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INVESTIGATION OF THE POSSIBILITY AND EFFICIENCY OF RECYCLING OF RECYCLED RECYCLED CONCRETE AND REINFORCED CONCRETE STRUCTURES IN THE CONSTRUCTION OF REINFORCED CONCRETE BRIDGES

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A B S T R A C T

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.

K E Y W O R D S

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

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.

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

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.

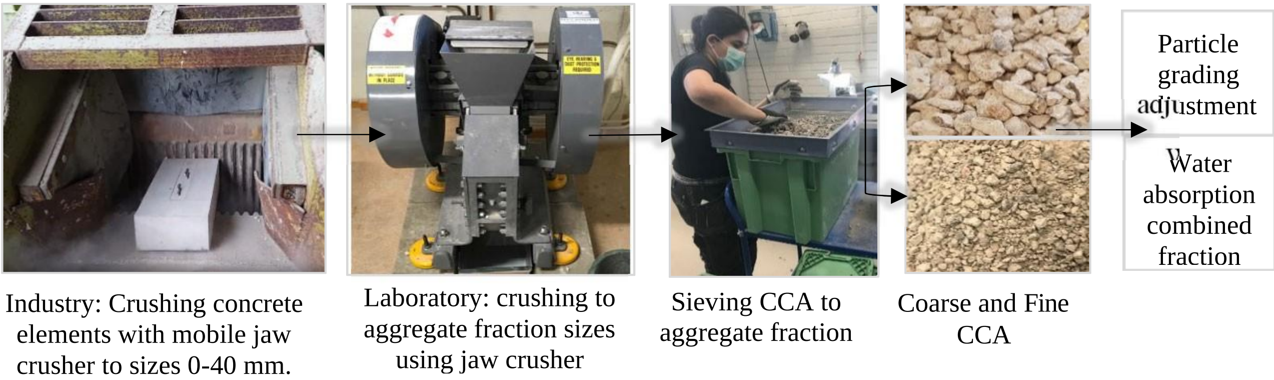

Figure 1. Production process of CCA for 50% and 100% CCA replacements

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 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.

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 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 2. Mechanical pre-processing of CCA for 50% and 100% CCA replacements

Figure 2. Mechanical pre-processing of CCA for 50% and 100% CCA replacements

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 C3S and C2S forming calcium silicate hydrates (C-S-H) on hydration also called cement-gel, equation 1 [1,2,3].

$$C\text{-}S + H - C\text{-}S\text{-}H + CH \qquad (1)$$

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 2.

$$CH + S + H - C\text{-}S\text{-}H \quad (2)$$

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 [4,5]. As the pozzolanic reaction involves calcium hydroxide implies that the strength development from pozzolanic reaction is delayed till sufficient calcium hydroxide is produced [6,7]. 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 [8,9].

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 [10]. 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 [11,12]. 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. A more recent research has validated this relationship to justify compressive strength improvements occurring with binary and ternary combinations of SCM and cement .

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 [1]. Validated by microscopic imagery in the respective studies [2]. 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 [3]. Such effect is referred in literature as micro-filler effect and is implemented by surface coating treatments on CCA [4]. Also by mixing methods with stage-wise addition of mixing water to pre-wetted CCA mixed with SCM [5].

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 [6]; fineness measured by specific surface is an indication of SCM reactivity and the potential for micro-filler effect [7]. The reactive oxide contents describe composition of three main oxides CaO, SiO2 and Al2O3 making up the four main calcium silicate and aluminate compounds of cement [8].

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.1.

Table.1 Reactivity parameters of investigated SCM

SCM	Classification	Reactive oxide composition (%)				Compact density (kg/m^3)	Fineness by specific surface (m^2/kg)
		CaO	SiO2	Al2O3	Fe2O3		
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 particlesize 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.

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 [9]. This study investigates GGBS, GP as replacement and partial addition as shown in figure1.

