SBUF
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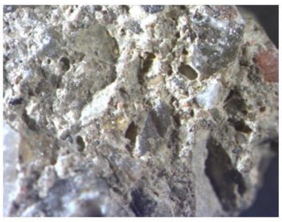
High Quality Reclaimed Concrete Aggregates for new concrete

- Återvunnenbetong som ballast i ny betong



Patrick Rogers, Katja Fridh, Hans-Erik Gram och Mikael Westerholm

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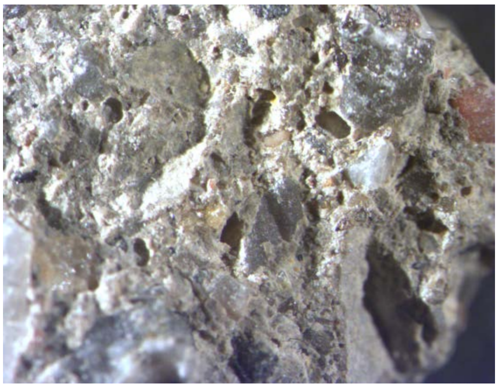

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Förord

Projektet var ett bra samarbete mellan industripartners Strängbetong AB, Abetong AB och Cementa AB samt forskningsinstitut CBI Betonginstitutet AB och Lund Universitet. Huvudandelen av projektet utfördes hos CBI Betonginstitutet AB i Stockholm från 2014 till 2016. Projektgruppen tackar SBUF som huvudfinansiär.

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Summary

Reclaimed concrete aggregates (RCA) or waste concrete aggregates (WCA) from waste hollow core slabs (HCS) and decommissioned railway sleepers (S) were analysed for their material characteristics and successfully used as aggregate replacements in two types of concrete. Three different size fractions were investigated, 0-4mm, 4-8mm and 8-16mm. The first concrete was a self-compacting concrete with 350 kg/m^3 of CEM II A/V 52.5 R and 0.5 water-to-cement ratio (w/c). The second was a freeze thaw resistant concrete w/c 0.4 based on 420 kg/m^3 of CEM I 42.5 N LA SR3. The reference concrete contained natural aggregates (NA) 0-16mm. The aggregate replacement guidelines in SS 13 70 03:2015 were used for the experimental setup.

Fresh and hardened concrete properties were tested in the SCC. The workability was affected by replacing the 0-4mm natural aggregates with an equal volume of RCA. The HCS RCA affected the plastic viscosity, i.e. the internal resistance in the cement paste, the most and was noticeable even at 5% volume replacement. The sleepers 0-4mm RCA was less noticeable until 22-33% volume replacement. 100% replacement of natural aggregates with HCS 0-4mm RCA was possible with similar superplasticizer (SP) requirement as the reference concrete. The 100% replacement of NA 0-4mm with (S) 0-4mm RCA required twice the amount of SP to obtain a SCC (7.3 kg/m^3).

The compressive strengths improved or remained the same with each increase of replacement volume with the RCAs except in the 0-4mm size range. Most improvement was obtained with the 8-16mm materials from both source materials, HCS (+18 %) and Sleepers (+12%). The reference concrete's f_{ck} was 55.8 MPa. The complete replacement of 0-4mm NA with RCA resulted in a drop of compressive strength , HCS (-5%) and Sleepers (-15%), compared to the reference. The 4-8mm volume was smaller than the other two size fractions but a positive trend was seen in both replacement materials.

The drying shrinkage was carried out on all mixes and no noticeable difference was seen in the 0-4mm size fraction apart from the complete replacement where shrinkage of 0.67‰ (+15%) was obtained with both materials. In the larger size fractions, the complete replacement of NA 8-16mm with (S) or (HCS) 8-16mm caused a 0.70‰ (+20%) and 0.65‰ (+12%) shrinkage respectively.

The freeze thaw resistant concrete series were based on a similar setup as the SCCs but with a lower w/c (0.4) and higher cement content (400 kg/m^3). The different size fractions of RCAs were used. Air was entrained to at least 4.5% (d_{max} 16mm). The SP used was kept constant at 4.4 kg/m^3. All cured concretes were tested for scaling as per SS 13 72 44:2005 via freeze thaw cycles. All passed, with a maximum scaling of 0.05 kg/m^2 and lay within the very good classification. Compressive strengths were also tested. A select choice of suitable concretes were tested further for chloride migration (NT BUILD 492) and the results were very similar and in the region of $D_{NTBuild492}$ =6.6 - 7.3x 10^{-12} m^2/s.

Concurrently, uptake of CO_2 into the above named RCAs was being measured over an 18 month period. The grading of the crushed concrete aggregates into the three size fractions improved the CO_2 diffusion into the cement pastes and increased the carbon sink in the aggregates. The main portion of the cement paste accumulated in the 0-4mm size fraction and also experienced the highest carbonation amount. This though was only experienced in the outer layers of the RCA pile. The centre layers carbonated at a lower rate due to the higher gas diffusion resistance created by the finer particles. In the size fractions 4-8 and 8-16mm less gas diffusion resistance was experienced and

the carbonation rates and levels were similar throughout the whole pile. The RCAs need to be kept dry in order to reduce the internal humidity and hence increase the rate of CO_2 gas diffusion into the cement paste. This though would increase the cost of handling the RCA material.

Sammanfattning

Återvunnenbetongballast (förkortning på engelska : RCA) eller krossbetongballast (förkortning på engelska : WCA) av Håldäck (på engelska : hollow core slab; HCS) och nedlagda järnvägssliprar (på engelska : sleepers ;S) användes som naturballast ersättare i två typer av betong. Dessa återvunna betongballasterna undersöktes och deras materialegenskaper analyserades. Tre olika storleksfraktioner, 0-4 mm, 4-8 mm och 8-16mm, användes. Den första betongtypen var en självkompakterande betong (SKB) med 350 kg/m^3 CEM II A/V 52,5 R och 0,5 i vatten-cement-tal (vct). Den andra betongtypen var en frostresistent betong med vct 0,4 baserat på 420 kg/m^3 CEM I 42,5 N LA SR3. Referensbetongen innehöll naturballast 0-16mm. De riktlinjerna som står i SS 13 70 03: 2015 användes för provningsmatrisen (dvs. natur- eller krossballastens ersättningsnivåer).
De färska och hårdnade betongegenskaperna analyserades i den SKB. Arbetbarheten påverkades genom att ersätta 0-4 mm naturballasten med en lika stor volym av de krossade betongballasterna. HCS betongballast påverkade den plastiska viskositeten, dvs. det inre motståndet i cementpastan, mest och märktes även vid 5 % volymersättning. Den plastiska viskositeten i sliprarna (S) 0-4 mm var mindre märkbar förrän 22-33% volymersättning. 100 % ersättning av naturballast med (HCS) 0-4 mm var möjligt med liknande superplasticerare (SP) behov som referensbetongen. 100 % volymersättning med (S) 0-4 mm krävde dubbeldosering (7,3 kg/m^3) för att erhålla likanade flyttande egenskaper som en SKB.
Tryckhållfastheten förbättras eller förblev densamma med varje ökning av ersättningsvolym med krossbetongballast förutom i 0-4mm storleksfraktionen. Mest förbättring erhölls med storleksfraktion 8-16mm från båda källmaterial, en ökning av + 18 % (HCS) och + 12 % (S) var resultaten. Referensbetongens tryckhållfasthet efter 28 dygn, f_{ck} , var 55,8 MPa. Den fullständiga ersättningen av 0-4 mm naturballast med krossbetongballast resulterade i en minskning i tryckhållfasthet, -5 % (HCS) och -15 % (S), jämfört med referensen. Ett optimum tryckhållfasthet erhölls med 33 % ersättning. Den 4-8 mm volymen i referensbetongen var mindre än de andra två storleksfraktioner, men en positiv trend sågs ändå i båda ersättningsmaterial.
Uttorkningskrympning utfördes på samtliga blandningar och ingen märkbar skillnad sågs i 0-4 mm storleksfraktionen bortsett från den fullständig ersättning av naturballast med krossbetongballast, där en krympning av 0,67 ‰ (+ 15%) noterades med båda materialen. I den storleks fraktionen, 8-16mm noterades en krympning av 0,70 ‰ (+ 20 %) och 0,65 ‰ (+ 12 %) i (S) respektive (HCS) med en hel ersättning av naturballast med krossbetongballast.

Den frostbeständiga betongens provningsserie baserades på den i ovannämnda SKB:en, men med ett lägre vct (0,4) och högre cementhalt (400 kg/m^3). De tre olika storleksfraktionerna av krossbetongballast användades som naturballastersättare. Lufthalten i samtliga prov var åtminstone 4,5 % (d_{max} 16 mm). SP halt behölls konstant vid 4,4 kg/m^3. Alla betonger i serien frostprovades enligt gällande standard SS 137244:2005. Samtliga var frostbeständiga och en maximal avskalning av 0,05 kg/m^2 noterades. Tryckhållfastheten provades också. Några utvalda betongrecept provades ytterligare för kloridmigration enligt NT BUILD 492 och resultaten var mycket lovande och låg inom ramen av $D_{NTBUILD492}$ 6,6 - 7.3x 10^{-12} m^2 / s.

Samtidig pågick CO_2 upptagningsförsök över en period av 18 månader med de olika krossbetongmaterial och storleken. Graderingen av de krossadebetongballasterna i de tre storleksfraktionerna förbättrade CO_2 diffusion i ballasthögarna och ökade kolendioxid upptag. Huvud

andelen av den cementpastan samlades i 0-4 mm storleksfraktionen och hade därmed också den högsta karbonatiseringsgrad av alla storleken. Detta var dock bara fallet i de yttre skikten av den krossbetongballasthögen. Innersta skikten karbonatiserade till en lägre grad på grund av den högre diffusionsmotstånd som skapats av de finare partiklarna i denna storleken. I storleksfraktionerna 4-8 och 8-16mm fanns mindre gas diffusionsmotstånd och karbonatiseringshastighet och graden var mer jämt fördelat i hela högen. De krossbetongballastarna behövde hållas torra för att minska den inre fuktigheten och därmed öka hastigheten för gasdiffusion av CO_2 in i cementpastan. Detta förvaringen skulle dock öka kostnaderna för hantering av krossbetongballast material.

Introduction

The production of precast concrete, e.g. hollow core slabs, roof tiles etc., creates both the desired concrete product both also waste. The amount of waste produced, due to either “cut offs” or the initial start and finishing casts is estimated to be approx. 5-6 % of annual production. Other examples of waste concrete are decommissioned railway sleepers. This concrete waste accumulates if not reused, recycled or sent to landfill. The recycling of this waste back into the concrete factory in the form of reclaimed aggregates would be ideal as this negates the need to sell the material to other markets. The main hinder, cost not being considered, is the Swedish application of SS-EN 206, SS 137003:2015 (Swedish Standards Institute, 2015) for the use of these waste concrete aggregates. The maximum % wt. mass replacement is currently 30% in the coarse fraction (>4mm) for any concrete exceeding exposure class XO. This reduces to 0% in exposure classes higher than XF1, XD1, XA1 unless the WCA was derived from a better or equal concrete exposure class as the new concrete. This means crushed concrete aggregates from a XF4 concrete can be used in a new XF4 concrete etc. 5% wt. of the total aggregates can always be replaced by crushed concrete or reclaimed concrete aggregates. No mention is given to the fine (0-4mm) fraction in the standard.

The main external demand for the waste concrete aggregates or reclaimed concrete aggregates comes the from road construction industry. The material is used as a sub grade material.

In Sweden the use of crushed aggregates ≥ 4mm is very common. The tax levied on the extraction of natural glaciofluvial materials was sufficient to encourage its use, currently at 40 SEK/t. Relatively few operational issues arise from the use of these crushed materials in that size fraction. Crushing concrete though does not only produce above 4mm sized aggregates, but also fine materials.

The cost per ton of extracting virgin aggregate materials is relatively cheap, it is the transport of these materials to the factory and the aggregate tax that have a large impact on the cost per ton of the aggregate material. This fact explains the relatively poor uptake of crushed concrete aggregates in Swedish concrete. The handling costs of the waste, i.e. the separation of rebar from the concrete and additional equipment costs impacts the cost of production negatively, i.e. cost prohibitive compared to natural or crushed bedrock. WCA/RCA also has negative performance issues well established by research.

Research into the use of waste concrete aggregates (WCA) is mainly concerned with that obtained from construction and demolition waste (CDW) due to the prevalence and volumes involved. In Sweden ca. 990,000t of CDW were produced in 2012 (EUROSTATS, 2016) Reduction in compressive strengths ranging from 5% - 40% have been observed, especially in replacing the finer fractions, i.e. <2mm (Meyer, 2009) but in (Levy & Helene, 2004) this was not the case as even at 100% replacement. Similar concrete compressive strengths were obtained as with virgin material, this was for concrete in the range of 20-40 MPa. The outcome of the new concrete’s properties (using RCA) is based on the quality of the concrete from which the RCA was obtained (Kou & Poon, 2015). High quality concrete using RCA from high performance concrete can even be better than solely using virgin aggregates.

In this project the quality of the RCA is very pure as these have not been in contact with other materials such as gypsum, bricks, bitumen etc. Separation of steel from the concrete is an established and efficient procedure. These therefore would not suffer from issues encountered with construction and demolition waste (CDW). The decommissioned railway sleepers have been exposed to outdoor conditions but never to deicing salts.

The project has used different size fractions of waste concrete aggregates; 0-4, 4-8 and 8-16mm. Washed natural aggregates in the same size ranges were used in combination with these RCA/WCAs to produce concretes ranging in replacement levels from 0 to 100% in each size fraction. The effect of the crushed concrete aggregates on the workability, compressive strengths, drying shrinkage , freeze thaw resistance and chloride diffusion were studied. Two types of concrete were produced, a self-compacting concrete SCC with a water-to-cement (w/c) ratio of 0.5 and another at 0.4 and air content above 4.5% for the freeze thaw and chloride diffusion testing.

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Aim and goal(s)

The aim of this project was twofold, one was to successfully use the reclaimed concrete aggregates (RCA), obtained from crushing decommissioned railroad sleepers and relatively new hollow core slabs, in the production of two types of concrete; the other was to determine the rate of CO_2 uptake of the crushed concrete size fractions in a sheltered outdoor environment. The concretes were self-compacting with a water to cement ratio (w/c) of 0.5 and a freeze thaw resistant (XF4) concrete with a w/c 0.4. Understanding the limits to which the concrete's properties are not negatively affected would increase use of the RCA into new concrete production and increase confidence in its use.

The production of clinker in cement is the main contributor of CO_2 release and embodied energy in the production of concrete. Over time and depending on the concrete's quality, concrete can incorporate CO_2 into its pore structure. The crushing of concrete would increase its exposed area enormously and so should increase the rate of CO_2 incorporation compared to the same concrete in its original geometry. The incorporation of CO_2, if any, could then be used to negate some of the CO_2 released in the clinker's production.

By using size fractioned crushed waste concrete as an aggregate, instead of a sub grade material in road construction, would provide the concrete factory with an additional source of aggregates, be less sensitive to supply and demand of road construction activity and even enhance their "green credentials" by incorporating waste streams into production.

Reclaimed concrete aggregates material properties

Aggregate characterization

The reclaimed crushed aggregates (RCAs) from the precast concrete elements of hollow core slabs (HCS) and sleepers (S) were characterized with both wet and dry methods. Prior to the analysis the aggregate were divided in the following fractions: 0-0.125 mm, 0-4 mm, 4-8 mm and 8-16 mm. The aggregates were characterized by determination of:

- Particle size distribution by dry sieving according to SS-EN 933-1.
- Particle size distribution of the filler fraction (0-0.125 mm) by laser diffraction.
- Specific surface area (BET) of the filler fraction (0-0.125 mm)
- Fineness modulus.
- Particle density and water absorption according to SS-EN 1097-6.
- Voids at loose and compressive packing.
- Mortar rheology (0-2 mm)
- Micro mortar rheology (0-0.125 mm)

Results

Particle size distribution and specific surface area

The particle size distribution of the aggregates from the RCAs is presented in Figure 1. Despite that the reclaimed crushed aggregates originated from precast products of different quality, with aggregates of different origin and that they were crushed at different plants, the particle size distributions were relatively similar.

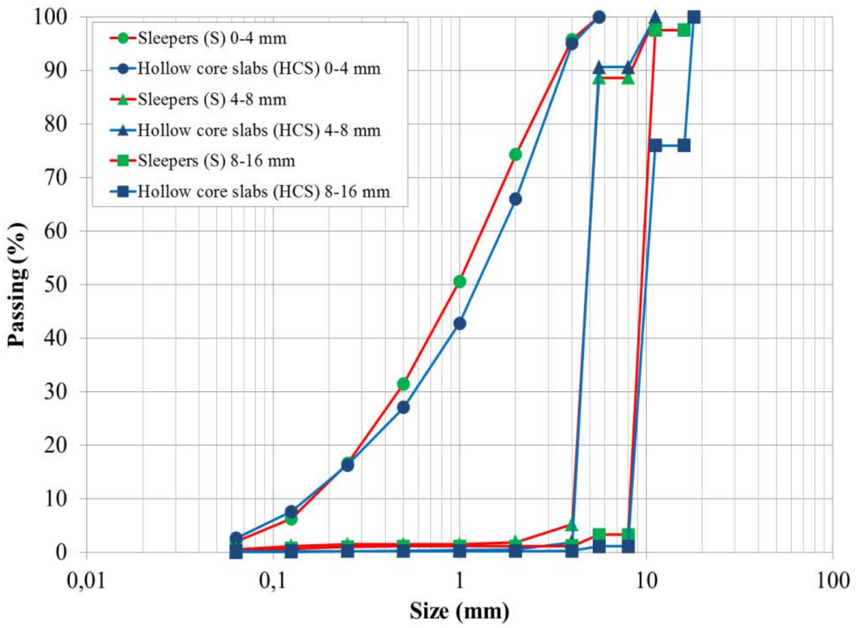

Figure 1 Particle Size Distribution determined by dry sieving according to SS-EN 933-1

The particle size distribution and specific surface area of the filler fraction from the hollow core slabs and sleepers are presented in Figure 1 and Figure 2. According to the analysis the filler fraction from the crushed sleepers was finer, both regarding the particle size distribution and specific surface area.

