [63, 85].

A dense packing of aggregates is jointly contributed by aggregate shape, grading, density and unit weight [14, 82, 86]; mechanical pre-processing in this research influences these properties based on the pre-processing duration investigated, 10 and 15 minutes. A comparison of the effects of pre-processing duration on CCA properties is seen in article 3. The packing density, which is jointly influenced by all these properties, is seen to increase with increasing pre-processing duration showing corresponding improvements in concrete strength and workability for both CCA replacement ratios, see figure 3.6.

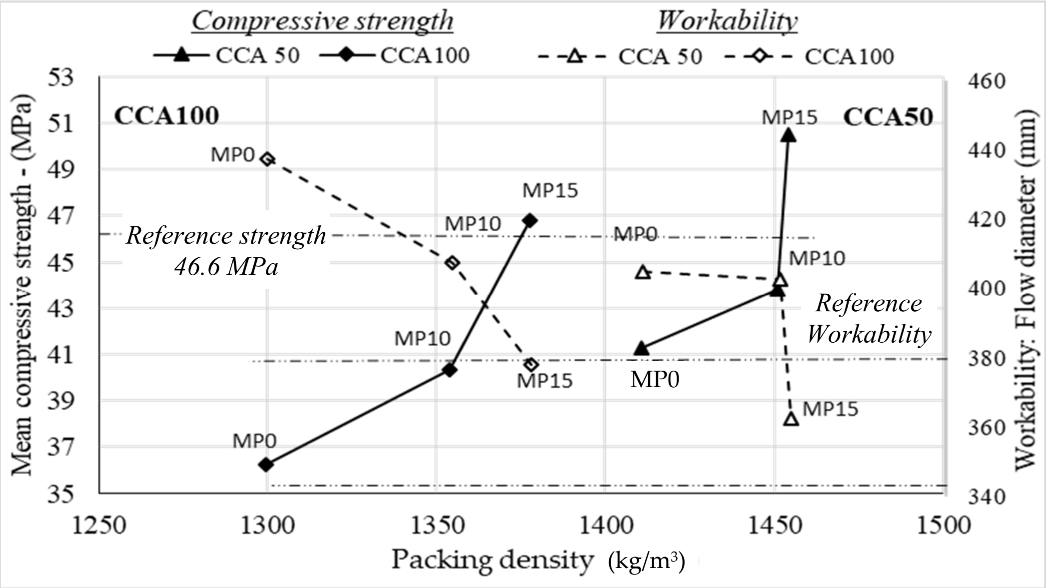

Figure 3.6 Packing density of aggregate related to concrete compressive strength and workability

The compressive strengths values in figure 3.6 represent an average of three specimens whereas the workability stands for a single sample. MP0, MP10 and MP15 refer to pre-processing alternatives such as no preprocessing, 10-minute and 15-minute pre-processing respectively.

Since the CCA packing density related to concrete compressive strength and workability, it maybe used as a quality assessment index in addition to physical properties like particle density and water absorption. The packing density could be used to check the physical compatibility of CCA for a certain structural concrete.

4 PROPERTIES OF RECYCLED CONCRETE

This chapter discusses the compressive strength and workability of concrete resulting from:

- the replacement of aggregates with CCA
- densification of CCA by mechanical pre-processing
- densification of paste with secondary cementitious materials (SCM)
- added effect of densification of CCA and paste

4.1 Replacement of aggregates

This research investigates two CCA replacement scenarios in the reference concrete recipe, replacement of fine aggregates, denoted CCA50 and the overall replacement of fine and coarse aggregates, CCA100.

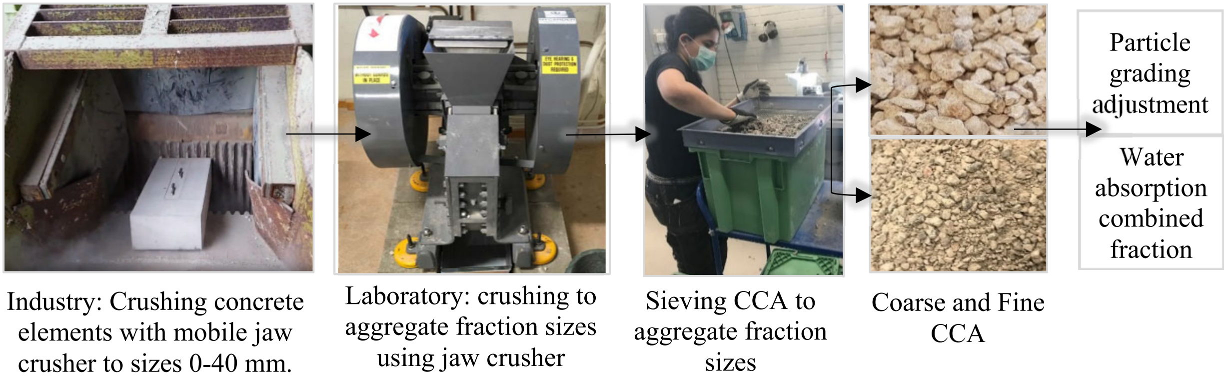

Figure 4.1 Production process of CCA for 50% and 100% CCA replacements

CCA is produced from prefabricated concrete waste by two-stages of crushing using jaw crushers, first at the industry location and then at the laboratory. The CCA fractions are prepared by sieving, figure 4.1. As a rule, the particle grading adjusted to nearly match reference concrete aggregates, water absorption measurements by modified pycnometer method are conducted to determine the pre-soaking water added before concrete mixing.

4.2 Mechanical pre-processing of aggregates

With the goal of adhered mortar removal, improvements to physical properties and packing density of CCA, mechanical pre-processing is pursued as shown in figure 4.2. Besides abrasion of adhered mortar, partial breaking down of aggregate particles occurs resembling a mild crushing process. Therefore, particle-grading adjustments along with re-assessment of water absorption is done following pre-processing.

Figure 4.2 Mechanical pre-processing of CCA for 50% and 100% CCA replacements

4.3 Cement and cement replacement

The hydration reaction between Portland cement clinker and water leads to the formation of cement-gel, which is the densest part of hardened cement paste imparting strength to concrete. The cement clinker is made up of calcium silicates (C-S) occurring as compounds C_3S and C_2S forming calcium silicate hydrates (C-S-H) on hydration also called cement-gel, equation 4.1 [44, 87, 88].

$$\text{C-S} + \text{H} \rightarrow \text{C-S-H} + \text{CH} \qquad \textit{Hydration of Portland cement} \quad (4.1)$$

In addition to the formation of cement-gel, calcium silicate undergoes hydrolysis to release calcium hydroxide, denoted as C-H in equation 4.1. The calcium hydroxide presents the opportunity for further densification of cement paste when SCM (S) is introduced together with Portland cement in concrete. The SCM in combination with calcium hydroxide produces hydration products similar to Portland cement such as cement gel leading to cement paste densification [89], equation 4.2.

$$\text{CH} + \text{S} + \text{H} \rightarrow \text{C-S-H} \qquad \textit{Pozzolanic reaction} \quad (4.2)$$

On the basis of reactivity SCM is classified as latent hydraulic such as blast furnace slag (GGBS) and pozzolanic such as fly ash, silica fume and activated glass powder [90]. The reaction of latent hydraulic SCM is triggered by increased alkalinity in pore water due to the dissolution of calcium hydroxide. Whereas pozzolanic materials chemically combine with calcium hydroxide (C-H) to produce hydration products [89].