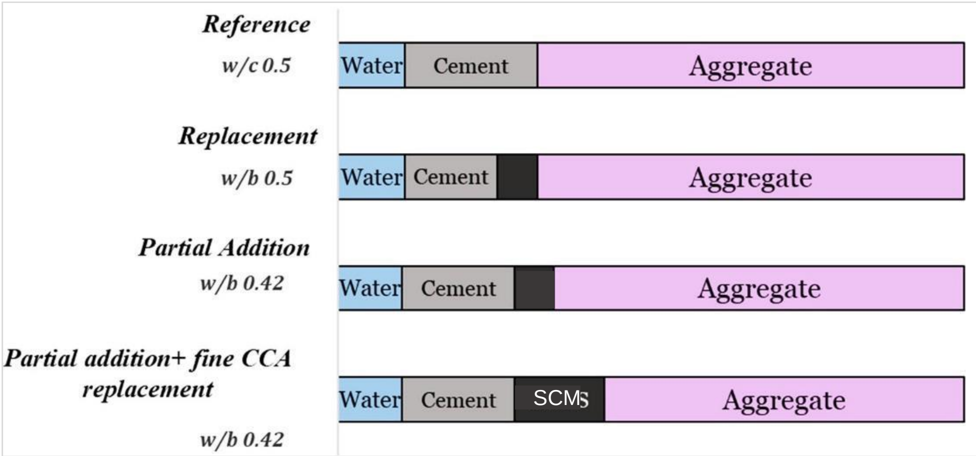

Figure 2. Schematic on the SCM addition scenarios

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 [10]; seen in literature as the most conventional way of proportioning SCM in concrete.

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 [11]. This is remedied by either reducing the water/cement ratio before SCM replacement [12] or by increasing total binder content, seen as both partial replacement and addition at the same time [10]. 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 [13]. 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 2.

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. 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.

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 [13] because it commences the strengthening of CCA-cement paste interface while the mixing is on-going, workflow in figure.3.

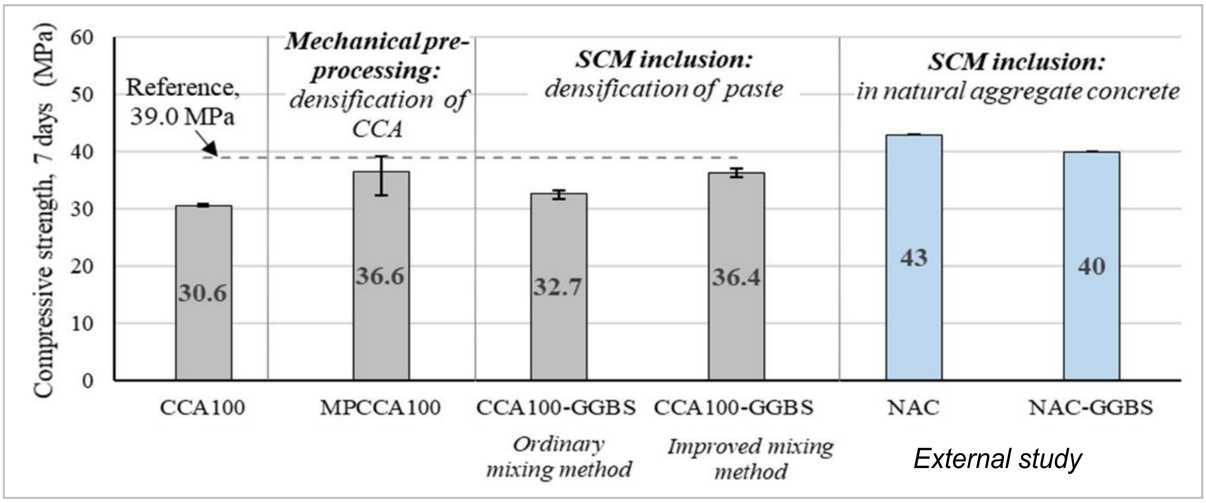

Figure 3. Compressive strength at early-age, CCA concrete, natural aggregate concrete.

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.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 bythe 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. Figure 3 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.