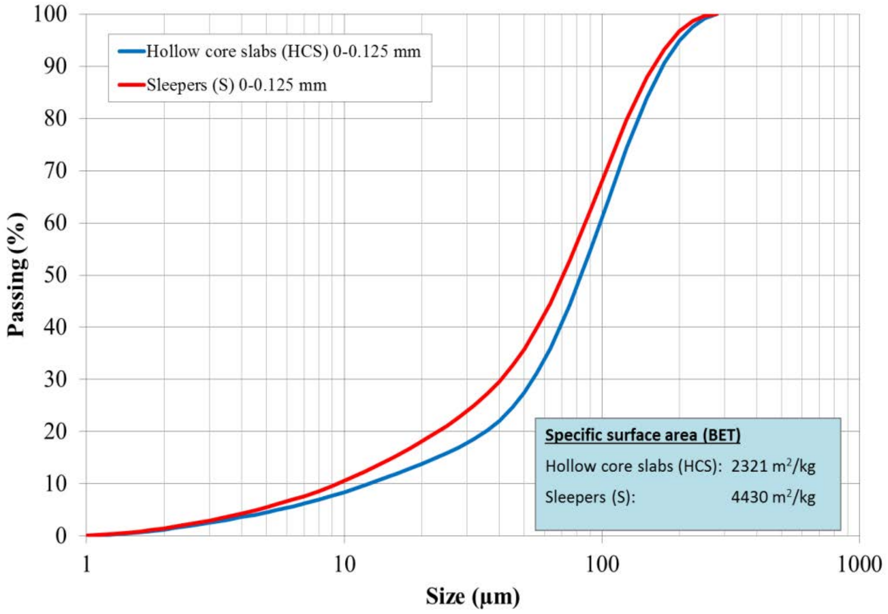

Figure 2 Particle size distributions and specific surface area of the filler fraction (0-0.125mm) determined by laser diffraction and with N_2 adsorption by BET-measurements, respectively.

Particle density, water absorption and fineness modulus

The results from the determination of particle density, water absorption and fineness modulus are presented in

Table 0-1 Particle density, water absorption and fineness modulus of the reclaimed crushed aggregates

Aggregate	Particle density (kg/m^3)	Water absorption (%)	Fineness modulus (-)
Hollow core slabs (HCS) 8-16 mm	2545	2.0	6.72
Sleepers (S) 8-16 mm	2574	2.7	6.43
Hollow core slabs (HCS) 4-8 mm	2581	2.6	5.56
Sleepers (S) 4-8 mm	2525	6.8	5.50
Hollow core slabs (HCS) 0-4 mm	-	-	2.99
Sleepers (S) 0-4 mm	-	-	2.77

The water absorption was higher for the aggregates originating from the sleepers, especially in the 4/8 mm fraction which was more than twice as high as for the corresponding fraction from the Hollow core slabs(HCS).

Aggregate	**Particle density (kg/m^3)**	**Water absorption (%)**	**Fineness modulus (-)**
Hollow core slabs (HCS) 8-16 mm	2545	2	6,72
Sleepers (S) 8-16 mm	2574	2,7	6,43
Hollow core slabs (HCS) 4-8 mm	2581	2,6	5,56
Sleepers (S) 4-8 mm	2525	6,8	5,5
Hollow core slabs (HCS) 0-4 mm	-	-	2,99
Sleepers (S) 0-4 mm	-	-	2,77

Aggregate voids determined by packing measurements

The voids, determined by loose packing, of the reclaimed crushed aggregates from the hollow core slabs (HCS) were smaller than the voids in aggregate from the crushed sleepers (A), see

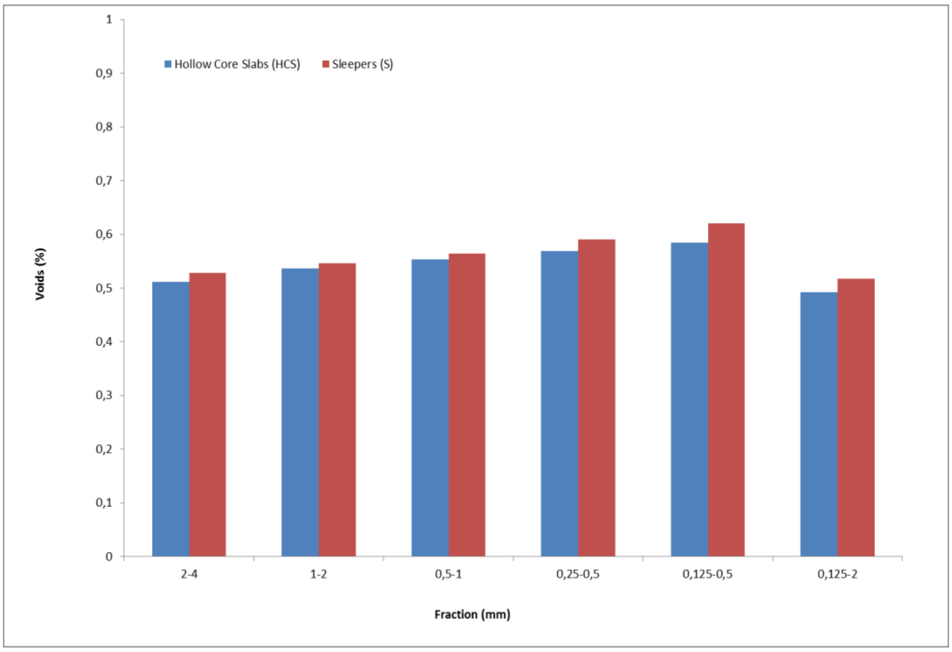

Figure 3 Voids of the different fractions of reclaimed crushed aggregates determined by loose packing

This indicated that the particle shape differed somewhat and that the aggregate from the crushed hollow core slabs would require less paste to fill the voids. In Figure 4 the results from loose and compressive packing were compared.

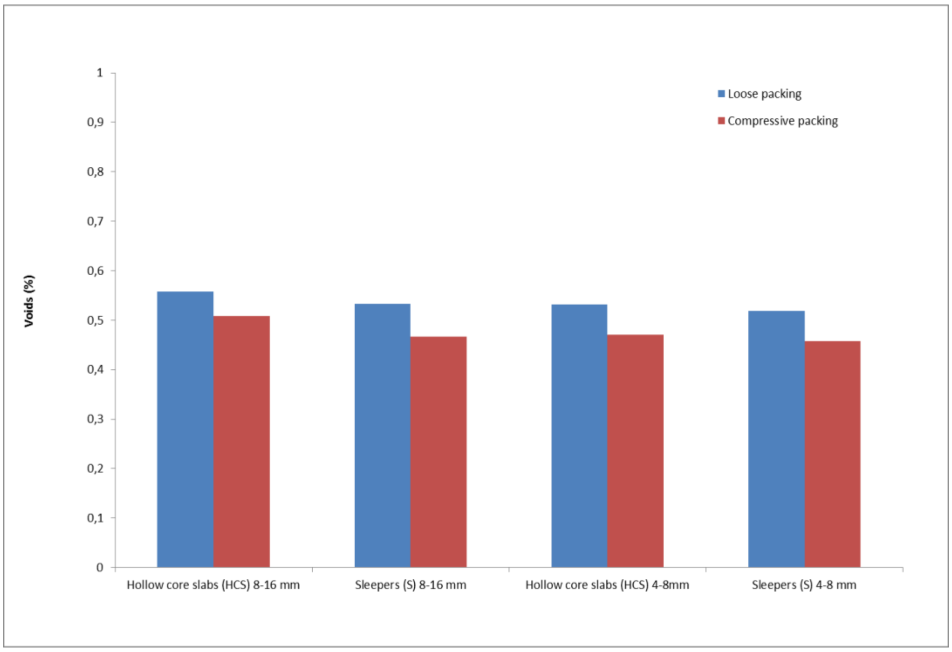

Figure 4 Comparison of voids at loose and compressive packing

Characterization by micro mortar and mortar test

The fine aggregate fraction (0-4 mm) and the filler fraction (0-0.125 mm) were evaluated in mortar tests (wet method). The materials were evaluated with increasing water content, i.e. both increased w/c-ratio and paste volume. The micro mortar composed of 30 g filler; 60 g cement (Bascement) and 36 g, 45 g and 54 g of water. The results showed that the water demand of the micro mortar containing filler from the sleepers was higher than when filler from the hollow core slabs was used, see Figure 5. This could be expected due to the higher fineness and specific surface area of the material from the crushed sleepers, see Figure 2.

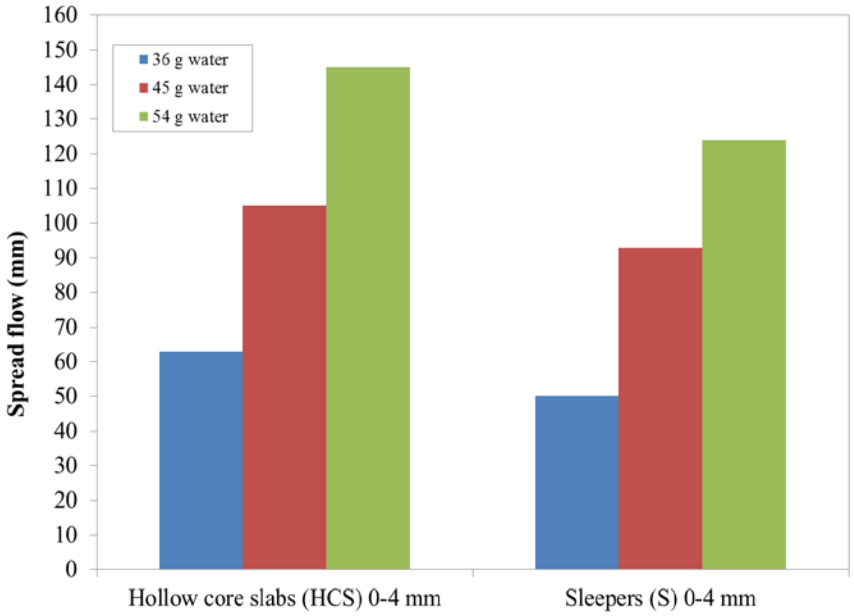

Figure 5 Spread flow of micro mortar with filler from the crushed hollow core slabs (HCS) and sleepers (S) with increasing water content. The diameter of the base of the mini slump cone was 38 mm.

The mortar consisted of 790 g of fine aggregate (0-4 mm), 360 g cement (Bascement), 244 g and 262 g water. The water demand was also greater when aggregates from the crushed sleepers (A) were used in the mortar tests, see Figure 6. Besides the difference in properties of the filler other material characteristics such as higher overall fineness (fineness modulus), higher water absorption etc. may play a role in the observed differences.

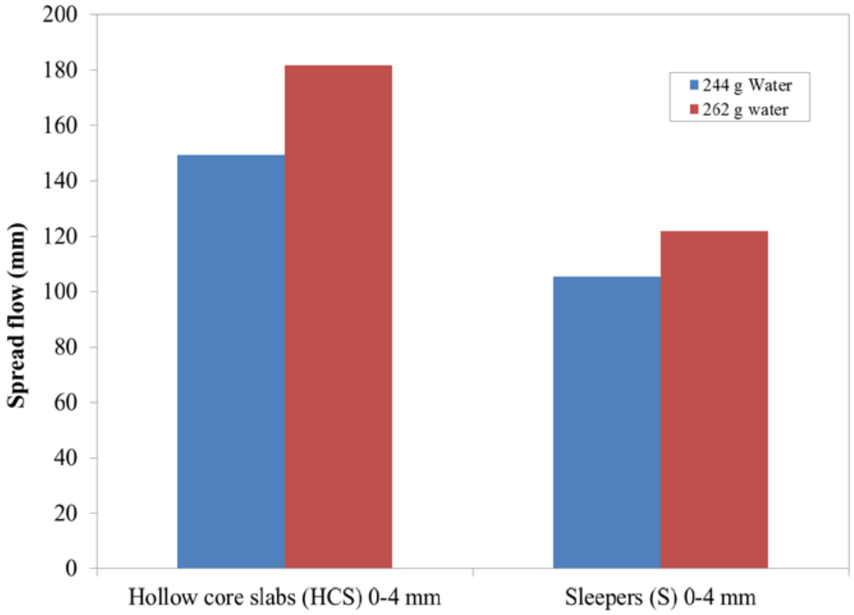

Figure 6 Spread flow of mortar with aggregates)(0-4mm) from the crushed hollow core slabs (HCS) and sleepers (S) at two different water contents. The base diameter of the slump cone (Hägerman cone) was 100mm.

Initial rheological evaluation of 0-4 mm RCA/WCA;Sleepers (S) and Hollow Core Slab (HCS).

The 0-4 mm materials from both sources and a natural aggregate were evaluated for their rheological behavior in a standard (CBI) mortar, in the rheograph these are referred to as “original”. In order to compare the effects of size optimization, both materials were sieved and separately blended to achieve a similar sieve curve, these are “graded”. This material was remixed into the standard (CBI) mortar and reevaluated. The class system refers to a desired area in which concrete aggregate fillers should fall into, class I being the most optimal etc.

The 0-4mm mortar testing needed density values in order to keep the volumetric ratios constant. The following results were obtained:

Table 0-1 RCA 0-4mm density results

Material	Density (g/cm³)
(S) 0-4mm	2.502
(HCS) 0-4mm	2.546

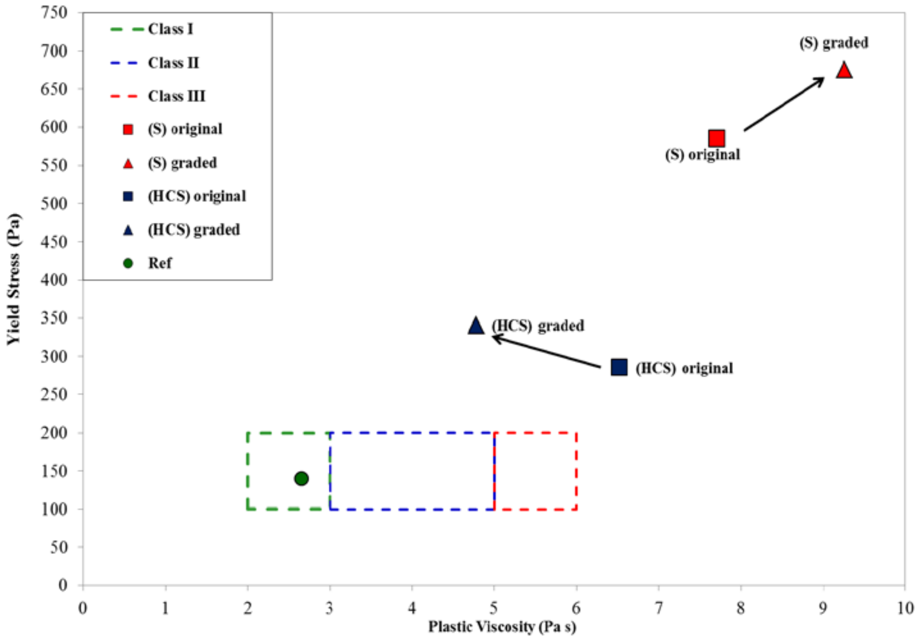

Figure 7 CBI standard mortar test on RCAs

The results in Figure 7 showed that the RCAs increased the yield stress (y axis) considerably especially the sleepers(S) material. This material also had the highest plastic viscosity (7.5 Pa s) compared to the hollow core slab(HCS) which was ca. 6.5 Pa s . The optimized grading had an effect on (HCS) but impacted negatively on (S) , see the series “ (S) graded” . Comparing the reference (Ref) with the other materials would imply that the concrete could be negatively affected with the use of these as substitute aggregates. Note that the mortar test was carried out with a whisk head attachment and had no superplasticizer added (w/c = 0.57).

Experiment

CO_2 uptake from crushed concrete aggregates

Introduction

To be able to present a correct model of the CO_2 emissions of a concrete structure during its entire life cycle, it is very important to describe the uptake of CO_2 in the material when the material is crushed correctly. Different models have suggested that the increase in uptake is only a function of the increased surface area of the material. This leads to a huge contribution of CO_2 uptake during the period the material was crushed. In (Andersson, Fridh, Stripple, & Häglund, 2013), the uptake in crushed concrete stored in piles was studied. It was shown that the uptake of CO_2 was very small since the concrete aggregate piles were not sorted nor sheltered against rain. Therefore it was extremely difficult for the CO_2 to reach the new concrete surfaces. It was also very difficult to take samples at different depths in the piles. To investigate if graded materials would have a better ability to absorb $CO_{2,}$ the two different concrete materials used in this study were sieved and placed outdoors and sheltered from rain.

Method

Concrete from railway sleepers (S) and hollow core slabs (HCS) were crushed and graded into three sizes 0-4 mm, 4-8 mm and 8-16 mm and placed in pallet collars with a net at the bottom, see Figure 8. To be certain of what depth the studied material had in the pallets, mesh baskets completely surrounding the material were used, see Figure 9 & Figure 10.

Figure 8 The six pallet collars with graded material. There were 100mm between the bottom of the pallet collar and the pallet.

Figure 9 Every pallet collar contained three baskets of the material

.

Figure 10 Mesh basket

After 1.5 years, one basket of each material was tested at four levels. 0, 12, 24 and 36 cm from the top surface, see Figure 10. Both the degree of carbonation and the amount of cement paste in each fraction was measured. The latter was important if the uptake should be properly modelled.

The degree of carbonation was measured with a technique where the material was dissolved in 18.5% HCl solution in a sealed container. The weight measured before and after the dissolution accounted for the amount of paste in each sample. To determine the degree of carbonation, the pressure increase in the vessel was measured and the amount of calcium was determined in the solution by ICP-AES.