As the pozzolanic reaction involves calcium hydroxide implies that the strength development from pozzolanic reaction is delayed till sufficient calcium hydroxide is produced [44]. Generally, pozzolanas react 3-14 days after mixing with water, this dormant period lasting until sufficient alkalis are dissolved in the pore solution to increase the pH to required level. Unlike pozzolanas, GGBS is reactive without Portland cement requiring just alkaline activators, and can therefore form a major portion of binder content [91].

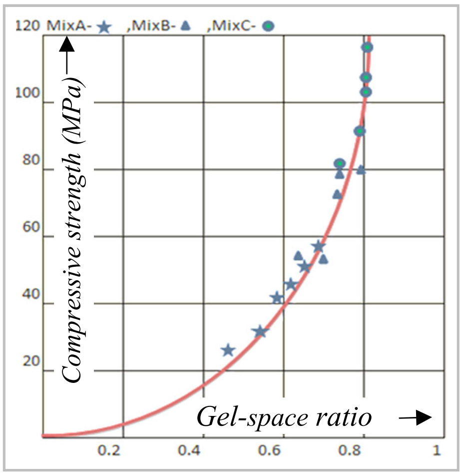

Figure 4.3 Power's relation between compressive strength and gel-space ratio [97]

The goal with SCM addition is to increase the strength of CCA concrete to meet reference concrete strength by the densification of cement paste. The cement paste is densest in the cement gel, the capillary pores formed by unbound water contribute largely to the porosity of the cement paste [41, 44]. The effects of SCM combined with cement may replace parts of capillary pore volume with denser hydration products such as cement gel, leading to the overall densification of the paste. This results in a denser and stronger concrete at the same water/binder ratio as reference concrete [92-94]. In theory, the **gel-space ratio** describes the volume of cement gel to the total volume of hydration products including capillary pores, is directly proportional to the compressive strength of concrete shown by Powers, [95, 96], relation in figure 4.3. A more recent research has validated this relationship to justify compressive strength improvements occurring with binary and ternary combinations of SCM and cement [94].

Along with paste densification, SCM with large fineness such as silica fume and GGBS contributes to the strengthening of interfacial transition zone (ITZ) between aggregate and paste [97, 98]. Validated by microscopic imagery in the respective studies [97, 99, 100]. Densification of the microstructure between aggregate and paste is shown to improve mechanical properties of conventional and CCA concrete due to better transfer of stresses between paste and aggregate [97, 99]. Such effect is referred in literature as micro-filler effect and is implemented by surface coating treatments on CCA [97]. Also by mixing methods with stage-wise addition of mixing water to pre-wetted CCA mixed with SCM [101].

The capacity of an SCM to densify cement paste depends on its reactivity, characterized by the glass content, fineness and reactive oxide content of the SCM. Glass content is a feature of an amorphous substance, usually representing a molten material [102]; fineness measured by specific surface is an indication of SCM reactivity and the potential for micro-filler effect [97, 103]. The reactive oxide contents describe composition of three main oxides CaO, SiO_2 and Al_2O_3 making up the four main calcium silicate and aluminate compounds of cement [104, 105].

The SCM investigated in this study is commercially produced GGBS and activated glass powder (GP) produced from the milling of container glass waste, reactivity parameters shown in table 4.1.

Table 4.1 Reactivity parameters of investigated SCM

SCM	Classification	Reactive oxide composition (%)				Compact density (kg/m^3)	Fineness by specific surface (m^2/kg)
		CaO	SiO_2	Al_2O_3	Fe_2O_3		
CEM II/A-LL	Hydraulic	61.4	18.7	3.9	2.8	3080	430-510
GP	Pozzolanic	9.9	72.5	1.8	0.25	2250	162
GGBS	Latent hydraulic	31	34	12	0.3	2800-3000	460-540

On comparing major reactivity parameters of the SCM to the reference cement, CEM II/A-LL, it can be seen that GGBS shows considerable fineness as cement. The GP is lacking in fineness, resulting in slower reactivity and lower strength than GGBS or reference concrete. Comparison of the particle size distribution of SCM with reference cement is shown in figure 4.4. Material having higher fineness measured by the specific surface shows finer particle grading like GGBS compared to GP and CEM II.

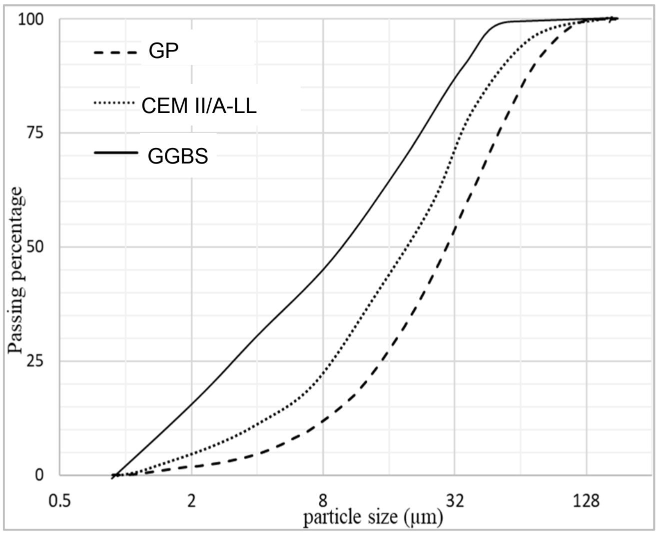

Figure 4.4 Particle size distribution of cementitious materials

SCM addition in CCA concrete

The SCM additives with cement need not always result in a higher compressive strength than the reference concrete with cement alone. Besides the reactivity of the SCM, other proportioning factors such as whether the SCM is a cement replacement or a partial addition to the cement influence concrete strength [92, 106, 107]. This study investigates GGBS, GP as replacement and partial addition as shown in figure 4.5.