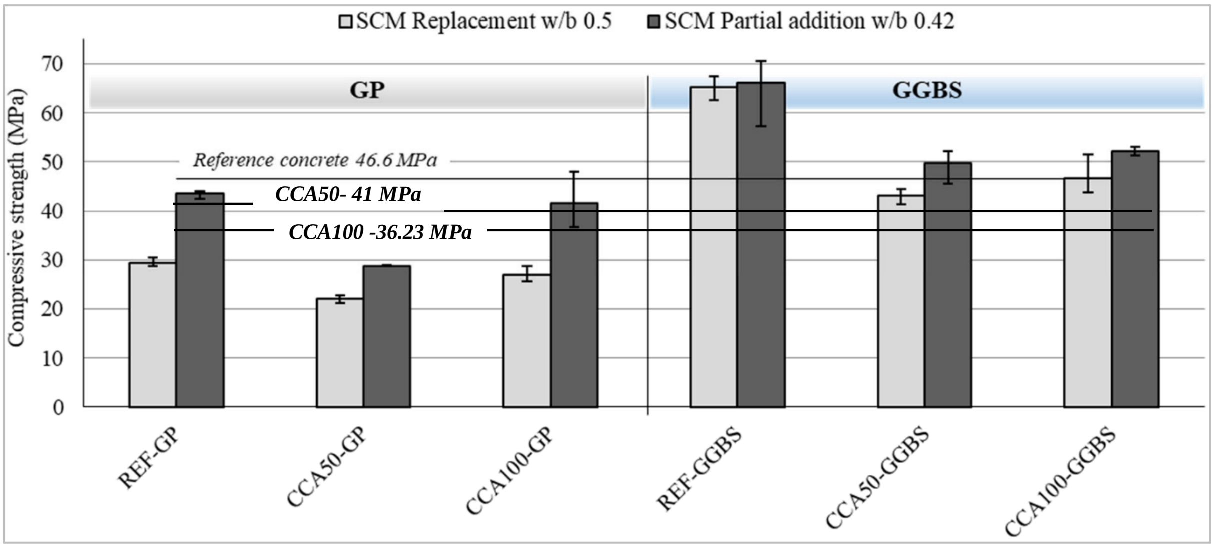

Figure 4. Compressive strength-28 days, concrete mixes with SCM

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% .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. 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/m2 compared to 450kg/m2. Previous research 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 and 90 days 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.

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 .

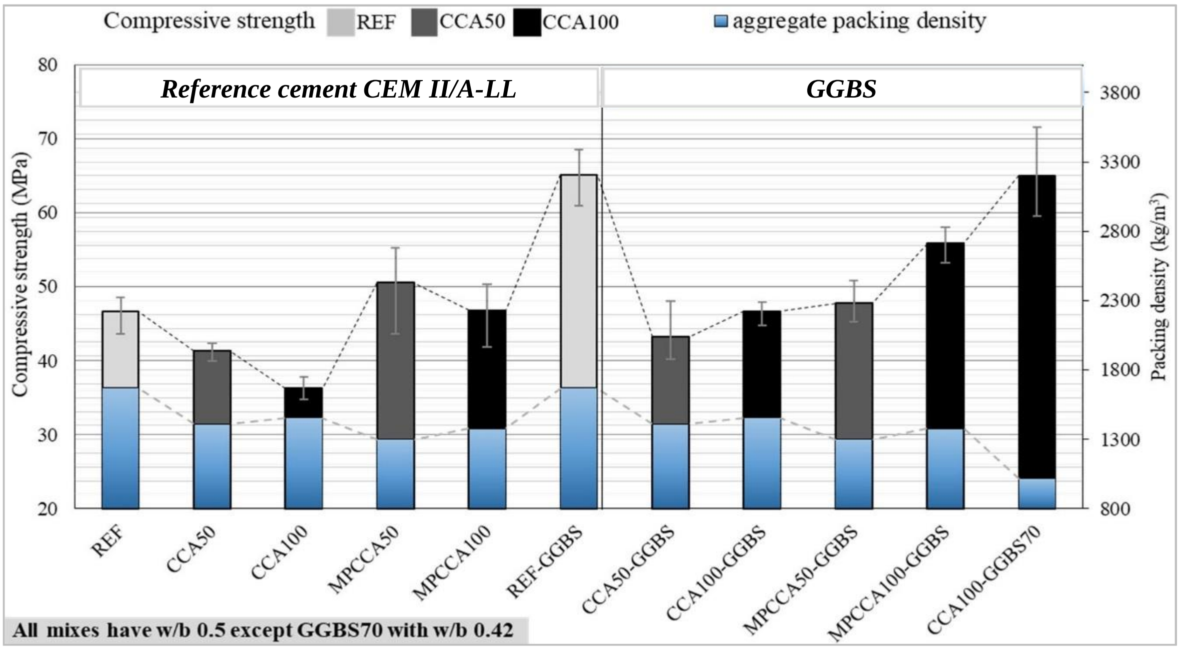

Figure 5. Compressive strength, aggregate packing density of mechanically pre-processed CCA, SCM addition.

Figure 5 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/m3, 1475 kg/m3). 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.

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. 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. 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.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. 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.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. 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. 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 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 6. 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. 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. 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 6.

Figure 6. Workability of CCA concrete shown by flow diameter, flow classes- SS EN 206

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. This study concludes that concrete produced with CCA without modification after crushing shows lower compressive strength than the reference concrete at both CCA replacements. 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. 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. Therefore in CCA50, mechanical pre-processing governs gains in compressive strength despite efforts for densifying paste with SCM.

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