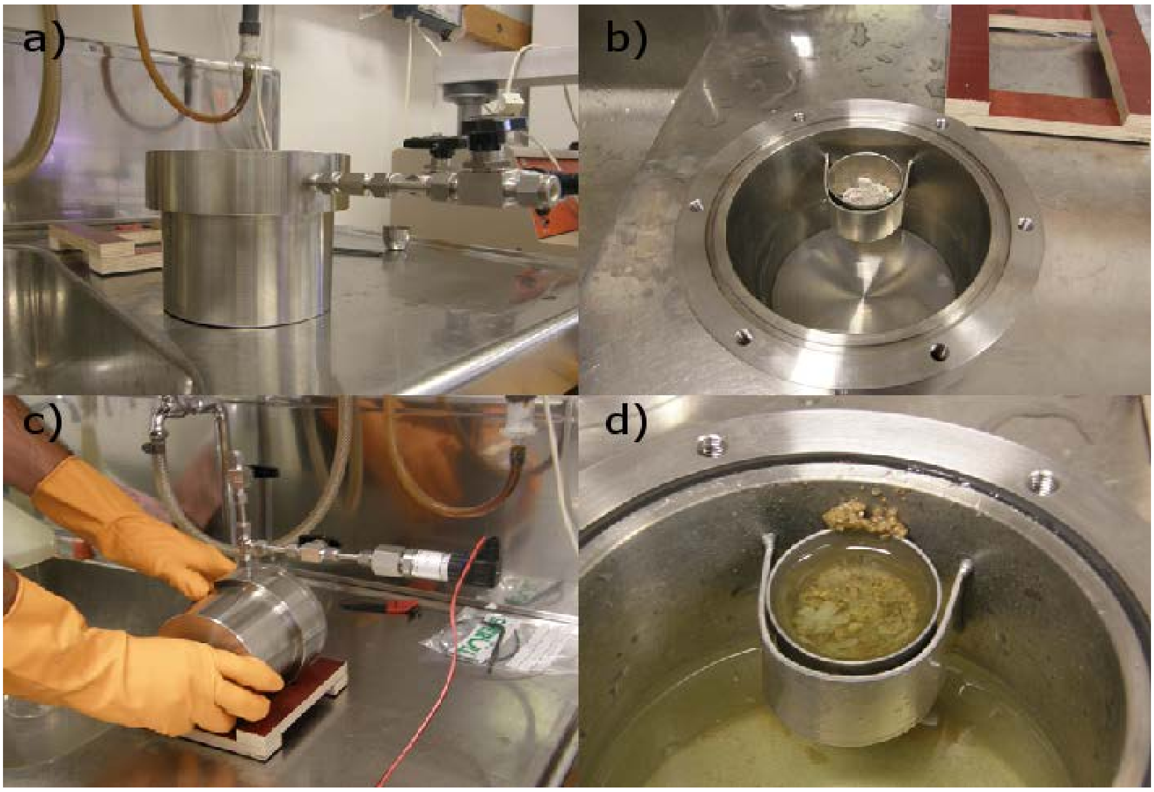

Figure 11 a) Vessel b) Concrete aggregates in vessel c) Pressure monitoring d) Concrete Aggregates after testing

Results

Figure 12 shows the weight loss of the samples after the dissolution in HCl. The concrete from the sleepers (S) contained the most cement paste regardless of size fraction. The largest variation occurred in the smallest fraction.

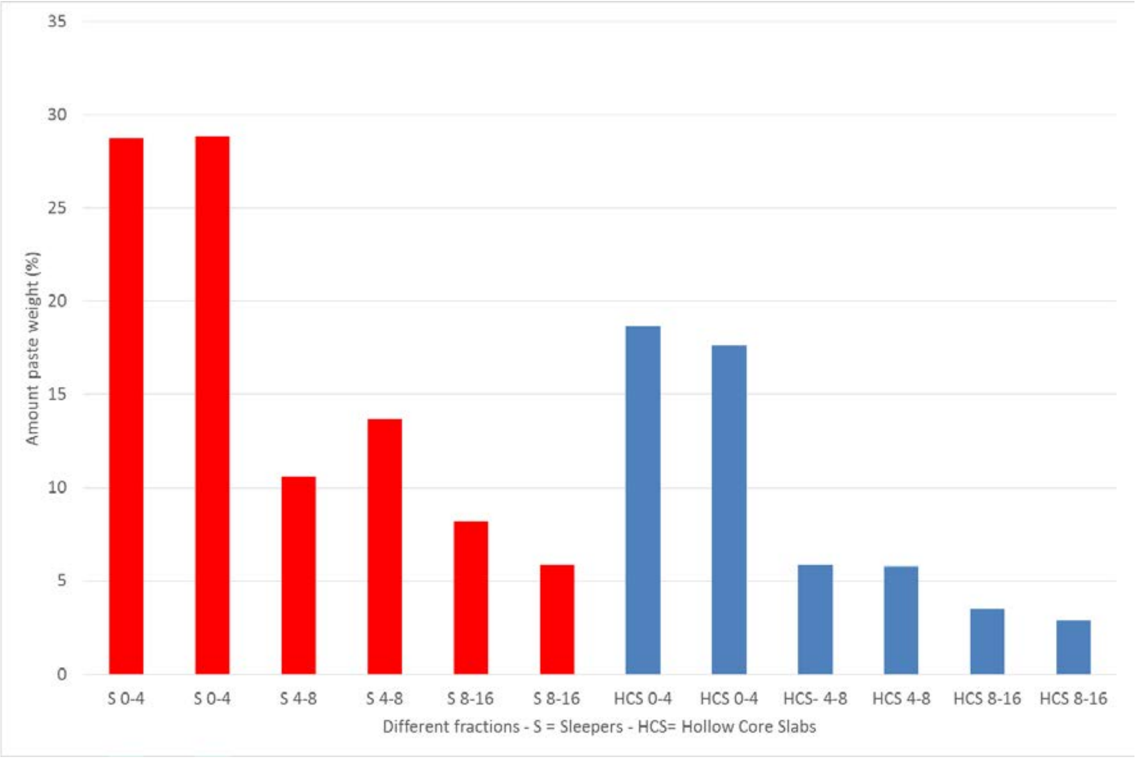

Figure 12 Amount of paste in the crushed material. Two samples of each fraction. "S" was concrete from Sleepers and "HCS" was concrete from hollow core slabs.

The degree of carbonation was measured at four depths; top surface (0cm), 12 cm , 24 cm and at the bottom (36cm). One measurement was made at every depth and for every material. The amount of calcium per sample was determined by ICP-AES. The degree of carbonation was determined as the ratio of moles CO_2 determined by the pressure measurement and moles Ca determined by ICP-AES measurement.

Figure 13-Figure 15 show the degree of carbonation at different depths for the two crushed materials.