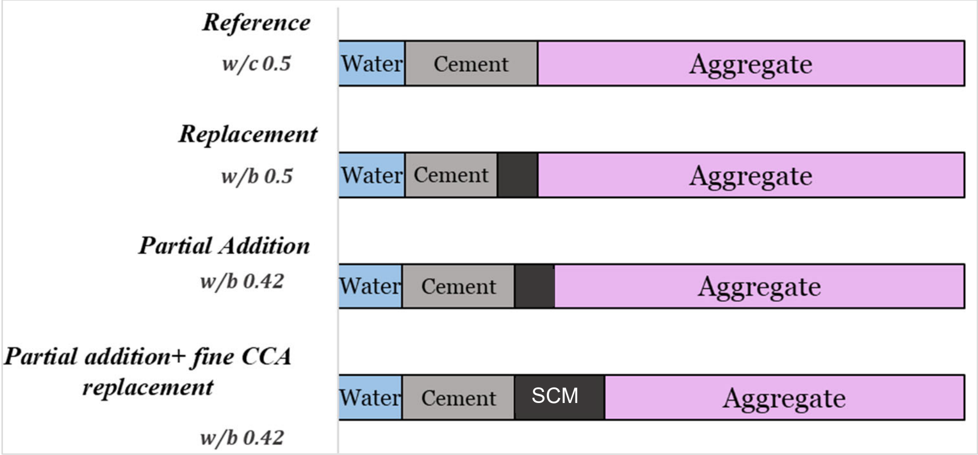

Figure 4.5 Schematic on the SCM addition scenarios

In this study, the SCM replaces 30% of the cement content at the same water/binder ratio 0.5 as the reference concrete, replacement in figure 4.5. This ensures a common ground to compare the performance of CCA concrete with different SCM by their capacity to densify cement paste. This also results in a climate optimized concrete due to reduction in the carbon dioxide emissions relating to binder [108, 109]; seen in literature as the most conventional way of proportioning SCM in concrete, literature review in article 4.

It is seen in previous research that CCA concrete does not always reach reference strength by SCM replacement, mostly because the SCM has slower or lower reactivity than cement [106, 110]. This is remedied by either reducing the water/cement ratio before SCM replacement [111, 112] or by increasing total binder content, seen as both partial replacement and addition at the same time [113]. Other alternative being addition of SCM to the original reference cement amount, which brings about no reduction in the cement content. This signifies a concrete that is not sufficiently climate optimized despite the addition of SCM [107]. This study reduces the water/binder ratio to 0.42 from 0.5 reference concrete to which a 30% replacement of SCM is made, partial addition in figure 4.5.

The industrial production of SCM concrete uses partial addition of SCM based on efficiency factor (k) characterizing the SCM. The k-factor considers contribution of SCM to concrete mechanical properties and durability with Portland cement as a reference. It is a ratio indicating how much SCM is considered equivalent to 1 unit weight of cement. The standards SS 137003 and SS-EN 206 prescribe the k-factors for SCM for example, 0.4 for fly ash, 0.6-0-8 for GGBS and 1 for silica fume [114, 115]. K-factors are taken as 1 in the case of commercially produced blended cement when on showing equivalent performance as concrete with Portland cement. One such example is the reference cement CEMII/A-LL used in this study where about 6-20% clinker is replaced by limestone.

This study investigates 70% GGBS replacement in CCA100 mix where GGBS partially replaces cement and fine CCA. This is similar to partial addition scenario and investigates if the excess GGBS replacing the aggregate has any cementitious properties verified by increased compressive strength.

4.4 Concrete mixing method

This study follows a step-wise mixing method where the CCA is momentarily pre-soaked with water based on the 15 min water absorption value determined by the modified pycnometer method, article 2. Thereafter, the cement/SCM is added and mixed momentarily under which time the coating of dry cement/SCM on moist CCA takes place. To address claims on high early-age strength, SCM is activated by soaking in mixing water for 8 hours and added at this step such that the CCA receives a coating of activated SCM. Subsequently, the step-wise addition of mixing water and superplasticizer, 70% of the total amount succeeded by remaining 30% with momentary mixing in between promotes further coating of wetted cement on CCA. This mixing method is prevalent in literature [38, 67] because it commences the strengthening of CCA-cement paste interface while the mixing is on-going, workflow in figure 4.6.

Figure 4.6 Workflow- mixing method CCA concrete with SCM

The interfacial transition zone (ITZ) between conventional aggregate-cement paste, is considered a weak zone caused by the contact of two different materials [41]. In comparison, the CCA with adhered mortar may have better adhesion with the new cement paste when the CCA undergoes repetitive coating with wetted cement along subsequent stages in the mixing process [67, 101]. The steps in mixing method altogether contribute to a better 28-day strength for concrete with SCM; by integrating pre-soaked GGBS to the mixing method pozzolanic reaction is boosted to give increased 7-day strength.

The industrial implementation of pre-soaking of CCA can be executed either by spraying the calculated amount of water on a measured volume of CCA or by storing the CCA outdoors so that it accumulates moisture like conventional aggregate. The latter scenario resembles the regular practice in industries where the mixing water content is adjusted based on the moisture content in aggregates determined by the “frying pan method” [44]. The execution of GGBS activation might require necessary infrastructure to manage the slurry received by pre-soaking the GGBS.

4.5 Early-age strength

Concrete with pozzolanic materials show delayed strength gain until sufficient calcium hydroxide is produced by cement hydration. This study investigates an SCM pre-soaking approach shown in previous research where the pozzolanic activity is boosted by an ion-exchange mechanism when SCM such as activated GP is soaked in water [116]. The study shows that soaking SCM for 8 hours leads to an earlier release of calcium and sodium ions from the respective oxides in GP by hydrolysis, one of the causes for delay in strength gain. Therefore, presoaking leads to formation of free ions to participate in hydration reaction therefore boosting pozzolanic activity. The mechanism is shown in equation 4.3

$$\begin{gathered} S+H \rightarrow S\text{-}H^{-} \\ CH+S\text{-}H^{-} \rightarrow C\text{-}S\text{-}H \end{gathered} \tag{4.3}$$

GGBS is pre-soaked in mixing water for 8 hours with superplasticizer corresponding to 8% of concrete mix to create a dispersive effect. By mixing along with the pre-wetted CCA a coating is created which is similar to the surface-coating approach adopted to bring about a densification of the aggregate-paste interface [101].

Compressive strength is tested on cylindrical specimens of size 100 x 200 mm, cured in a curing tank at temperature 20±2˚C. Details on relevant standards and procedures found in article 2,3,4.

In figure 4.7, the 7-day compressive strength of CCA100 concrete with improved mixing method and 30% GGBS replacement has equivalent effect as mechanical pre-processed CCA concrete. With the ordinary mixing method, the GGBS concrete does not reach the strength of mechanically pre-processed aggregates.

An external study with GGBS concrete with natural aggregates shows similar strength gain where 95-96% of reference concrete strength is reached with GGBS replacements of 25-30% respectively [117, 118]. One of the references is a Swedish study which uses the same cement as this study CEM II-A/LL however for concrete with natural aggregate and crushed rock, shown as NAC mixes in figure 4.7.

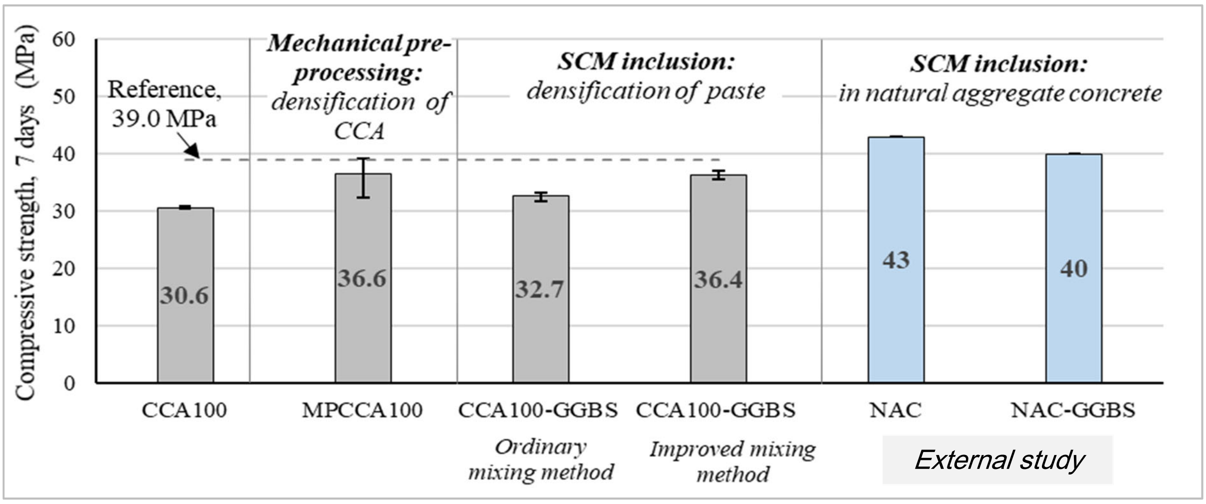

Figure 4.7 Compressive strength at early-age, CCA concrete, natural aggregate concrete [118]

To conclude, GGBS effect on early age strength is similar for CCA and natural aggregate concrete due to combination of improved mixing method and pre-soaking of CCA. The first one by increasing the rate of hydration and second by densifying/creating a coating around the aggregate.

4.6 Compressive strength and workability

The CCA directly from crushing does not fulfill the reference concrete strength at both replacement ratios 50% and 100%, identifying low packing density of the CCA as one of the reasons. The packing density combines the effects of physical properties such as particle grading, flakiness index, unit weight, particle density and void content to relate to CCA concrete strength. Thus, the improvements in these properties achieved through mechanical pre-processing of the CCA, show as improvements in packing density. Packing density correspondingly shows as improvements in concrete strength and workability, seen in figure 3.6.

The mechanically pre-processed CCA in both replacement mixes, MPCCA100, MPCCA50 achieve reference concrete strength at 28 days. Furthermore, MPCCA50 consisting of crushed stone and mechanically pre-processed fine CCA exceeds the reference concrete strength. The fine CCA fraction after partially losing adhered mortar through mechanical pre-processing can be compared to crushed rock fines, in this way MPCCA50 can almost be compared to concrete with full crushed rock replacement and therefore shows more strength than the reference concrete [119].

This study investigates 30% SCM additions using GGBS and GP at two scenarios, replacement and partial addition to reduce the embodied carbon coming from cement by the addition of GGBS to produce a climate optimized concrete with lesser carbon footprint. The aggregates investigated are CCA at both replacement percentages and with/without mechanical pre-processing.

Compressive strength: concrete with SCM

Figure 4.8 shows the compressive strength results for GGBS and GP concrete at both water/binder ratios for un-preprocessed CCA and reference aggregates. In general, GGBS due to high fineness shows a more benevolent effect on compressive strength in comparison to GP; contributing to compressive strength in the order REF>CCA100>CCA50.

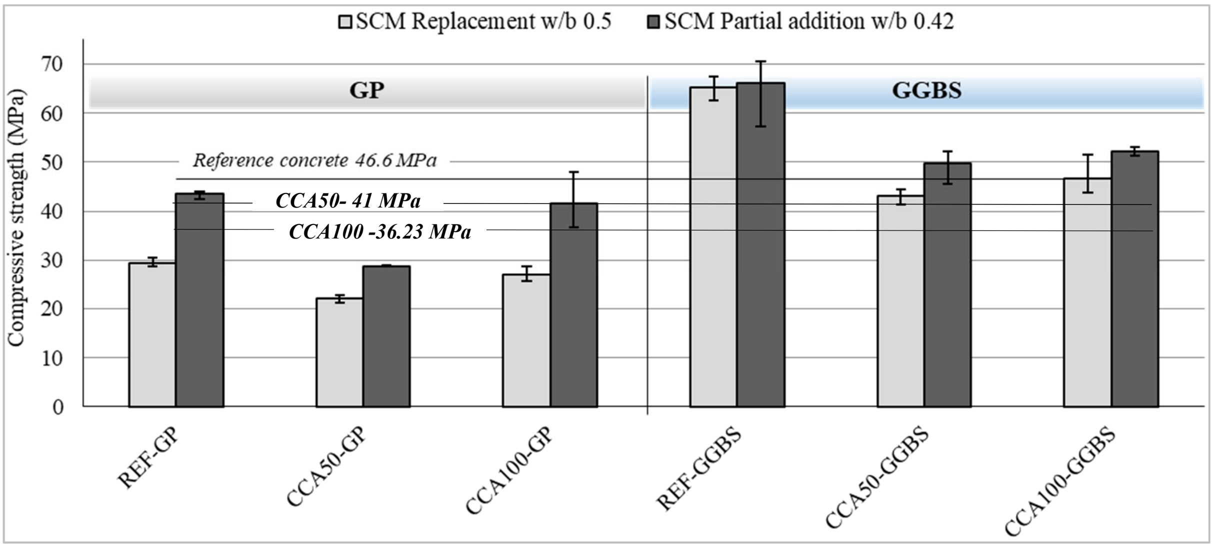

Figure 4.8 Compressive strength-28 days, concrete mixes with SCM

The CCA100 concrete with GGBS reaches reference concrete strength, 46.6MPa at both water/binder ratios. The CCA50 concrete reaches reference concrete strength at water/binder ratio 0.42. With GGBS the reference concrete increases from 46.6 MPa to 65 MPa, also seen in previous research where at 30% GGBS replacement strength of conventional concrete increases by 50% [120].