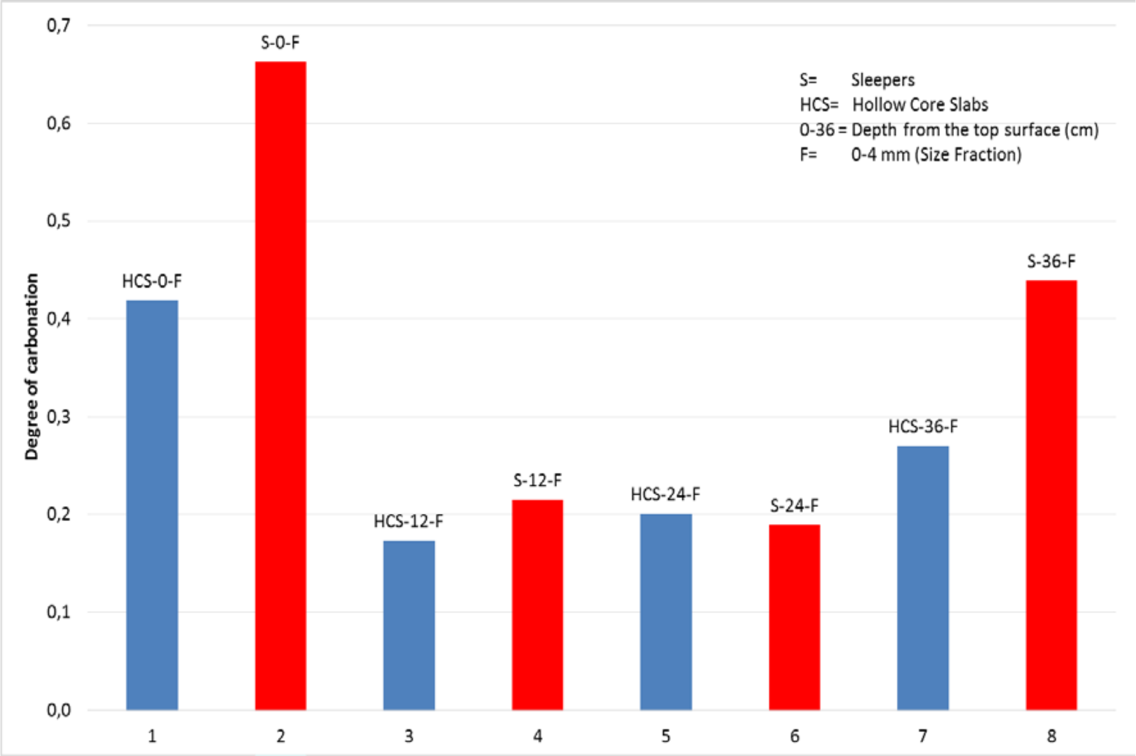

Figure 13 Degree of Carbonation 0-4mm

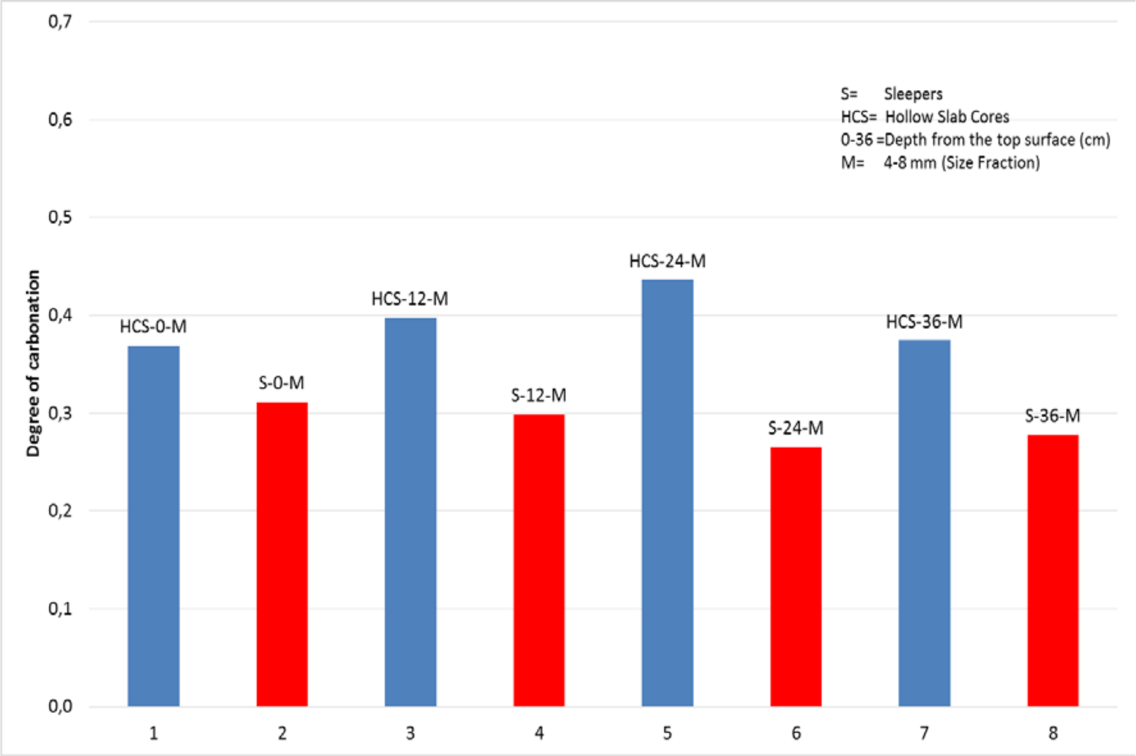

Figure 14 Degree of Carbonation 4-8mm

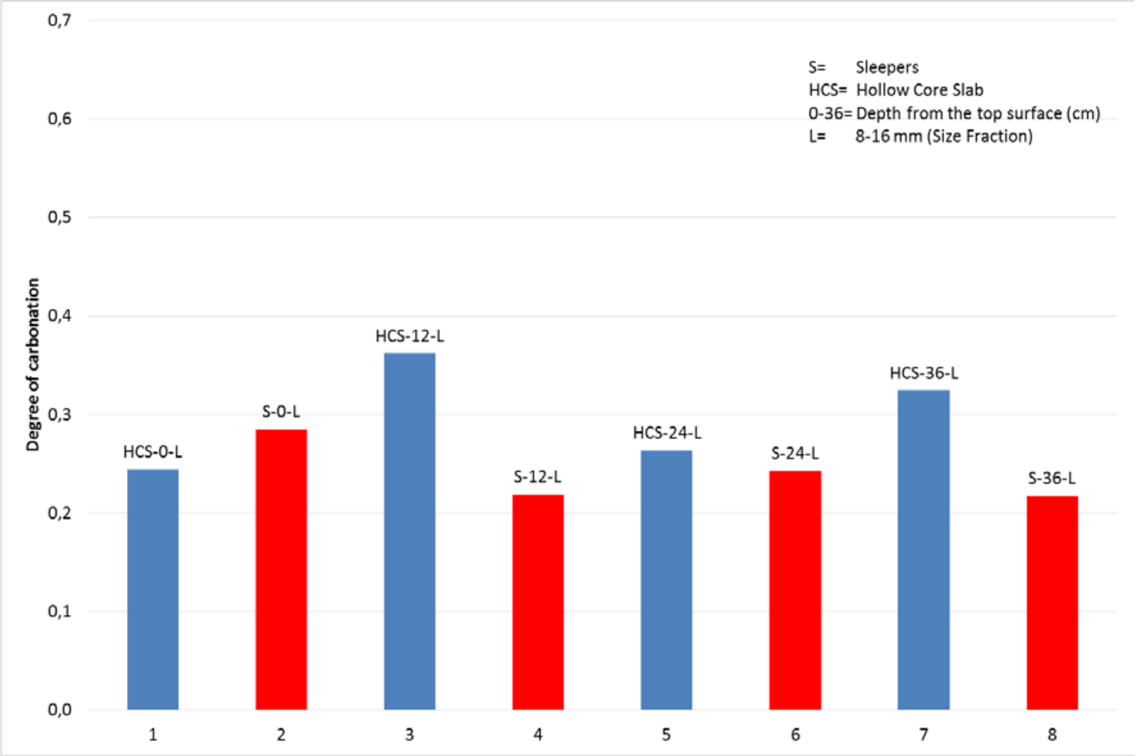

Figure 15 Degree of Carbonation 8-16mm

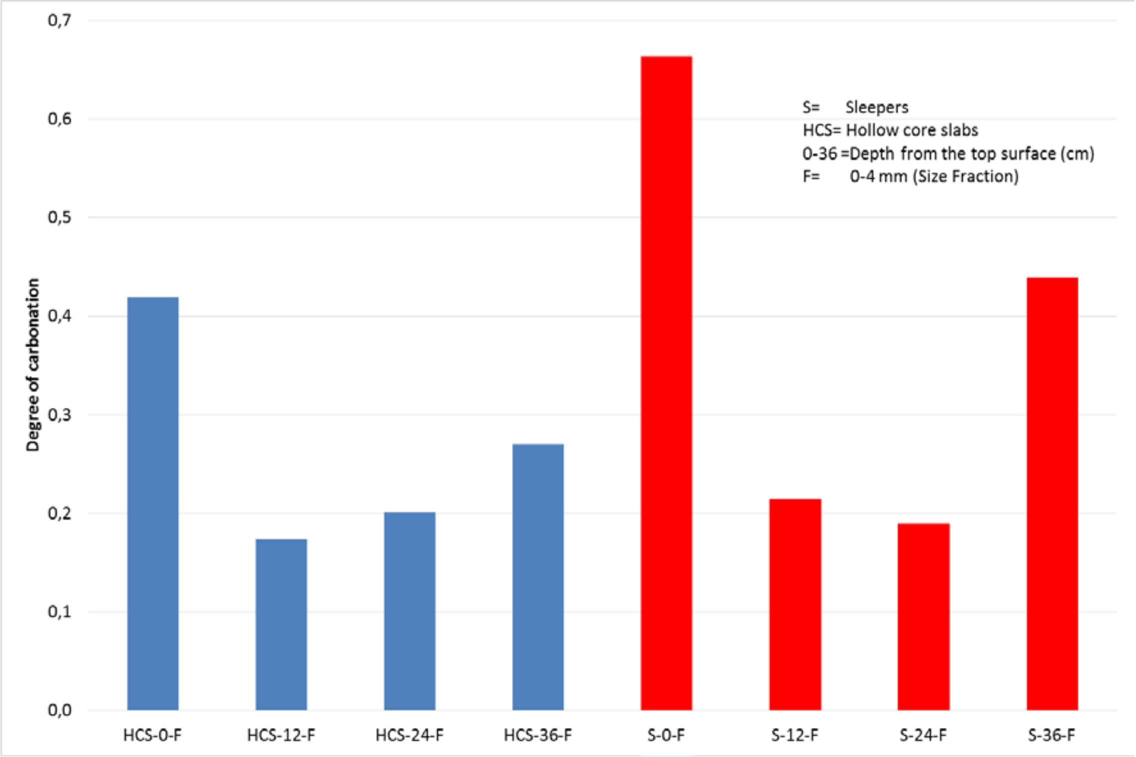

Figure 16 Carbonation profile for size fraction 0-4mm

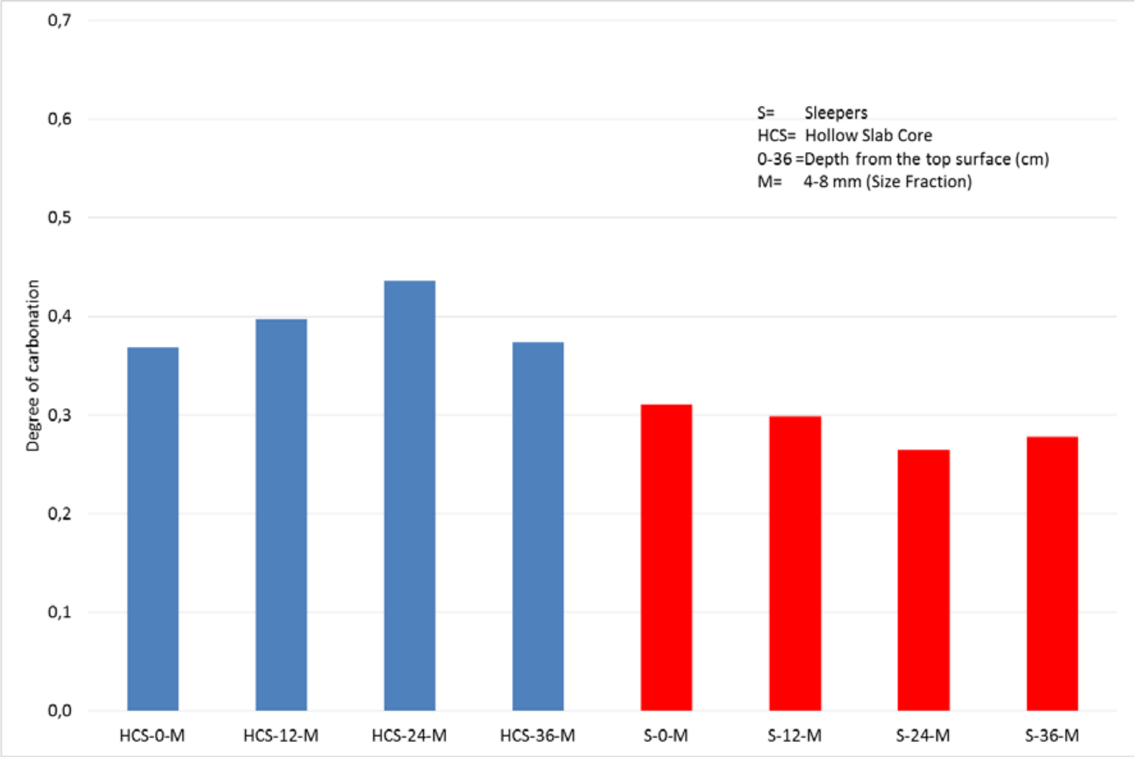

Figure 17 Carbonation profile for size fraction 4-8mm

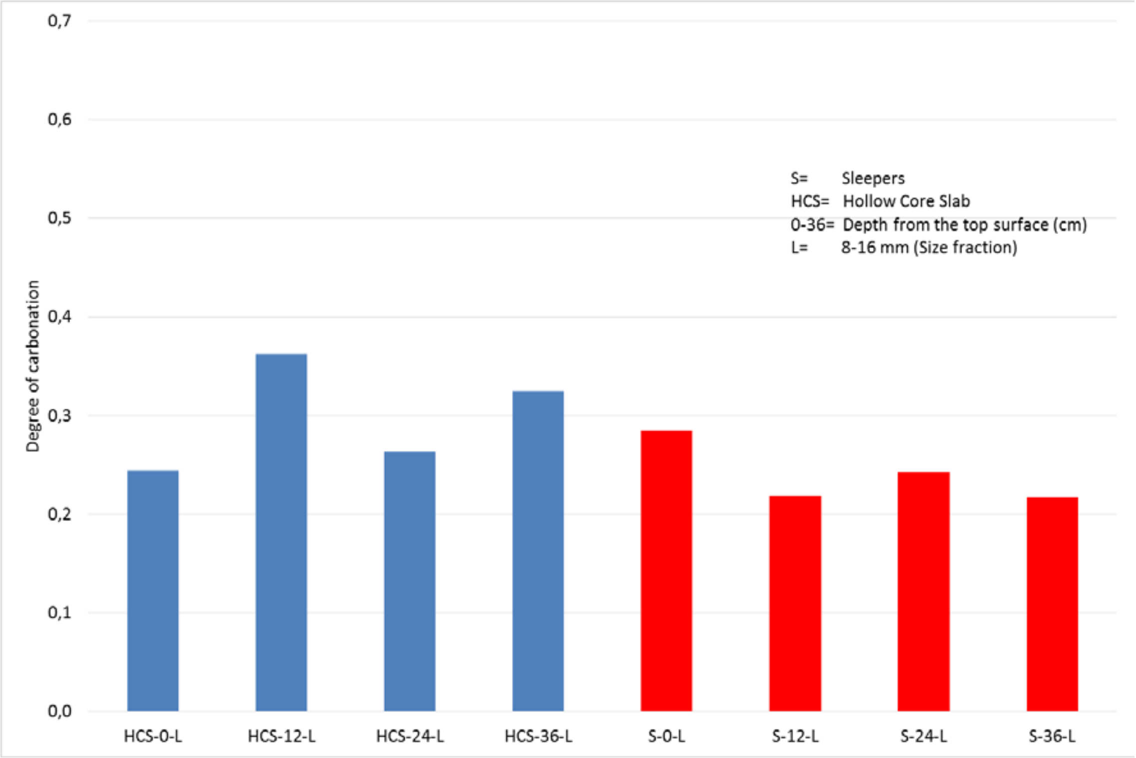

Figure 18 Profile Degree of carbonation for size fraction 8-16mm

Figure 16-Figure 18 show the carbonation profile of the two materials.

Discussion

All materials showed increased carbonation rates compared to the study of ungraded material without shelter from rain. It could be interesting to incorporate this knowledge into future waste handling of crushed concrete.

For the 0-4 mm material, it was found that the concrete from the sleepers (S) contained about 28 wt. % cement paste and the crushed concrete from the hollow core slabs (HCS) contained about 18 wt. % cement paste, Figure 12. The materials were crushed with two different crushers and it was not known how or if this affected these results. The degree of carbonation at the top (0cm) was 0.65 for the crushed concrete from sleepers(S) and 0.4 in the crushed concrete from the hollow core slabs(HCS), Figure 13. At the bottom (36 cm) the figures were 0.45 and 0.28 respectively, Figure 13. Since there was a difference between the top and bottom it was likely that the CO_2 transport hadn't been exactly the same on either sides, Figure 16. The grading of this 0-4 mm material wasn't that effective in order to increase the CO_2 transport into the centre of the material pile, the degree of carbonation was very low (0.2) , Figure 13. The 0-4mm concrete aggregates from the hollow core slabs (HCS) were exposed to rain which created a cement paste on the surface (0cm) which increased the degree of saturation and these combined prevented CO_2 flow into the centre.

For the size fraction 4-8 mm, it was found that the concrete from the sleepers (S) contained about 12 wt. % cement paste and the crushed concrete from the hollow core slabs(HCS) contained about 6 wt.% cement paste, Figure 12. The materials were crushed with two different crushers and it was not known how or if that affected these results. The degree of carbonation was 0.3 for the crushed concrete from sleepers (S) at all depths and 0.4 in the crushed concrete from the hollow core slabs (HCS) at all depths, Figure 14. It had been easier for the CO_2 to penetrate these materials which lead to the same degree of carbonation at all depths, Figure 17. The level of degree of carbonation was lower than for the 0-4mm materials (except for the case of HCS 0-4mm) and the amount of paste was also less. The aggregates are interfering with the CO_2 diffusion, making it harder for the CO_2 to reach all the paste. The specific surface of the 4-8 mm materials was also lower than in the smaller fraction and probably leading to fewer surfaces to carbonate. A somewhat higher degree of carbonation was found in the concrete of the hollow cores slabs and one explanation could be the slightly higher amount of voids in that crushed concrete.

For the material in size fraction 8-16 mm it was found that the concrete from the sleepers contained about 7 wt. % of cement paste and the crushed concrete from the hollow core slabs contained about 3 wt. % of cement paste, Figure 12. The materials were crushed with two different crushers and it was not known how or if that affected these results. The degree of carbonation was 0.25 for the crushed concrete from sleepers at all depths and 0.3 in the crushed concrete from the hollow core slabs at all depths, Figure 15. It had been easier for the CO_2 to penetrate these materials which lead to more equal degree of carbonation at all depths, Figure 18. The level of degree of carbonation was lower than for the 4-8 mm materials and the amount of paste was less. The aggregates are probably interfering with the CO_2 diffusion, making it harder for the CO_2 to reach all the cement paste. The specific surface of the 8-16 mm materials was also lower leading to a reduced amount of potential surfaces to carbonate. A somewhat higher degree of carbonation was found in the concrete of the hollow cores slabs and one explanation could be the slightly higher amount of voids in that crushed concrete.

Conclusions

- It was found that the larger the size fraction of crushed concrete, the lower the amount of attached cement paste.
- It was also found that the lower amount of cement paste in a size fraction, the lower the degree of carbonation. This is believed to be due to aggregates preventing the CO_2 transport and due to lower specific surfaces in the larger size fractions.
- The amount of paste on each fraction depended on the strength of the original concrete and for small size fractions there can be significant variations.

Future studies

- To be able to model the CO_2 uptake in crushed concrete accurately, a more thorough characterization of the cement paste in the different fractions are needed.
- It is important to continue to follow the increase in degree of carbonation over time for the materials in this study.This is possible since the experimental setup is still in place,Figure 8.
- These results should be tested against existing models for CO_2-uptake in crushed concrete.

Concrete

Primary materials

Natural aggregates 0-16mm

The natural aggregates used were supplied by Jehander, part of the Heidelberg Group, and came from Riksten, Botkyrka. The 0-8mm size fraction was sieved to remove ≥ 4mm particles. The 4-8 and 8-16 mm materials were thoroughly washed and dried to remove the variation of surface adhered fine materials that was discovered during the initial experimentation and effected comparisons in workability.

SIEVE CURVE

Cement

The cement used in the self-compacting concretes, with a w/c = 0.5, was a CEM II A-V 52.5N from Cementa. Commercially it is referred to as “Bascement” and incorporates a certain amount of fly ash which offsets the amount of clinker used in the cement and hence reduces its CO_2 footprint.

Anläggningscement (CEM I 42.5 N LA MH SR3) from Degerhamn was used for the freeze-thaw resistant concrete, i.e. the concrete with a w/c = 0.4 plus entrained air.

Filler

The filler used in the project, Limus 25, was finely ground limestone and was produced by Nordkalk.

Superplasticizer

One superplasticizer was used in the project and was based on a those used in the prefabricated concrete industry. In this case BASF’s Glenium ACE 30 was used.

Air Entrainer

The air entrainer, MicroAir 100 (TA 10-12%), was used in the concretes with a w/c of 0.4. This was used to create a freeze thaw resistant concrete. The air entrainer was a tenside based concentrate.

Reclaimed Concrete Aggregates

The crushed concrete consisted of two source materials. Recently produced hollow core slabs from Strängbetong and decommissioned railroad sleepers located at Abetong’s Vislanda factory(information about the crushing is unknown) . The material from Strängbetong came from the Nykvarn factory and was crushed in two stages. Firstly the concrete was processed through a jaw crusher then followed by a further size reduction in a cone crusher. The material was delivered dry whereas the material from Abetong was damp on arrival. The three size fractions of both materials (0-4mm, 4-8mm and 8-16mm) were oven dried at 40 °C for at least a week. The 0-4mm materials were collected from the oven and divided into representative samples in order to reduce variation.

Both suppliers were responsible for the production and delivery of the crushed concrete to CBI in Stockholm. No testing of the aggregates such as SS-EN 1744 , EN 933 or EN 1097 was carried out during the experiments.

The original recipe of the hollow core slab was provided by Strängbetong

Table 0-1 Hollow Core Slab recipe

Material:	kg/m^3
Cement CEM I 52.5 R	345
Macadam 6-11mm	1330
Concrete aggregates 0-8mm	1575
SP	1.1
Water	132
w/c	0.385
Density	2480

Figure 19 RCA a) HCS ; b) Sleepers

Concrete Experiments

The reference recipe was based on a previous one from work carried out at CBI, the w/c was 0.5. The 0-4mm and 4-8mm fractions were based on sieving curve measurements and were divided up into 79 % wt. 0-4 mm and 21 %wt. 4-8mm. The replacement amounts in the lower fraction 0-4mm are comparable to the limits set out by SS 137003. The amount set out on the standard is based on % mass, but in order to have comparable rheological results and take the two different material densities into account, % volume was used. The total aggregates content was 1719 kg/m^3 or 648 $litres/m^3$.

The densities of the size fractions differed between sources and even within the different size fractions. The density difference between the natural aggregates 2650 kg/m3 and the recycled aggregates ca. 2540 kg/m^3 is approximately 4%.

Table 0-2 Base recipe; SCC w/c 0.5

Material:	**kg/m^3**
Bascement CEM II A/V 52.5 N	350
Limus 25	78
NA* 0-4mm	826
NA* 4-8mm	193
NA* 8-16mm	700
Water	175

*NA : Natural Aggregates

Experimental Matrix:

Table 0-3 Experimental matrix; SCC w/c = 0.5.

Replacement of:	**% volume NA**						
NA 0-4mm with RCA* 0-4mm	0	5	11	22	33	66	100
NA 4-8mm with RCA* 4-8mm	0			50			100
NA 8-16mm with RCA*8-16mm	0			50			100

*RCA: Reclaimed Concrete Aggregates

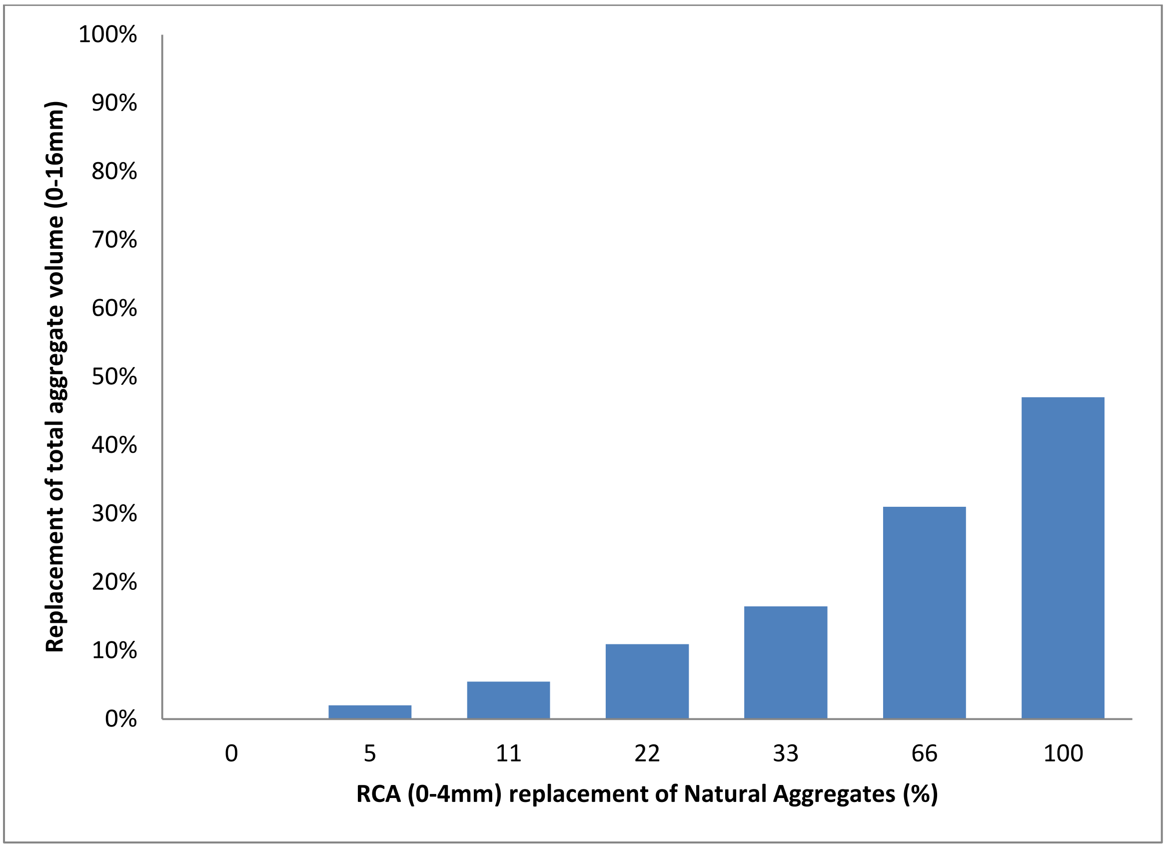

Figure 20 Replacement level; 0-4mm.

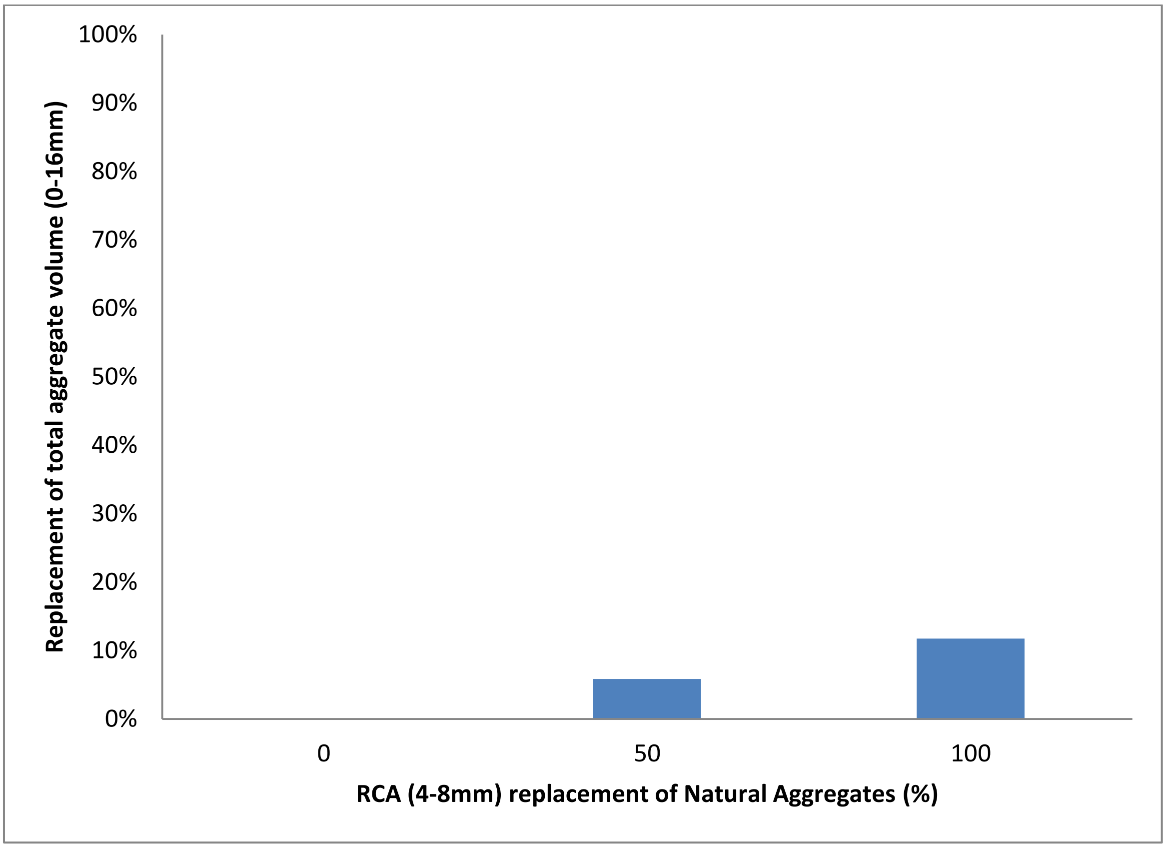

Figure 21 Replacement levels; 4-8mm.