The reasons for the strength of GGBS concretes CCA100 exceeding CCA50 can be attributed to the strengthening of the adhered mortar and interface by GGBS, since the CCA100 has a larger volume of adhered mortar available for strengthening. Similar observation and clarification is made in previous research with GGBS concrete [108]. Concrete mixes with GP also display the same trend even if they are unable to achieve the reference concrete strength.

GGBS addition at lower water/binder ratio 0.42 induce differences only in the range of 5-10 MPa however, the CCA50 mix achieves reference concrete strength. Therefore, the partial addition of GGBS is suitable for concrete where CCA replaces the fine aggregates. Concrete with full CCA replacement fulfills reference strength at the replacement scenario itself, water/binder 0.5.

All CCA replacements including reference aggregates fall short of reference strength with GP at both water/binder ratios. This is due to slower reactivity of GP due to reduced fineness compared to GGBS and reference cement, specific surface 162 kg/m^2 compared to 450 kg/m^2. Previous research [90] shows that GP lesser than 25 µm shows most pozzolanicity; such particles occupy only 28% of the particle size distribution in this study, as seen in figure 4.4, therefore amount of GP showing pozzolanic activity is less. It is shown in literature that GP contributes to a delayed strength gain seen at 56 days [109] and 90 days [121] which is not a priority for industrial concrete production and is therefore not addressed in this research.

Since GGBS contributes to compressive strength increase for all CCA replacement percentages, it is evident that GGBS is more reactive than GP with a better cement-gel forming capacity. The combination of GGBS/cement 30% as replacement and partial addition show higher compressive strength than reference cement CEM II/A-LL alone, implying that the combination likely produces more cement-gel than only cement.

Compressive strength: mechanical pre-processing and its added effect with SCM

Mechanical pre-processing combined with SCM has a positive effect on the compressive strength of CCA concrete due to the added effect of CCA and cement paste densification by mechanical pre-processing and SCM addition respectively. At a first glance, there are not many research works investigating the effects of both CCA, paste densification in concrete. One study researches addition of activated GP combined with mechanically pre-processed CCA where considerable compressive strength is observed even at higher CCA replacement ratios for pre-processed CCA [121].

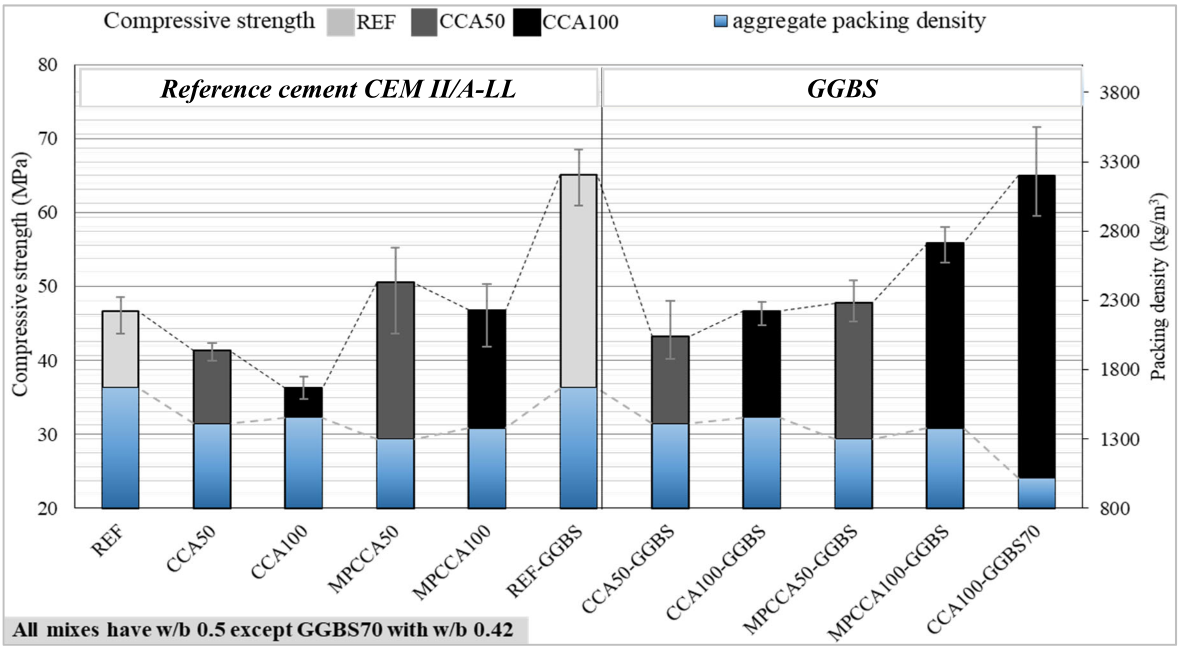

Figure 4.9 Compressive strength, aggregate packing density of mechanically pre-processed CCA, SCM addition

Figure 4.9 shows that only with mechanical preprocessing both 50 and 100% replacement mixes achieve reference concrete strength of 46.6 MPa. While GGBS addition shows increase only for the concrete with 100% CCA. The added effect on CCA100 shown by mix MPCCA100-GGBS can be seen as a bonus effect since the strength is 20% more than the reference. Thus allowing a choice between mechanical pre-processing and GGBS replacement. However, in the case of MPCCA50-GGBS the added effect is necessary for the mix to reach reference concrete strength. Therefore, the choices in this case is to either to mechanically pre-process CCA or combine pre-processing with addition of SCM.

In comparison to concrete with SCM, the compressive strength of mechanically pre-processed CCA shows a larger spread of results. This could be attributed to the quality variation occurring in CCA due to the washing process in mechanical pre-processing. The extra energy inputs arising with mechanical pre-processing negatively influencing the overall sustainability maybe balanced by $CO_{2,eqv}$ reductions resulting from the replacement of cement with GGBS. Moreover, mechanical pre-processing efforts are reduced by half in the case of CCA50 where only fine CCA to be pre-processed.

The CCA100 mix with 70% replacement of GGBS partially replacing fine CCA and cement by partial addition is denoted CCA100-GGBS70 in figure 4.9. This concrete shows higher compressive strength than reference concrete (65 MPa, 46.6 MPa) and almost equal strength as the reference concrete with GGBS. The contribution of aggregate packing density in this case is the least among all CCA alternatives due to GGBS having a lower unit-weight than fine CCA (1138 kg/m^3, 1475 kg/m^3). Despite this, the mix achieves highest strength maybe because the excess GGBS is available to coat and densify the CCA and interface. Alternatively, it can be that the GGBS added to replace fine aggregates show cementitious properties. A similar occurrence in previous research shows CCA100 compressive strength to surpass reference concrete when silica fume replaces fine CCA [122].

Practical effects related to hardened concrete

Preliminary drying shrinkage tests conducted before grading adjustments and pre-soaking modifications to CCA50 and CCA100 concrete mixes show higher drying shrinkage than the reference concrete at 56 days. Due to the adhered mortar the CCA offer lesser restraint to unbound water compared to denser reference concrete aggregates causing larger loss of water by evaporation [33, 123]. Shrinkage maybe reduced by mechanical pre-processing of CCA due to the removal of adhered mortar, or by densifying the CCA with SCM of high fineness such as silica fume or GGBS.

Besides the densification of CCA, these techniques also strengthen CCA-paste interface which in turn leads to reduced drying shrinkage [124]. Literature shows that the interface formed between aggregate and paste is the weakest link due to differences in the stiffness of these materials [41]. However, with CCA densified by SCM coating on pre-soaked CCA or sequential mixing shows a merging of the interface zone with CCA leading to homogenizing a usually weak zone [97, 101].

SCM addition binds more capillary water to the cement gel leading to volumetric shrinkage of the hardening paste in comparison to its mix constituents. Such autogenous shrinkage is seen at lower water/cement ratios and causes the concrete to lose water rapidly by self-desiccation [93, 125]. Such dehydration is beneficial in practical applications such as the laying of floor coverings on concrete slabs after casting, a process largely dependent on the rapid loss of moisture from concrete [126].

This research undertakes a prognosis of alkali-silica reactions (ASR) arising from CCA in concrete by a rapid test on mortar bar specimens at 16 days according to ASTM C1260. Since the reference concrete aggregates already satisfy reactivity claims, it is assumed that the increase in alkalinity in CCA arising from adhered mortar may increase reactivity leading to expansions in concrete. The test at completion shows negligible expansion in mortar bars indicating that CCA may have reduced ASR potential; however, more thorough testing is required for conclusive results. In case of CCA showing more proneness to ASR, CCA alkalinity maybe reduced with adhered mortar removal resulting from the mechanical pre-processing of CCA.

Workability

Concrete workability indirectly measures the deformation of fresh concrete, mainly influenced by the type, proportions of aggregate, cement paste and mixing contents in concrete. The common methods to measure concrete workability and rheology are the slump test and flow diameter, with criteria established in standard SS EN 206. In concrete where the workability is the governing criterion such as self-compacted concrete, deformational properties are investigated by advanced equipment such as viscometer [44, 64]. This research being a complement study in concrete recycling investigates CCA concrete workability by the flow diameter. Moreover, the industry bases the workability criteria of the reference concrete on this test.

CCA concrete workability is largely governed by the water absorption of CCA due to porous adhered mortar which absorbs part of the mixing water meant for workability [42, 112]. There are however, other aggregate properties such as particle grading, flakiness index and unit weight influencing concrete workability, which are extensively researched for crushed rock aggregates but not in the same extent in CCA concrete research.

This research produces CCA concrete at two replacement ratios for a workability comparable to reference concrete by addressing firstly the CCA water absorption criteria. Secondly addressing physical properties of aggregates by a characterization based on packing density [14, 82, 86] which shows a direct influence on CCA workability, article 3. Sufficient mixing water is made available for concrete workability by pre-soaking CCA before concrete mixing with water corresponding to only 50% of the 15-minute water absorption value of a combined CCA fraction. In combination with the particle grading adjustment after crushing, the mix shows a flow diameter corresponding to the flow-class succeeding reference flow diameter; seen as reference and CCA100 in figure 4.10.

The mechanical pre-processing has a favorable effect on the physical properties of fine CCA by considerably reducing flakiness index and improving particle grading to almost match the fine natural aggregates of reference concrete. The over-all improvement in CCA properties is reflected as an increase in the packing density. The increase in packing density optimizes the void content so that the CCA has sufficient contact and mobility with the available cement paste showing therefore improved workability, see figure 3.6. Both the 50% and 100% mechanically pre-processed CCA mixes show flow diameters in the same flow class as reference concrete. MPCCA shows flow diameter just 3mm lesser than reference concrete.

GGBS has a water-reducing quality such that workability of GGBS concrete resembles workability of concrete with more mixing water [117]. For all CCA replacements, GGBS concrete with reference water/binder ratio 0.5 results in slightly increased flow diameter. However, at lower water/binder ratio 0.42, the flow diameter values are in the range of F2 class as reference concrete, CCA100-GGBS in figure 4.10.

Reference - 380 mm, F2 class

CCA100- 437.5 mm, F3 class

MPCCA100- 377 mm, F2 class

CCA100-GGBS – 355 mm, F2 class

Figure 4.10 Workability of CCA concrete shown by flow diameter, flow classes- SS EN 206

5 CONCLUSIONS

The required compressive strength of CCA concrete suiting structural concrete is the primary aspect investigated by this study. By fulfilling the reference concrete compressive strength the CCA concrete becomes eligible for further investigations on its mechanical properties and durability performance.