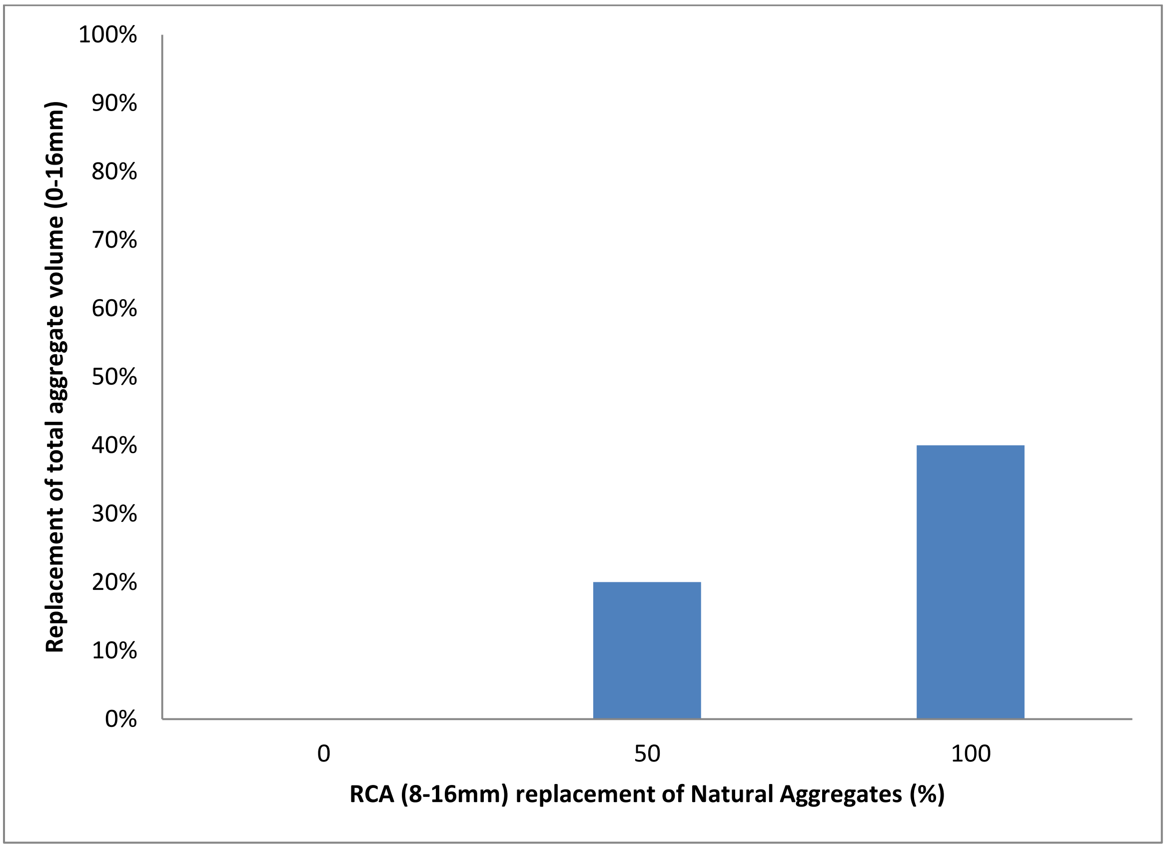

Figure 22 Replacement levels; 8-16mm.

Table 0-4 Numerical replacement level of self-compacting concrete w/c =0.5.

Replacement 0-4mm	**Total aggregate vol. 0-16mm**	**Replacement 4-8mm**	**Total aggregate vol. 0-16mm**	**Replacement 8-16mm**	**Total aggregate vol. 0-16mm**
%	%	%	%	%	%
0	0	0	0	0	0
5	2	50	6*	50	20
11	5*	100	12	100	40***
22	10				
33	15				
66	30**				
100	46				

* The limit, 5%, whereby any reclaimed aggregates or reclaimed concrete aggregates can be mixed into any exposure class of concrete

** The limit of reclaimed concrete aggregates, by mass, allowed in the coarse fraction of a concrete. RCA quality is better or equal to the new concrete. No mention of fine fraction 0-4mm in standards.

*** 10% over the allowed limit according to SS 137003:2015 table 6 if this applied for fine fraction.

Table 0-5 Base recipe; Freeze-thaw resistant concrete w/c = 0.4.

Material:	kg/m^3
Anläggningscement CEM I 42.5 N	420
Limus 25	48
NA 0-4mm	866
NA 4-8mm (washed)	203
NA 8-16mm (washed)	600
Water	168
MicroAir 100 (TA 10-12%)	0.27

Table 0-6 Experimental matrix for the freeze thaw resistant concrete w/c = 0.4.

Replacement of:	% volume of natural aggregates						
NA 0-4mm with RCA 0-4mm	0	5	11	22	33	66	100
NA 4-8mm with RCA 4-8mm	0			50			100
NA 8-16mm with RCA 8-16mm	0			50			100

Mixing

The mixing equipment used in the project was an EIRICH model R 09 T with a delta star agitator and counter current mixing pattern (18kW). This was used for the self-compacting concrete 0.5 w/c.

Figure 23 EIRICH Mixer R09 T; SCC concrete mixing w/c 0.5.

Figure 24 Power draw gauge for EIRICH mixer agitator.

For the freeze-thaw resistant concretes, a smaller scale mixer was used to batch the 20 litres of concrete, a 50 UEZ Mischtechnik (5kW)

Figure 25 Mixer used for the freeze thaw resistant concretes ; ZM 50 UEZ.

Mixing times and methodology

Self-compacting concrete w/c 0.5 (80 litre batches)

All concretes were prepared and mixed in the same fashion.

1. All dry materials were weighed up and added into the mixer pan (EIRICH).
2. Dry mixing for 60 seconds; slow speed agitator and mixing pan.
3. The water was added to the dry mix and both bowl and agitator were turned on (slow).
4. The power draw on the star shaped agitator was recorded every 10 seconds (analogue).
5. 100 g of SP (2,1kg/m^3) was added.
6. The mixer was turned on for an additional 120 seconds.
7. Approx. 10l of concrete was removed and tested for slump and the time was noted.
8. All concrete was returned to the mixer.
9. Additional SP was added until it was deemed a self-compacting concrete was obtained and mixed for 60 seconds.
10. The concrete was measured for slump flow and the time was noted.
11. Additional mixing and SP was added until slump flow > 680mm.
12. The rheology mixing bowl was filled and the SCC was quickly measured in the rheometer.
13. The entrained air was measured and recorded.

Freeze thaw resistant concrete w/c 0.4 (20 litre batches)

All concretes were prepared and mixed in the same fashion.

1. All dry materials were weighed up and added to the mixer (ZM 50).
2. Dry mixing for 60 seconds
3. The air entrainer was added into the water
4. The water was added to the dry mix, WAT started.
5. A fixed amount of SP 90g (approx. 4.4 kg/m^3)was added 30 seconds after WAT.
6. The mixer was allowed to mix for 180 seconds.
7. The concrete was removed and tested for slump and the time was noted.
8. The entrained air was measured and recorded.

During the workability measurements (rheology), the following specimens were cast:

- 100mm x 100mm x 100mm cubes for 1, 7 and 28 day compressive strengths
- 3x shrinkage prisms (100mm x 100mm x 400mm) for each series (SCC w/C 0.5 only)
- 150mm x 150mm x 150mm cubes for freeze thaw and chloride diffusion testing (for freeze-thaw resistant concretes only)

Self-Compacting Concrete

Results (fresh properties)

Power draw measurements (Swedish :omformningstal)

The power draw from the star shaped agitator was recorded after the water was added into the mixer pan (EIRICH). This was denoted WAT (water added time) and is “0” on the diagrams. After 60 seconds 100 g of SP was added and its effect can be seen after “60”, see along the x-axis.

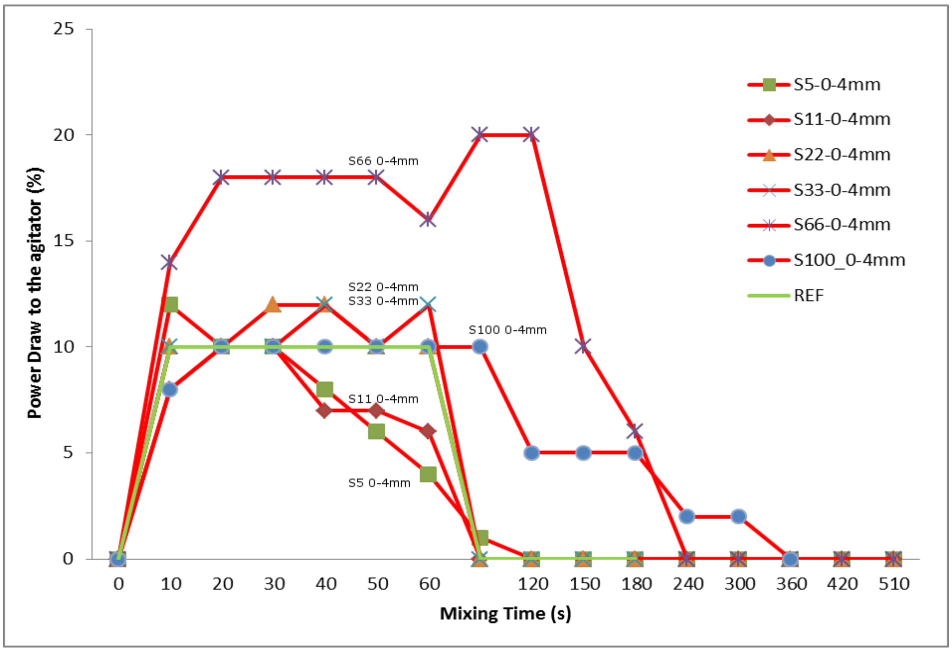

Figure 26 Power Draw during mixing Sleepers 0-4mm (agitator)

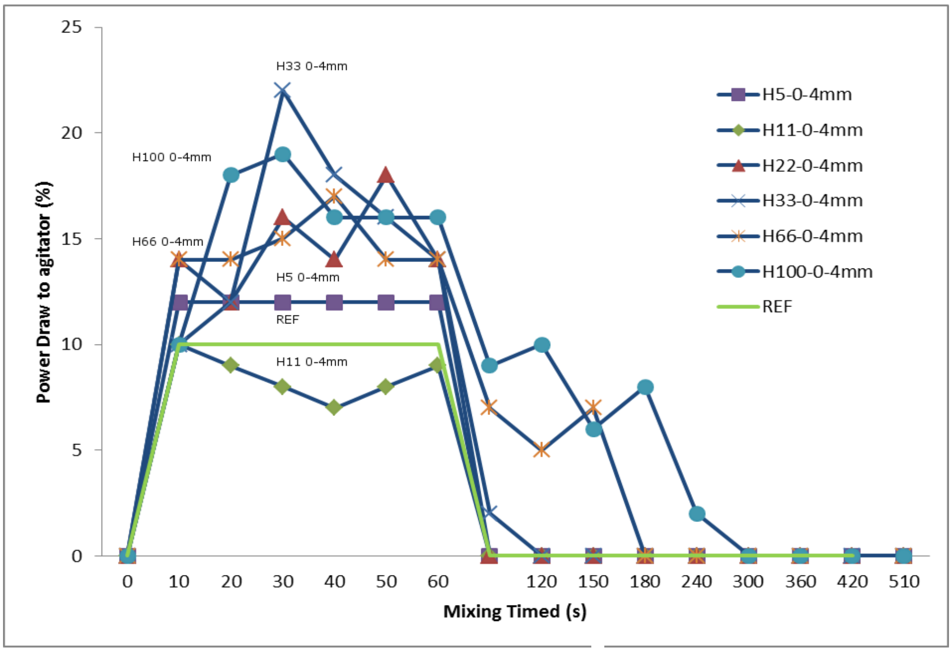

Figure 27 Power Draw during mixing HCS 0-4mm (agitator)

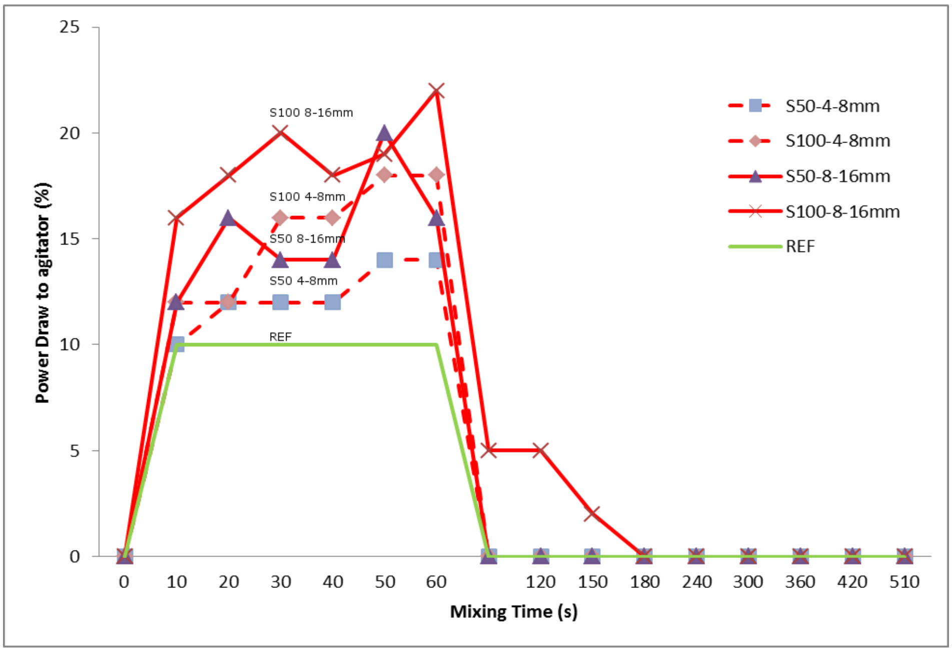

Figure 28 Power draw during mixing Sleepers 4-16mm(agitator)

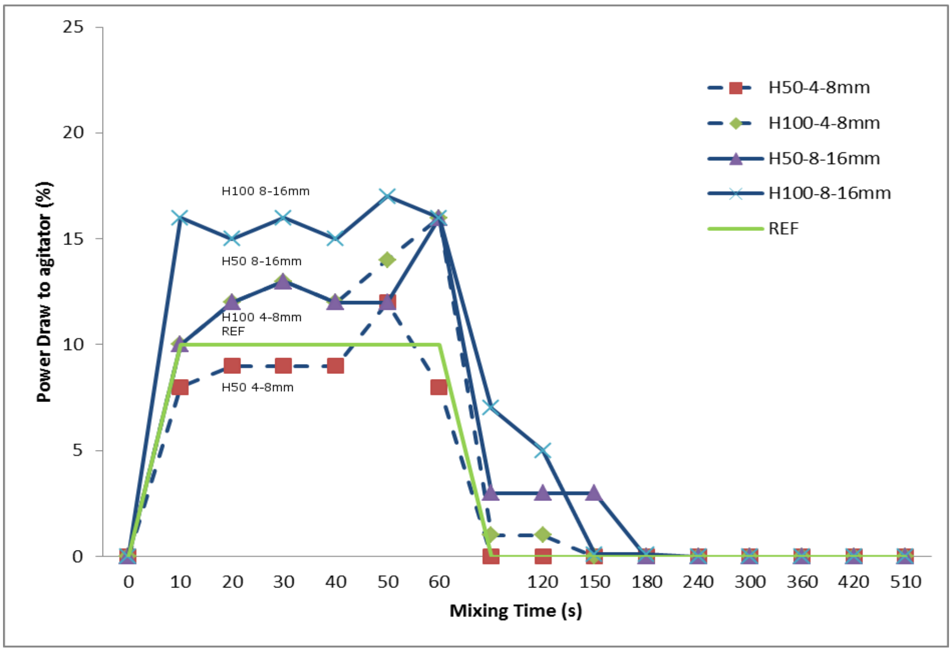

Figure 29 Power draw during HCS 4-16mm (agitator)

Discussion (Power Draw)

0-4mm

The reference (green line) shows the internal resistance for 0-4mm natural aggregates. It remains stable during mixing. Increasing amounts of Sleepers or HCS 0-4mm increased the internal resistance of the mixture, except in cases S5,S11 and H11 -0-4mm, until the SP was added into the mix (after 60 seconds). There were trends to be observed:

1. Generally the higher replacement level of NA with RCA caused a higher internal resistance.
2. The HCS material had a more proportional behavior than Sleepers, i.e. a higher power draw was noted for increasing amounts of the material.
3. The initial internal resistance was an indication of the amount of SP required to obtain similar slump flows.

The S100 0-4mm batch saw a drop in the power required due to the water absorption and surface area of the material and created a very dry mix, with very little internal resistance. The drops in S5 and S11 before SP is added was noticeable and even reflected in the slump flow and dosage required; 2.1 and 3.4 kg/m^3 respectively, see Table 0-6. It cannot be ruled out that the mixing procedure caused a milling effect and hence increased the surface area compared to the initial material. See Grinding effect during concrete production in the Appendix for pictures obtained after the mixed concrete (freeze thaw resistant w/c 0.4) was cleaned and sieved in the size fraction 4-5.6 and 5.6-8mm. The recycled concrete can be clearly identified. The initial concrete only had RCA in the 8-16mm size fraction, see Figure 57 & Figure 58.

4-8mm & 8-16mm

The amount of resistance experienced in the Sleepers 4-8 mm & 8-16mm was higher than in HCS 4-mm and 8-16mm. It was also noted that the resistance increased as the mixing progressed. Reasons for this can be contributed to the amount of fine material found in the surface of the Sleepers material and due to the breakdown of the aggregate into smaller particles.

The type of crushing may also have a bearing on the internal cracks and weaknesses in the recycled product. The ratio of aggregates to cement paste per m^3 in the HCS original product was higher than for the Sleepers product and could also lead to fewer weaker points between the aggregate and cement paste. No information on the tensile strength of the original products was available at the time of writing.

Conclusion (Power Draw)

The materials underwent an internal milling effect in the counter current pan mixer and caused an increased surface area. This led to a “stiffer” mix i.e. more energy required in the agitator. This may not be negative as the “faults” and “weaknesses” in the cement paste and aggregate in the RCA were reduced by this milling action. This though causes issues with determining the rheology/workability of these products as variations in mixing times probably result in different amounts of new surfaces being created.