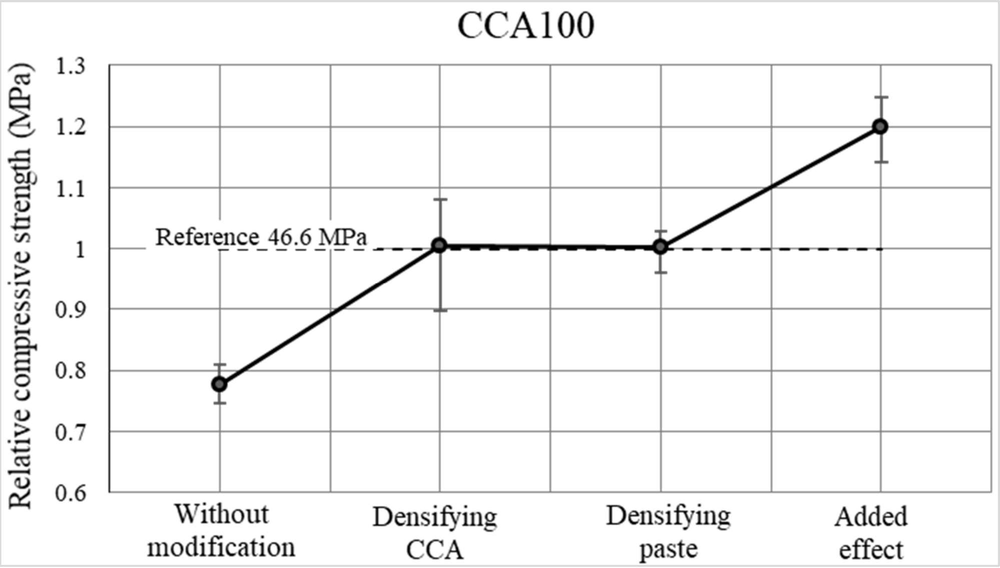

Figure 5.1 Compressive strength improvement in CCA100 concrete

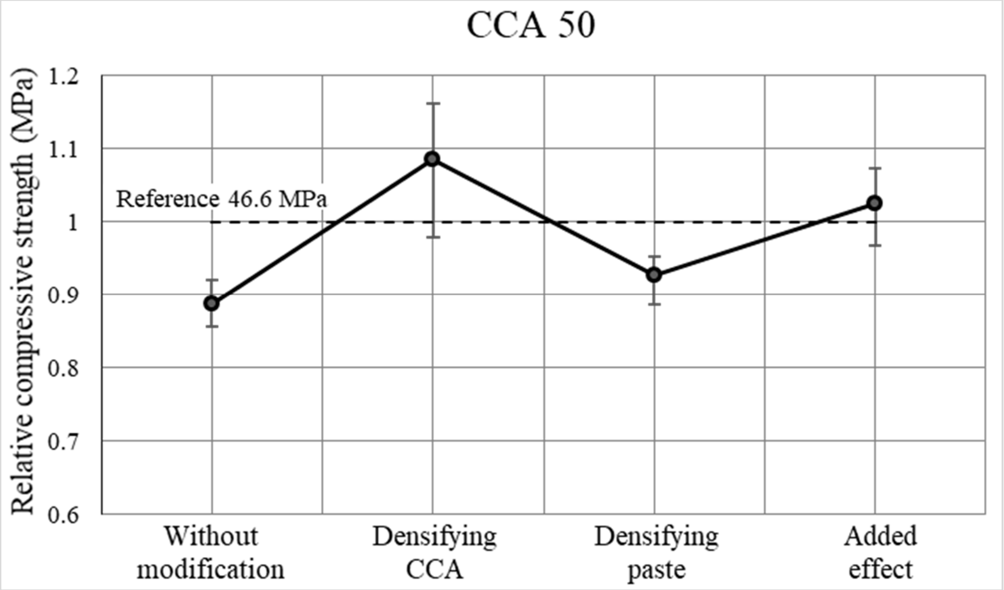

Figure 5.2 Compressive strength improvement in CCA100 concrete

This study concludes that concrete produced with CCA without modification after crushing shows lower compressive strength than the reference concrete at both CCA replacements, figure 5.1and 5.2.

It is seen that particle grading adjustments, CCA water absorption requirements addressed by pre-soaking and a customized mixing sequence are not sufficient by themselves in raising the CCA concrete strength to meet the reference’, noted without modification in figure 5.1 and 5.2. These supporting procedures require backing by modifications to densify CCA by mechanical pre-processing or densifying paste by GGBS or both.

The first modification, densification of CCA implemented by mechanical pre-processing brings an increase in CCA packing density. Packing density is identified as a key aggregate property showing a close relation to compressive strength of CCA concrete, such that the increase in packing density increases concrete compressive strength. The resulting compressive strength of CCA100 rises to match reference concrete strength, figure 5.1 and CCA50 exceeds reference concrete strength, figure 5.2.

The second modification investigates densification of the paste by the addition of blast furnace slag (GGBS) to replace 30% of the cement content. The CCA100 strength matches the reference value without improvements to packing density, indicating that GGBS contributes to cement paste densification. However, the CCA50 shows reduction in strength which points towards the idea that GGBS due to its fineness strengthens the adhered mortar on CCA besides its contribution to paste densification by the formation of hydration products. Since the CCA50 has lesser adhered mortar content compared to CCA100 there is lower contribution to CCA densification in the former. It is interesting to see that the adhered cement mortar, which in its default state is responsible for inferior properties of CCA concrete is reinforced with introduction of secondary cementitious materials like GGBS to show improved concrete strength.

The combination of CCA and paste densification is benevolent for CCA50, which reaches reference concrete strength. The CCA50 alternative maybe similar to industrial concrete recipes with crushed rock as coarse and fine fractions, such that the combination of two flaky materials demands improvements in aggregate packing to result in favorable concrete properties. In the case of CCA50, the fine CCA and coarse crushed stone are flaky which show improved packing with mechanical pre-processing. Therefore in CCA50, mechanical pre-processing governs gains in compressive strength despite efforts for densifying paste with SCM.

5.1 Statistical significance of results

The compressive strength results show that the densification of CCA, paste and combined CCA-paste result in improved compressive strength; however, to verify whether these improvements are significant, a statistical analysis is required. This study uses a paired T-test, where the strength results of CCA mix without any modification is chosen as a base-line and analyzed with the other modifications to paste, CCA and so on.

The tested modifications are mechanically pre-processed CCA, GGBS addition and a combination of GGBS and mechanical pre-processing. Modifications are tested for CCA50 and CCA100 mixes at water/binder ratio 0.5. The statistical analysis is by a paired-T test, table 5.1, the sample parameters are 28-day compressive strength, mean and standard deviation based on three cylinder specimens.

Concerning CCA100, all the three modifications show significant improvements in strength, GGBS addition by itself and in combination with mechanical pre-processing being the most significant. On the contrary, statistically significant improvements in strength are seen only for the combination of mechanical pre-processing and GGBS for CCA50 mix.

Table 5.1 Test on statistical significance of compressive strength results

Modifications / Sample parameters	Un-preprocessed CCA	Mechanically pre-processed CCA	GGBS addition	Mechanically pre-processed CCA and GGBS addition
CCA100				
Mean strength (MPa)	35.17	46.82	46.74	55.88
Standard deviation	1.50	4.42	1.71	2.47
P value	-	0.049	0.0031	0.0011
T-test	-	4.32	8.81	12.41
Significance	-	significant	very significant	very significant
CCA50				
Mean strength (MPa)	37.85	47.06	43.21	47.76
Standard deviation	1.66	6.14	4.2	2.87
P value	-	0.128	0.176	0.014
T-test	-	2.50	2.05	5.17
Significance	-	not significant	not significant	significant

5.2 Sustainability analysis

Results from this study show that concrete containing CCA as both fine and coarse fractions, CCA100 achieves reference concrete strength at either mechanical pre-processing or GGBS replacement. By choice, a cementitious material replacement would be enough to produce likewise strong and climate optimized concrete instead of an energy consuming procedure such as mechanical pre-processing. Thus, an assessment of the sustainability benefits in ways of estimated amount of $CO_{2,eqv}$ emissions is presented here.

With data on $CO_{2,eqv}$ emissions, CEM II/A-LL = 730 kg $CO_{2,eqv}$/ton, GGBS = 30 kg $CO_{2,eqv}$/ton from [127]. The $CO_{2,eqv}$ emissions per m^3 of reference concrete with 100% CEM II/A-LL is 357 kg $CO_{2,eqv}/m^3$ (corresponding to cement content 490 kg/m^3). When GGBS replaces 30% of the cement content, the $CO_{2,eqv}$ emissions per m^3 of concrete reduces to 255 kg $CO_{2,eqv}/m^3$. This implies that the CCA100 mix reaches reference concrete strength along with a reduction of 102 kg of $CO_{2,eqv}$ emissions (28%) by GGBS replacement implying a stronger and climate optimized concrete.