Slump flow

Table 0-7 Slump flow SCC w/c 0.5 Sleepers

Replacement of:	**% volume of natural aggregates**						
Sleepers 0-4mm	REF	5	11	22	33	66	100
Slump flow (mm)	680	680	720	690	690	715	620
SP ACE 30 (kg/m^3)	3.5	2.1	3.4	3.0	3.1	4.5	7.3
Sleepers 4-8mm				50			100
Slump flow (mm)	680			690			690
SP ACE 30 (kg/m^3)	3.5			3.5			3.5
Sleepers 8-16mm				50			100
Slump flow (mm)	680			690			680
SP ACE 30 (kg/m^3)	3.5			3.36			3.8

- All concretes obtained an air content below 2%

Table 0-8 Slump flow SCC w/c 0.5 Hollow Core Slab (HCS)

Replacement of:	**% volume of natural aggregates**						
HCS 0-4mm	REF	5	11	22	33	66	100
Slump flow (mm)	680	650	680	730	680	680	710
SP ACE 30 (kg/m^3)	3.5	3.3	3.1	3.7	3.7	3.0	3.0
HCS 4-8mm				50			100
Slump flow (mm)	680			680			680
SP ACE 30 (kg/m^3)	3.5			3.0			3.0
HCS 8-16mm				50			100
Slump flow (mm)	680			670			650
SP ACE 30 (kg/m^3)	3.5			3.3			3.9

- All concretes obtained an air content below 2%

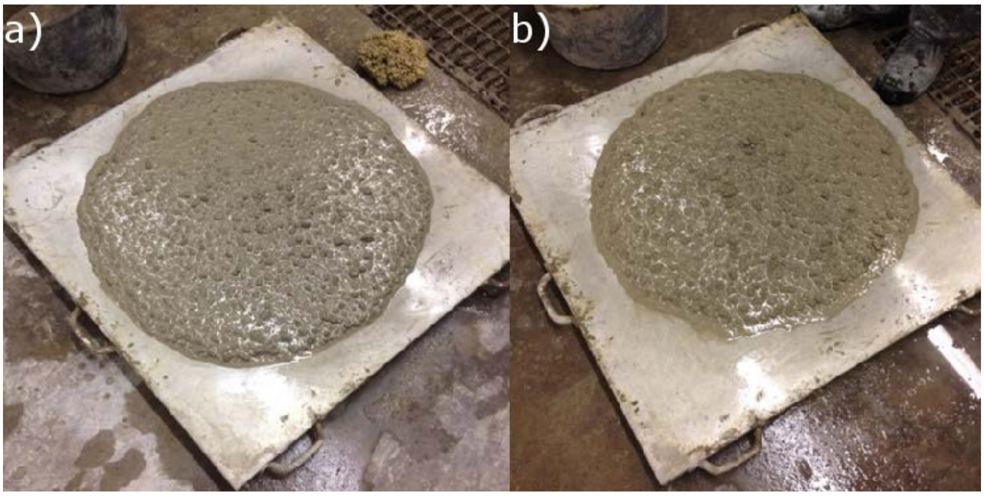

Figure 30 SCC a) w/c 0.5 S100 8-16mm b) w/c 0.5 H100 8-16mm

Rheology

All self-compacting concretes with a w/c of 0.5 were tested for their fresh properties over a set period of time. Once the concrete had reached a slump flow above 680 mm, it was transferred to a measuring cylinder and tested for yield stress and plastic viscosity. The concrete was tested and for every measured point in time there is a point on the graph representing the plastic viscosity (Pa s ;X-axis) and the yield stress (Pa ; y axis). The is a correlation between yield stress and slump flow.The temperature was noted during the testing and was 20° C ± 2 . The final measurement was 60 minutes after the addition of water (WAT; water adding time)

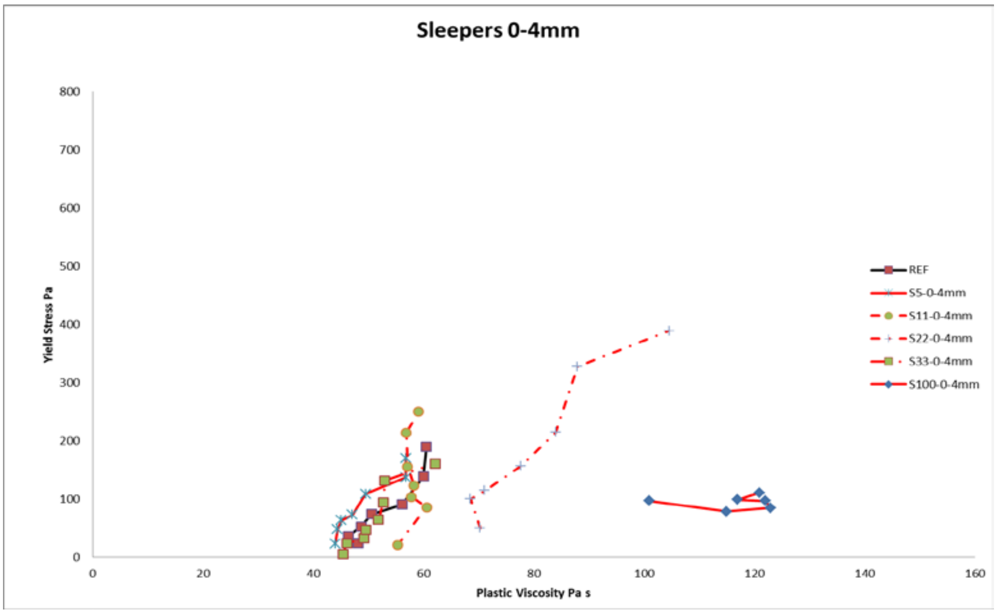

Figure 31 Rheology; Sleepers 0-4mm.

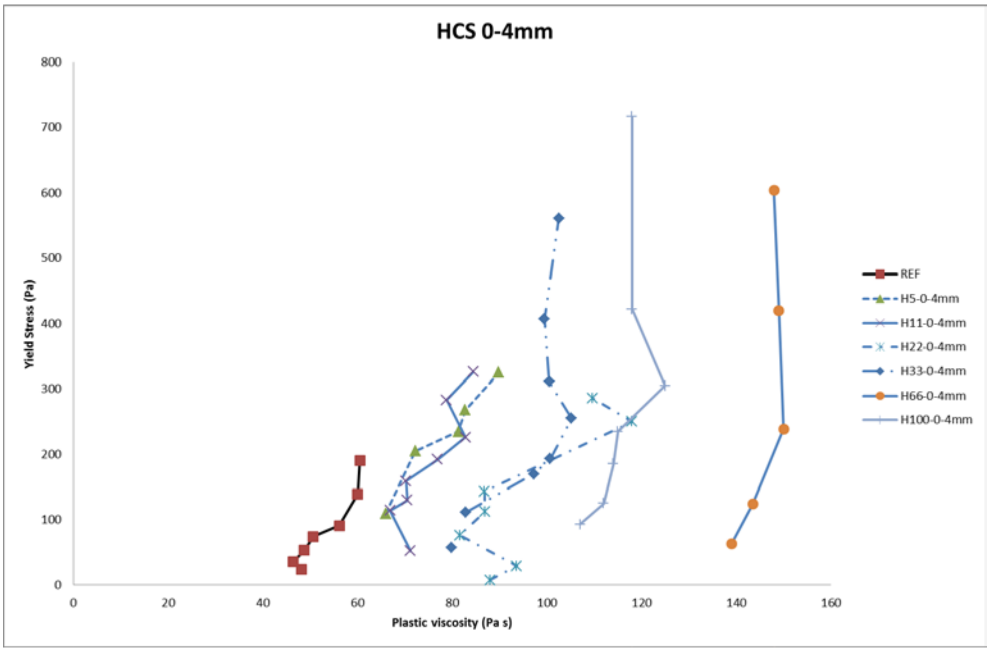

Figure 32 Rheology; HCS 0-4mm.

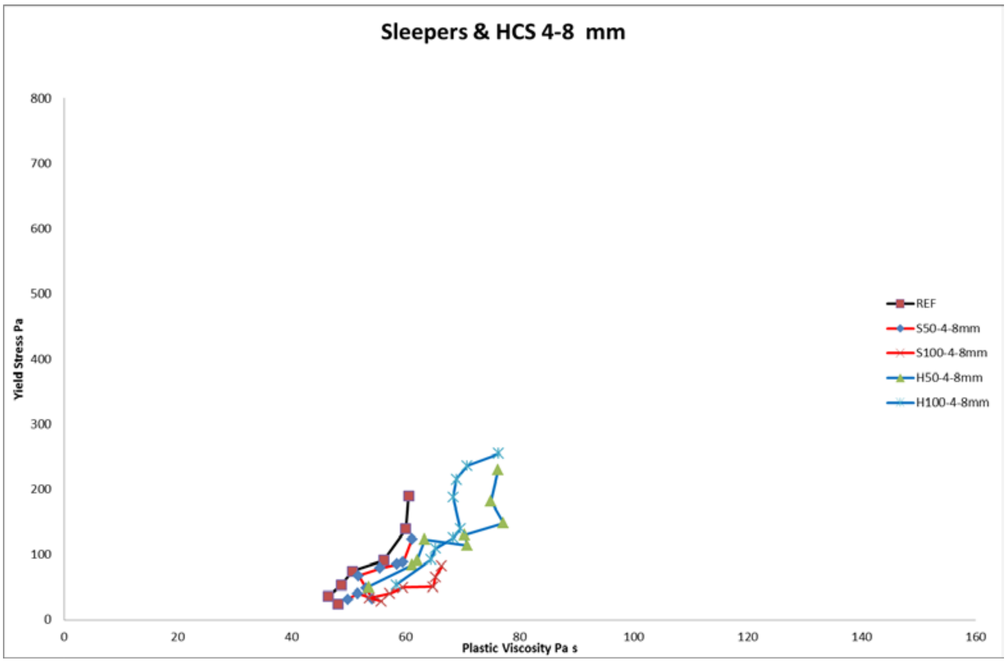

Figure 33 Rheology; Sleepers & HCS 4-8mm.

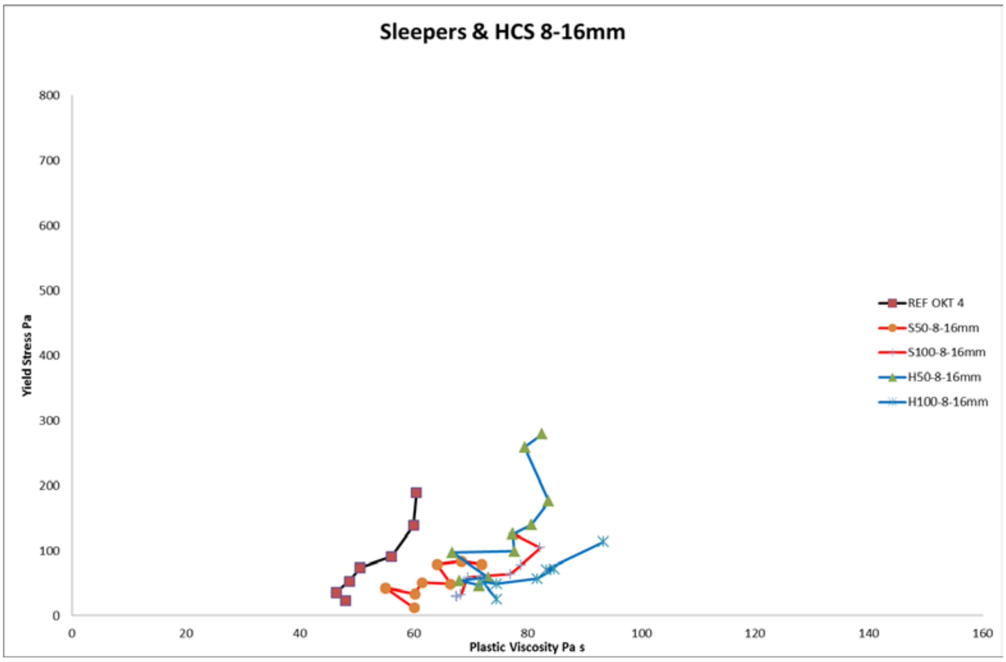

Figure 34 Rheology; Sleepers & HCS 8-16mm.

Discussion (Rheology)

0-4mm

The 0-4mm size fractions in both materials had the most influence on the rheological properties, especially the plastic viscosity. The yield stress is the amount of energy required in order for the material to start moving, whereas the plastic viscosity describes the speed at which it flows and the amount of energy required to increase the flow of the material once it has started to move. It can also be described as the internal resistance in a fluid (Perry, Green, & Maloney, 1997).

The HCS 0-4mm material increased the internal friction of the concrete more than the Sleepers 0-4mm material. This was contrary to the results that were obtained in the mortar test, see Figure 6. Note that this test was limited to 0-4mm, a Hobart paddle mixer and no SP was used. Possible reasons for the decreased plastic viscosity were the increased milling effect created in the concrete pan mixer compared to the Hobart mixer. This may have caused positive particle shape changes and an increase in the number of such particles with particle packing benefits; it may also be due to the SP having more cement paste to "work" on in the cement paste richer Sleepers material.

No particle shape analysis was done on the initial materials, but it is known that crushed particles are flakier than their natural aggregate equivalent (Lagerblad, Gram, & Westerholm, 2013). The plastic viscosity remains relatively constant throughout the 90 minutes of measuring.

The increase in NA replacement with RCA (Sleepers and HCS) did not follow a proportional increase in the rheological properties. The H66-0-4mm had a higher plastic viscosity than H100-0-4mm. This was also seen in the Sleepers series. Possible reasons could be in the different particle packings and also material differences from one batch to the next, this though was minimized by sub dividing all 0-4 mm materials from a "parent" 100 kg pile.

The amount of SP required with Sleepers 0-4 mm was less than HCS up to 66% replacement. At this level, the required dosage escalated to double the amount for 100% NA replacement.

4-8mm

The total volume of the 4-8mm size fraction was relatively small (ca. 12%) and so increased the plastic viscosity very little, see Figure 33 . There was though a difference between the HCS and Sleepers material after approx. 40 minutes (WAT).The yield stress and plastic viscosity increased.

More SP was required with the sleepers 4-8mm (+16%) than with HCS but this was the same as in the reference mix.

8-16mm

The volume of the 8-16mm fraction was 40% and had a more pronounced effect compared to the 4-8mm size fraction. The plastic viscosity starts between 60 and 75 Pa s compared to the reference of 47 Pa s. This increased steadily over the measurement duration. The higher volume replacement caused a more acute angle (the plastic viscosity increased more and faster).

The SP requirement increased with increasing replacement levels at 100% replacement , 8% more SP was required than in the reference.

Each recipe was mixed once and the results represent only that individual mix.

Conclusion (Rheology)

The 0-4mm replacement RCA had the most effect on the rheological properties due to the higher specific area and the relative volume of that size fraction. The sleepers material, with its higher BET and higher fines volume did not increase the plastic viscosity as significantly as with HCS which was unexpected as the mortar tests showed otherwise. The use of higher sized fractions >4mm caused a shift in the plastic viscosity (an increase) but the yield stress gain was similar to the reference concrete mix. The SP requirement was approximately the same.

Results (Hardened Properties)

Compressive Strength

Method

The concretes produced were cast into 100mm X 100mm X 100mm moulds and allowed to cure in a climate room (20°C and RH 98 ±2 %). At different time intervals, three cubes were tested for compressive strengths according to SS-EN 12390-1:2009 (Swedish Standards Institute, 2009)

This value was converted to compressive strengths of a 150 mm sided cube.

Results

Compressive strengths after 1, 7 and 28 days and density are summarized below.

Table 0-9 Numerical values of compressive strength SCC w/c 0.5

	Days	**1**	**7**	**28**	**Density**
		MPa	MPa	MPa	kg/m^3
	REF	-	46.5	55.6	2440
SLEEPERS 0-4mm					
	S5-0-4mm	32.2	46.4	54.7	2440
	S11-0-4mm	32.2	44.7	52.3	2410
	S22-0-4mm	33.9	49.9	57.5	2390
	S33-0-4mm	33.6	50.4	59.3	2390
	S66-0-4mm	31.9	47.7	56.9	2380
	S100-0-4mm	30.7	45.3	46.9	2350
HCS 0-4mm					
	H5-0-4mm	34.5	47.3	55.4	2420
	H11-0-4mm	31.7	47.4	56.0	2460
	H22-0-4mm	31.2	50.4	58.2	2390
	H33-0-4mm	38.1	49.5	59.2	2410
	H66-0-4mm	30.0	47.8	56.4	2410
	H100-0-4mm	29.8	45.7	52.8	2360
SLEEPERS 4-8mm					
	S50-4-8mm	35.2	50.1	57.4	2400
	S100-4-8mm	34.6	51.3	57.4	2450
HCS 4-8mm					
	H50-4-8mm	32.9	49.5	59.4	2430
	H100-4-8mm	30.1	50.2	59.9	2410
SLEEPERS 8-16mm					
	S50-8-16mm	32.7	51.0	62.4	2370
	S100-8-16mm	34.0	51.1	63.0	2350
HCS 8-16mm					

	H50-8-16mm	32.8	52.0	61.1	2380
	H100-8-16mm	35.2	56.2	65.9	2360

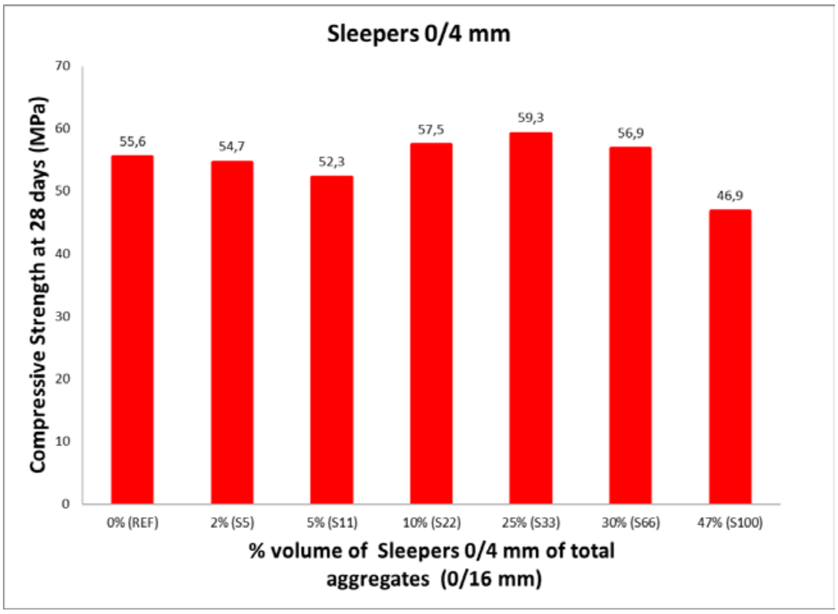

Figure 35 Compressive Strength Sleepers 0/4 mm (28 days)

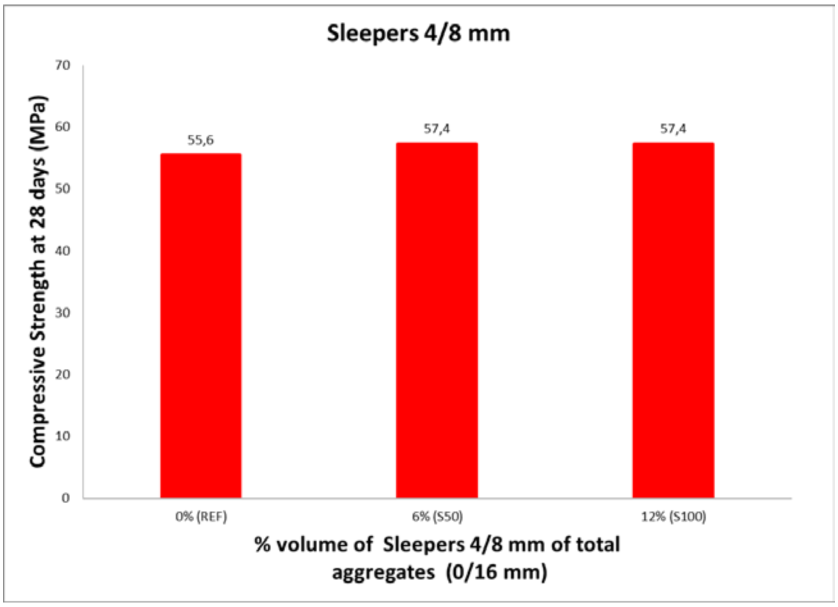

Figure 36 Compressive Strength Sleepers 4/8 m (28 days)

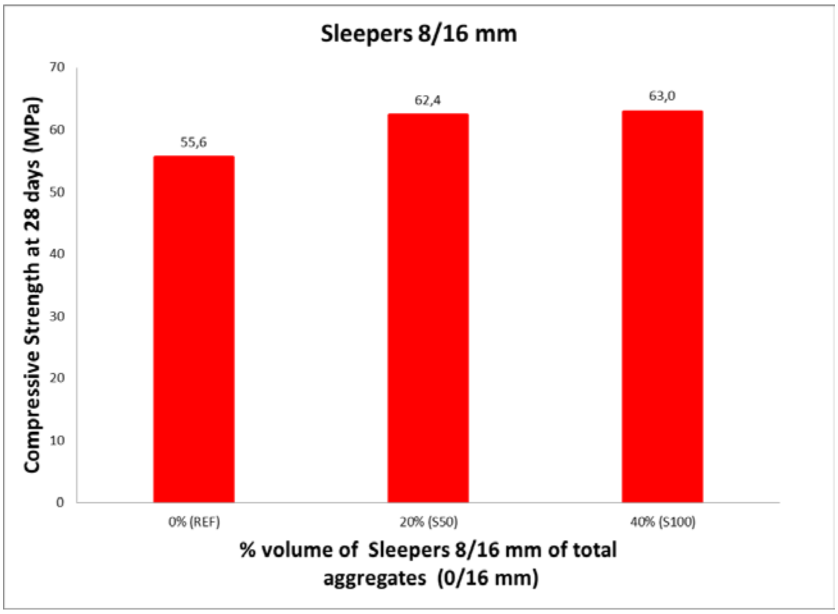

Figure 37 Compressive Strength Sleepers 8/16 mm

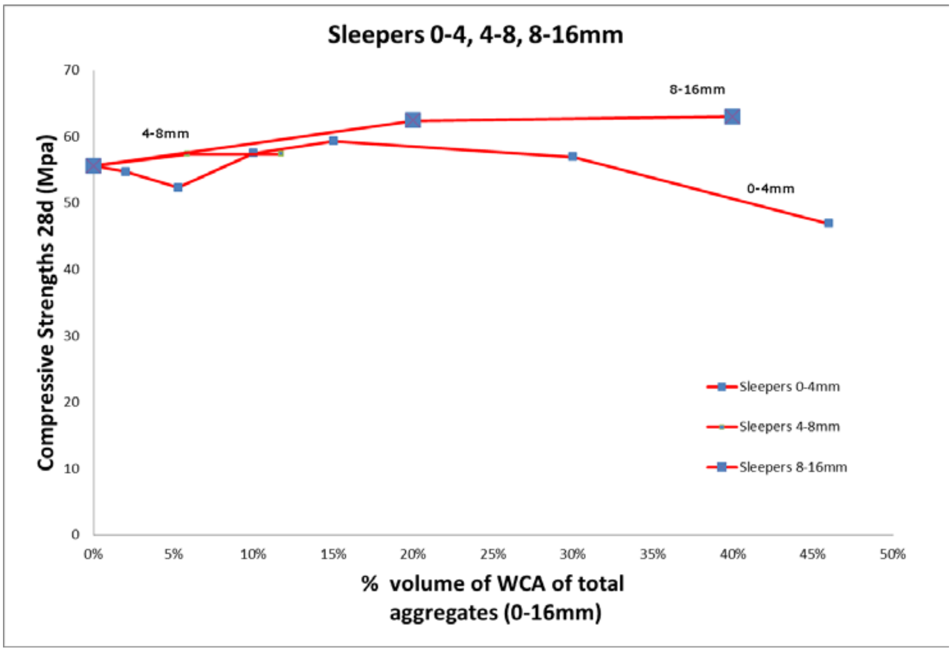

Figure 38 Compressive Strength; Sleepers 0-4, 4-8 and 8-16mm

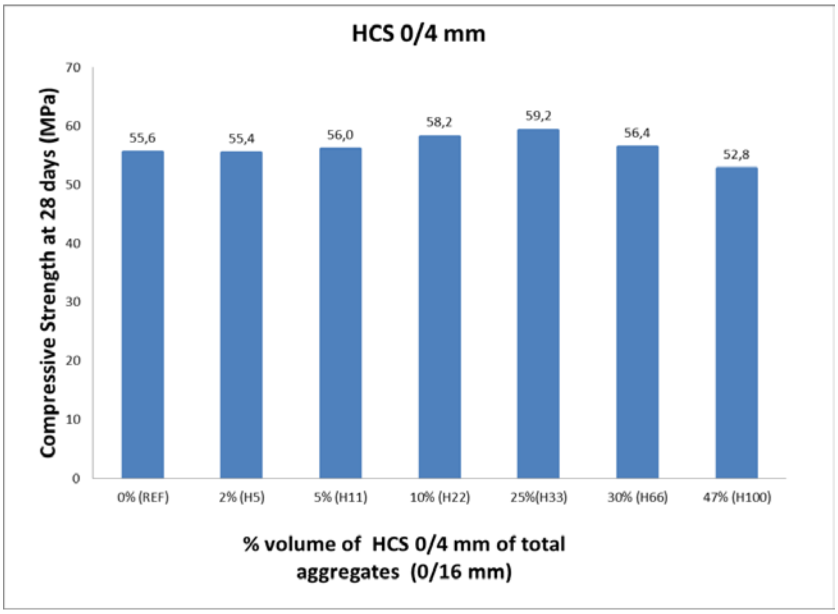

Figure 39 Compressive Strength HCS 0/4 mm

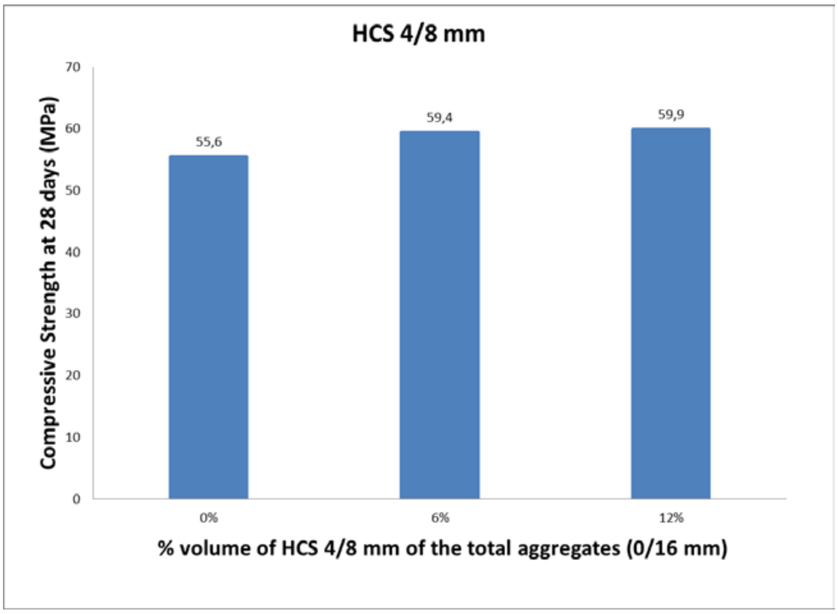

Figure 40 Compressive Strength HCS 4/8 mm

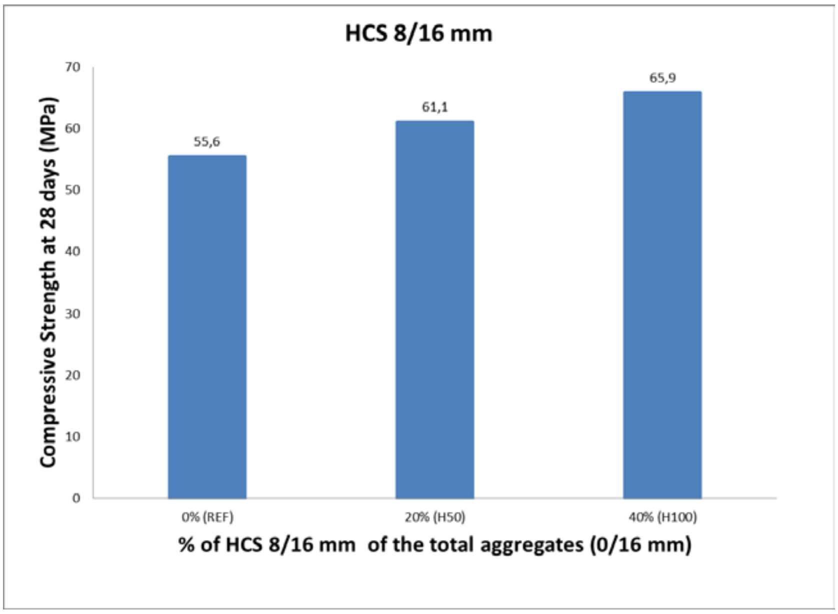

Figure 41 Compressive Strength HCS 8/16 mm

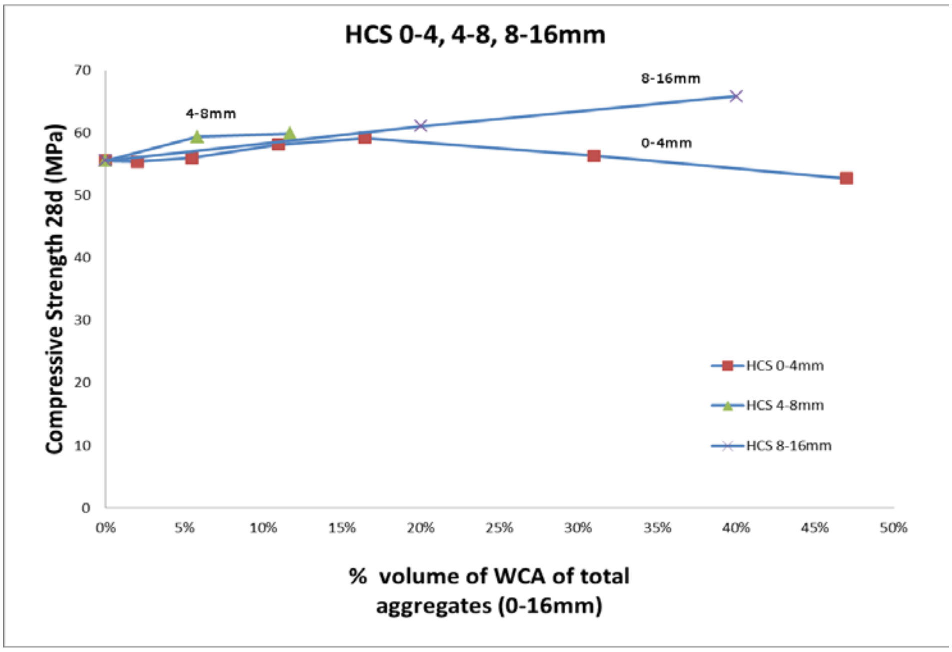

Figure 42 Compressive Strength; HCS 0-4 , 4-8 and 8-16mm

Discussion

The compressive strengths obtained with the replacement of reclaimed concrete aggregates vary. The reference strength was f_{ck} 55.6 MPa.

The 0-4mm size fraction provided both positive and negative results. Both materials followed a similar pattern, of no effect (with the exception of S11-0-4mm) up to 22% replacement , reaching a peak at 33% and thereafter dropping in compressive strength, see Figure 35 & Figure 39. The increasing amount of fines and the fragile “cement paste aggregates” accumulating in the 0-4mm RCA size fraction could be the cause for the drop of -15% and -5% respectively in the Sleepers and HCS 100% NA replacement series.

Use of RCA above 4mm resulted in higher compressive strengths regardless of its source. The highest compressive strength, f_{ck} , 65.9 MPa (+18%) was obtained with the complete replacement of the 8-16mm natural aggregates with 100% HCS 8-16mm, see Figure 41, this equated to 40 % replacement of the total aggregate volume. The replacement level of 50% or 100% in the Sleepers 8-16mm, see Figure 37, resulted in no difference in compressive strengths, 62.4 MPa(+12%) and 63.0 MPa (+12%) respectively.

The 4-8mm aggregate size volume is small (ca. 12 %) compared to the other two sizes, 0-4mm(47%) and 8-16mm(40%). A positive effect on the compressive strengths was obtained with all 4-8mm replacement levels, see Figure 36 & Figure 40. An increase of 3% and 7 % was obtained for Sleepers and HCS respectively, these low positive figures though could lie within a measurement uncertainty range.

Both profiles of compressive strength development followed a similar development, see Figure 38 & Figure 42. An optimum compressive strength can be seen in both concretes when the amount of replaced 0-4mm natural aggregates reached 33 % at 59.2MPa(+6%) and 59.3 MPa(+6%) for HCS and Sleepers respectively. This was an equivalent of 15 % of the total aggregate volume. A complete replacement of the 0-4mm aggregates resulted in a reduction in compressive strengths to 52.8 MPa (-5%) and 46.9 MPa (-15%) for HCS and Sleepers respectively.

Conclusion

The use of recycled crushed aggregates in all size fractions, in general, did not negatively affect the compressive strengths. The replacement of 0-4mm size fraction reached an optimum at approximately 33% (approx. 15% of the total aggregate volume). The replacement of 100% of 4-8 mm and 8-16mm resulted in increased in compressive strengths compared to the reference.

Dry Shrinkage

The SCCs with w/c = 0.5 were tested for shrinkage according to the Swedish standard SS 13 72 15 (Swedish Standards Institute, 2000). The results are an average of 3 prisms. The corresponding numerical values are found in Table 0-9.