In the case of CCA50 where the fine aggregates are replaced by CCA, the reference compressive strength is reached either with mechanical pre-processing or by the combination of mechanical pre-processing and GGBS addition.

The $CO_{2,eqv}$ emissions arising from mechanical pre-processing excluding washing is analyzed by assuming a ball mill of an industrial scale with 1-ton capacity consuming 30kWh energy. An estimate of the energy consumed in the 15-minute mechanical pre-processing of fine aggregates weighing 845 kg (approximated here for 1 ton) in 1m^3 is 7.5 kWh. The electricity source is fossil-fuel free energy in Sweden producing 13g $CO_{2,eqv}$ /kWh [128] , therefore the total $CO_{2,eqv}$ emissions from mechanical pre-processing would be approximately 100 g CO_{2eqv}/m^3 of concrete.

The amount of $CO_{2,eqv}$ emissions arising from mechanical pre-processing are very negligible since the ball mill is assumed sourced from wind energy; assuming other sources such as hydropower gives double, 24 g $CO_{2,eqv}$/kWh. On the contrary, a ball-mill powered by diesel would result in more emissions. This implies that the CCA50 may still be a climate optimized concrete with reduced $CO_{2,eqv}$ emissions resulting from GGBS replacement combined with mechanical pre-processing. The energy and resource consumption from washing and sieving operations needs to be considered for a more thorough assessment.

5.3 Future research

This thesis is a feasibility study on the potential of replacing fines /all aggregates with CCA in a concrete recipe with the goal of achieving concrete with compressive strength and workability comparable to reference concrete. Further analysis on the mechanical properties of concrete such as E-modulus, drying shrinkage, flexural strength, tensile strength, shear strength/pull-out strength are required. For structural applications, further analysis of fracture mechanics and of the structural behavior of elements with reinforced CCA concrete is required.

It would be interesting to see if the relationship between CCA packing density and concrete properties such as workability and compressive strength still hold for CCA from other parent concrete. Packing density can be regarded as a quality assessment parameter to verify the physical compatibility of CCA for a certain structural concrete.

The reference concrete in this study belongs to exposure class X0 corresponding to indoor applications. This exposure class is maintained for the new CCA concrete and thus just the durability aspect of alkali-silica reactions has been analyzed. For different exposure classes durability aspects like carbonation, chloride and freeze thaw resistance have to be investigated in order to certify the aggregates and the concrete respectively.
These investigations will probably lead to new recipes, thereby researching CCA potential in medium and high performance concrete. It is of interest to transfer this knowledge based on laboratory investigations towards industrial applications continuously as the techniques of concrete recycling develop.

The reference concrete strength and workability at both CCA replacement percentages are fulfilled by the research approach, see figure 5.3.

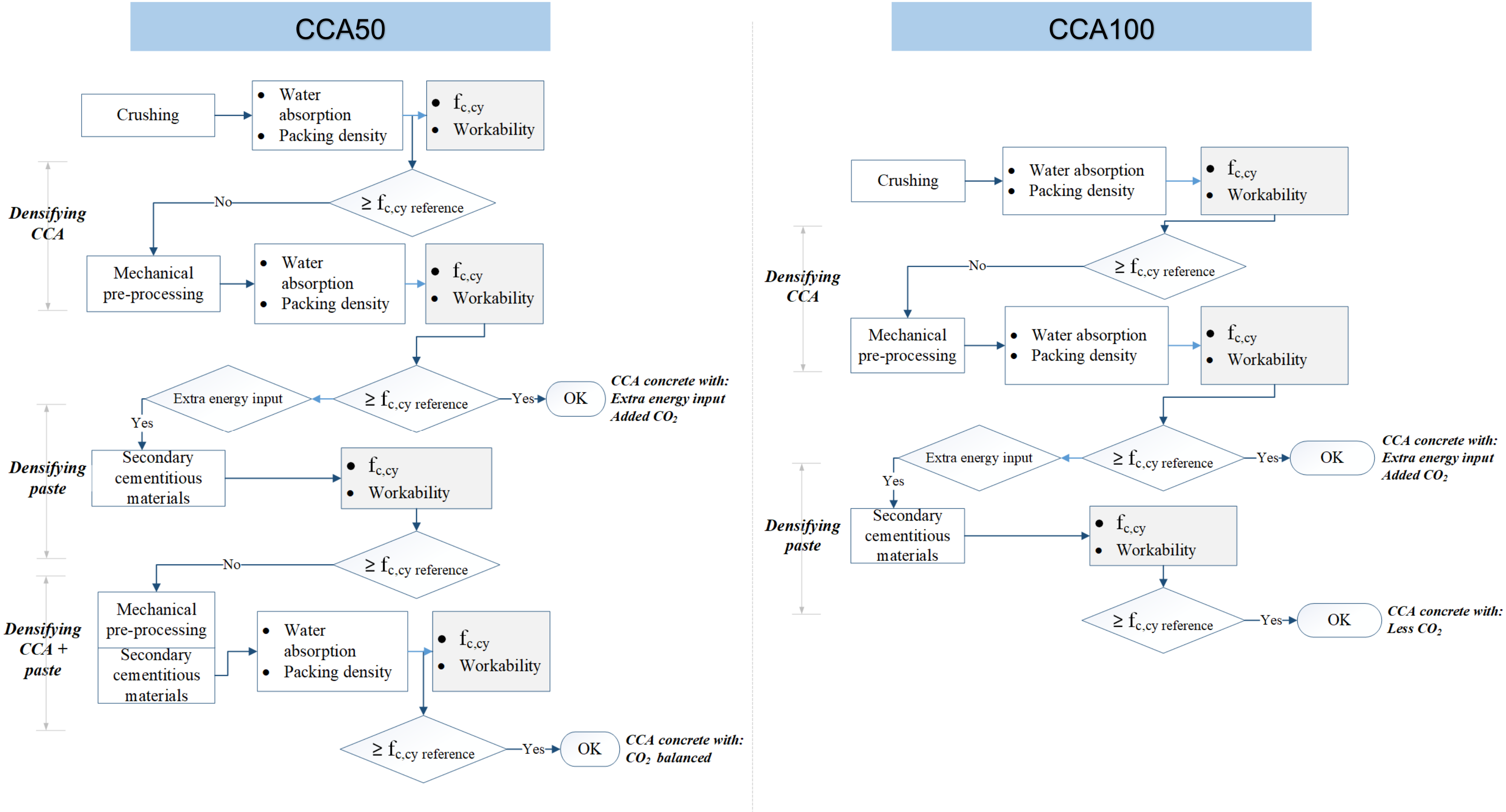

Figure 5.3 Concluding chart of research approach

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