Results

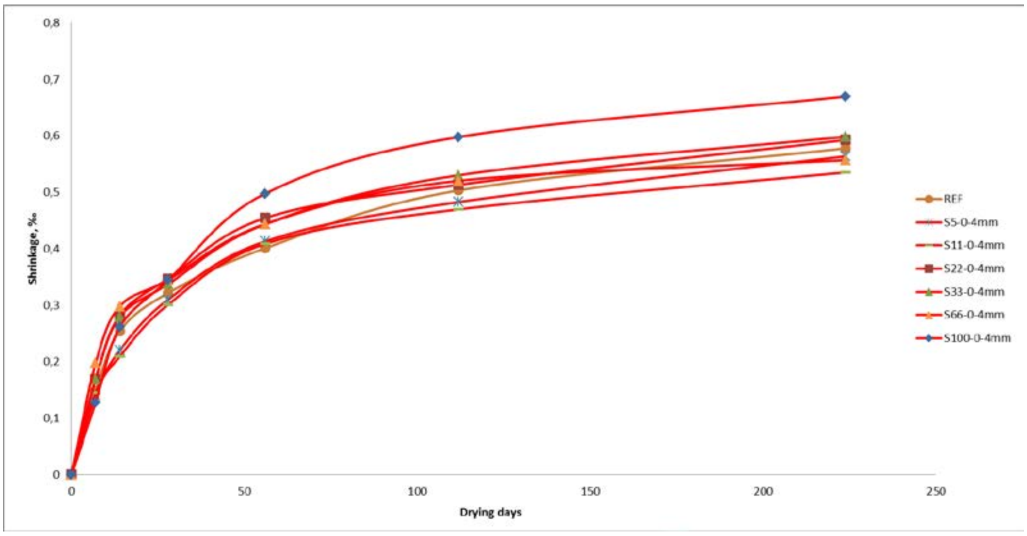

Figure 43 Drying Shrinkage; Sleepers 0-4mm

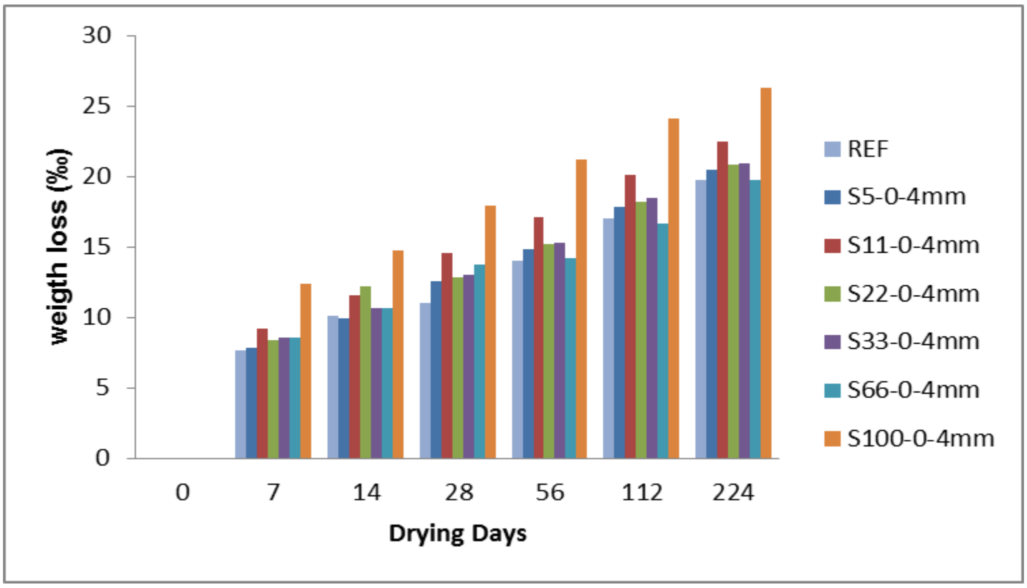

Figure 44 Weight loss Sleepers 0-4mm

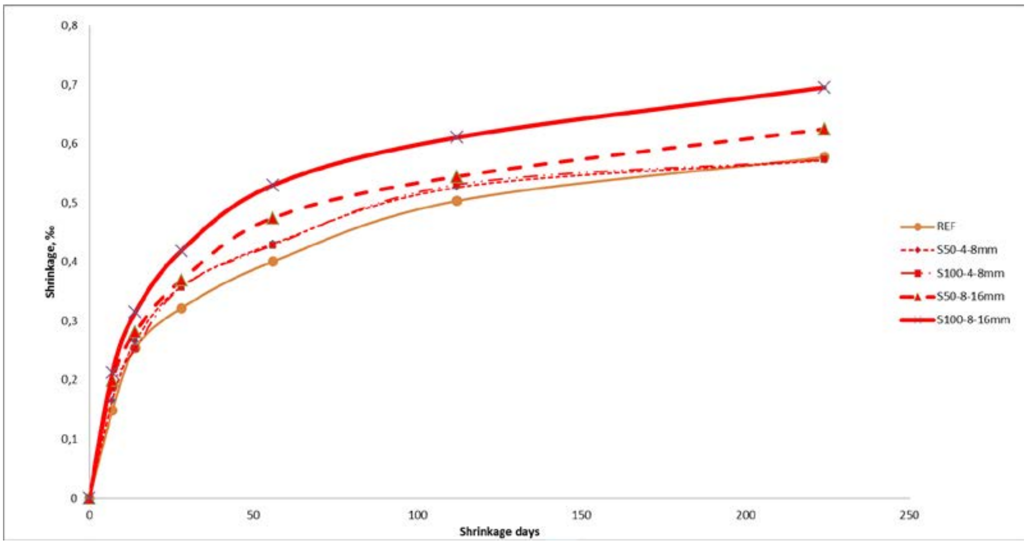

Figure 45 Drying Shrinkage; Sleepers 4-8 & 8-16mm

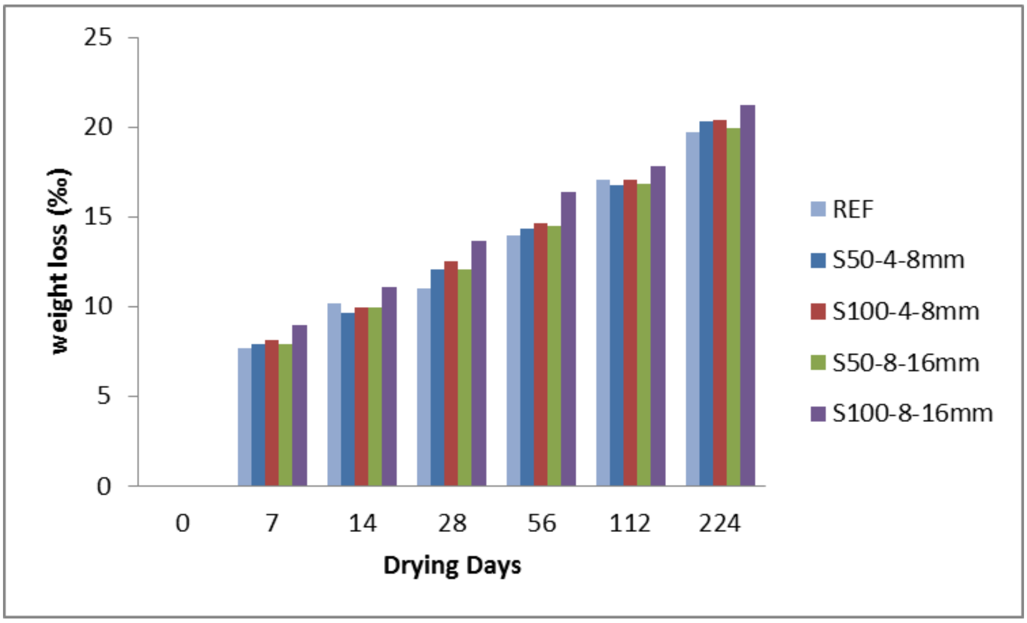

Figure 46 Weight loss Sleepers 4-16mm

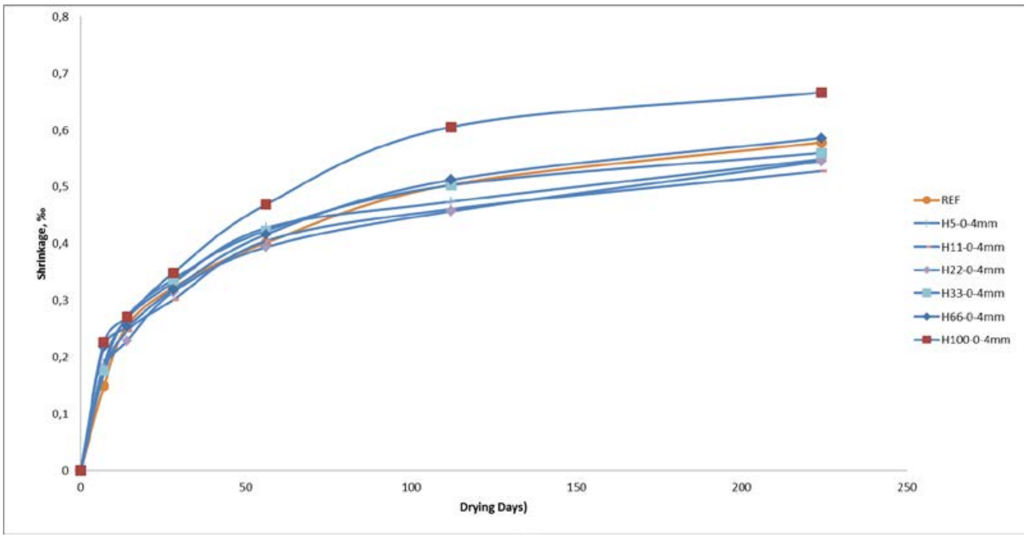

Figure 47 Drying Shrinkage; HCS 0-4mm

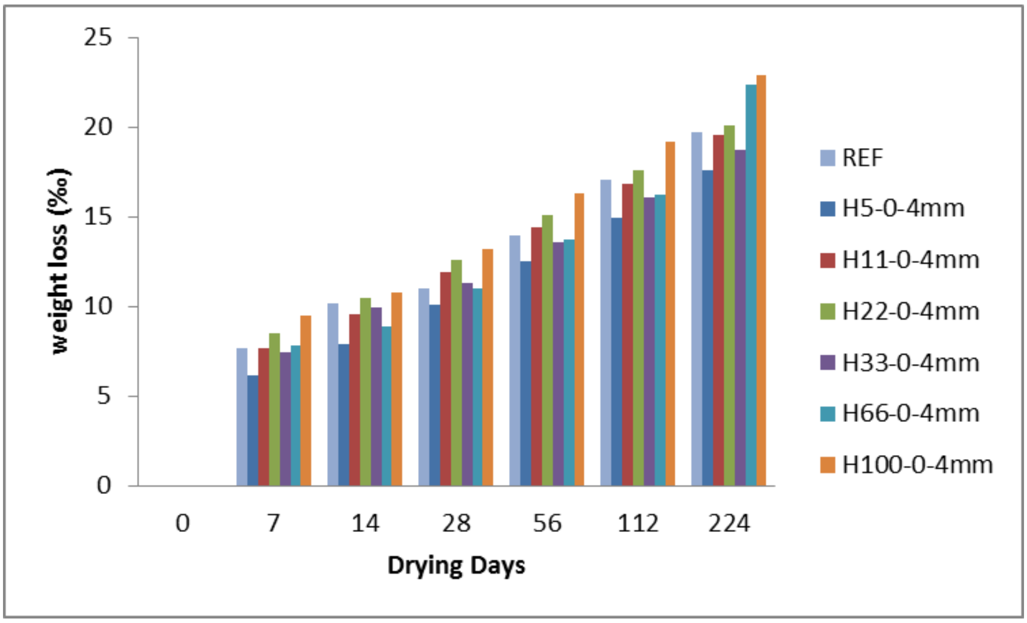

Figure 48 Weight loss HCS 0-4mm

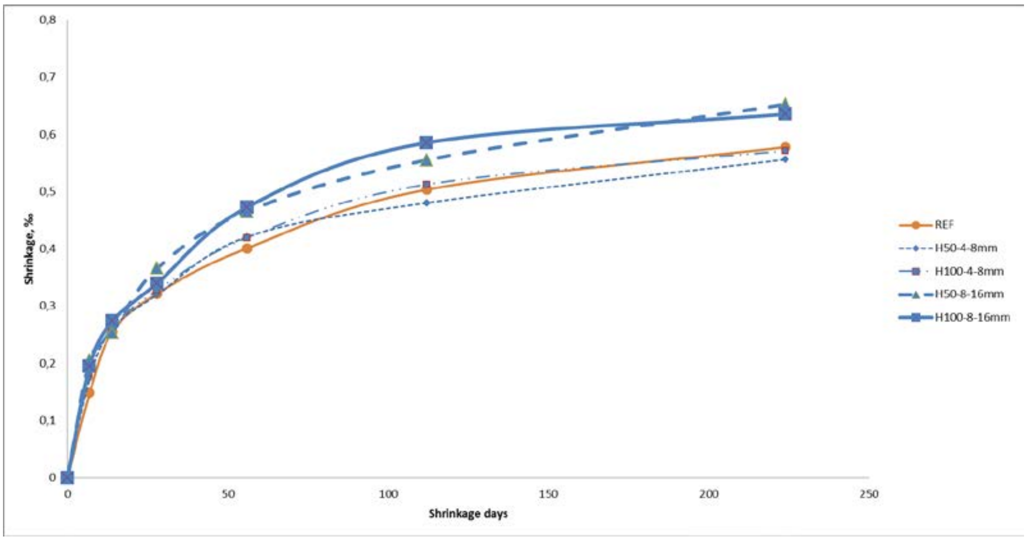

Figure 49 Drying Shrinkage; HCS 4-8 and 8-16mm

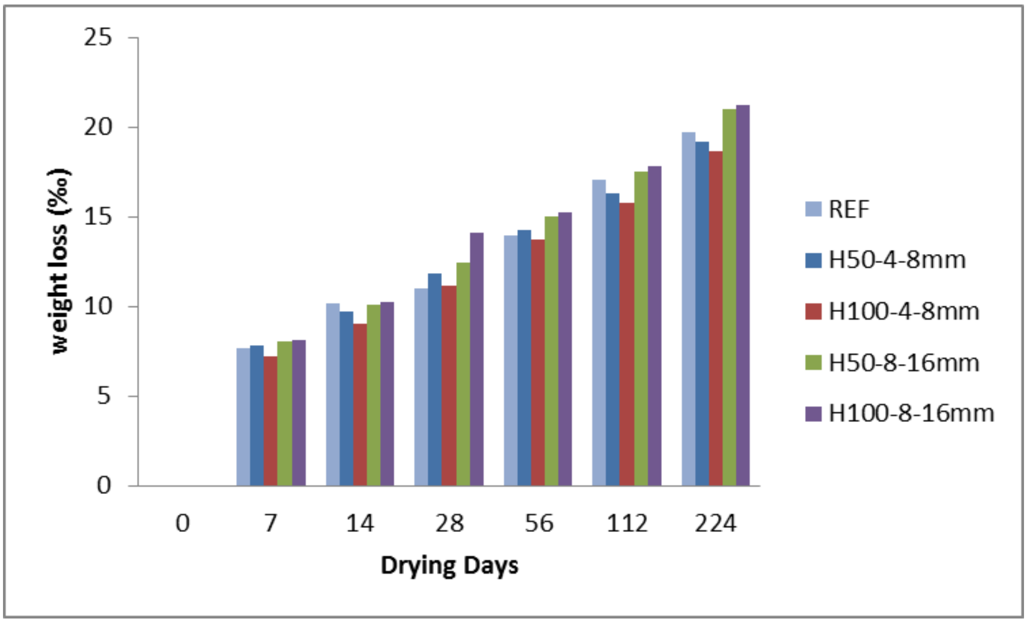

Figure 50 Weight loss HCS 4-16mm

Table 0-10 Drying Shrinkage results; SCC w/c 0.5

		After 224 days	Weight change
		‰	‰
	REF	0.58	19.7
SLEEPERS 0-4mm			
	S5-0-4mm	0.56	20.4
	S11-0-4mm	0.54	22.5
	S22-0-4mm	0.59	20.8
	S33-0-4mm	0.60	20.9
	S66-0-4mm	0.56	19.8
	S100-0-4mm	0.67	26.2
HCS 0-4mm			
	H5-0-4mm	0.55	17.6
	H11-0-4mm	0.53	19.5
	H22-0-4mm	0.54	20.0
	H33-0-4mm	0.56	18.7
	H66-0-4mm	0.59	22.3
	H100-0-4mm	0.67	22.9
SLEEPERS 4-8mm			
	S50-4-8mm	0.57	20.3
	S100-4-8mm	0.57	20.4
HCS 4-8mm			
	H50-4-8mm	0.56	19.2
	H100-4-8mm	0.57	18.7
SLEEPERS 8-16mm			
	S50-8-16mm	0.63	19.9
	S100-8-16mm	0.70	21.3
HCS 8-16mm			
	H50-8-16mm	0.65	21.0
	H100-8-16mm	0.64	21.3

Discussion

The reference concrete's shrinkage, ε_{s0} ,is approximately the same as that read of the graph , ca. 0.54 ‰ (concrete water content of 175 kg/m^3 w/c = 0.5 and a cement content of 350 kg/m^3) from figure 15.5:2 from Betonghandbok -Material (AB Svensk Byggtjänst, 2013)

The dry shrinkage results showed that the use of 0-4mm aggregates had little effect on the total drying shrinkage. Above a 66% volume replacement (0-4mm), there is a clear increase from the reference value of 0.58‰ to 0.67‰ (+15%), see Figure 43 & Figure 47 in both the Sleepers and the HCS material this also corresponds to a higher weight loss in terms of ‰ (+37%) and (+16%)

respectively. The 4-8 mm size fraction had no noticeable effect, see Figure 45 & Figure 49, but this is due the low volume it represents in the aggregate fraction. The use of the 8-16mm size fraction resulted in an increase in the shrinkage value. A 100% replacement of the natural aggregates for Sleepers 8-16 mm resulted in shrinkage of 0.70 ‰ (+20%). The equivalent for the HCS material resulted in a shrinkage of 0.64‰ (+10%). The weight loss was +8% higher than in the reference.

Conclusion

The use of smaller fractions of RCA, 0-4mm and 4-8mm, will have little effect on the drying shrinkage of the concrete in this particular mix. Above a volume replacement of 66% in the 0-4mm size fraction a clear increase is noticed at 100% replacement of both 0-4mm materials (Sleepers and HCS), an increase of +15% was recorded. The larger fractions, i.e. 8-16mm, resulted in an increase in shrinkage of between 9-20% depending on material and volume replacement.

Freeze-thaw resistant concrete

Results (fresh properties)

Slump flow and air content

Table 0-11 Entrained Air and workability of the freeze thaw resistant concrete w/c 0.4 Sleepers (S)

Replacement of:	**% volume of natural aggregates in their respective size fraction**						
Sleepers 0-4mm	REF	5	11	22	33	66	100
Slump flow (mm)	710	565	640	685	610	640	420
SP ACE 30 (kg/m^3)	4.3	4.4	4.5	4.5	4.4	4.4	4.5
MicroAir 100 (kg/m^3)	0.27	0.30	0.30	0.30	0.35	0.35	0.42
Entrained Air (%)	5.2	6.0	5.8	5.0	5.8	4.8	7.5
Sleepers 4-8mm				50			100
Slump flow (mm)	710			745			760
SP ACE 30 (kg/m^3)	4.3			4.5			4.5
MicroAir 100 (kg/m^3)	0.27			0.35			0.4
Entrained Air (%)	5.2			4.5			7.0
Sleepers 8-16mm				50			100
Slump flow (mm)	710			480			455
SP ACE 30 (kg/m^3)	4.3			4.5			4.5
MicroAir 100 (kg/m^3)	0.27			0.29			0.3
Entrained Air (%)	5.2			5.2			4.5

Table 0-12 Entrained air and workability; Freeze-thaw resistant concrete w/c 0.4 hollow core slab (HCS)

Replacement of:	**% volume of natural aggregates in their respective size fraction**						
HCS 0-4mm	REF	5	11	22	33	66	100
Slump flow (mm)	710	650	630	695	690	655	630
SP ACE 30 (kg/m^3)	4.3	4.4	4.4	4.5	4.5	4.5	4.5
MicroAir 100 (kg/m^3)	0.27	0.30	0.30	0.32	0.32	0.35	0.40
Entrained Air (%)	5.2	5.4	5.2	4.8	4.7	5.2	4.2
HCS 4-8mm				50			100
Slump flow (mm)	710			735			765
SP ACE 30 (kg/m^3)	4.3			4.4			4.4
MicroAir 100 (kg/m^3)	0.27			0.3			0.31
Entrained Air (%)	5.2			5.0			4.5
HCS 8-16mm				50			100
Slump flow (mm)	710			420			575
SP ACE 30 (kg/m^3)	4.3			4.3			4.4
MicroAir 100 (kg/m^3)	0.27			0.28			0.30
Entrained Air (%)	5.2			5.2			4.5

Results (Hardened properties)

Compressive Strength; Freeze Thaw Resistant Concrete

Method

The concretes produced were cast into 100mm X 100mm X 100mm moulds and allowed to cure in a climate room (20°C and RH 98 ±2 %). At different time intervals, three cubes were tested for compressive strengths according to SS-EN 12390-1:2009 (Swedish Standards Institute, 2009).This value was converted to compressive strengths of a 150 mm sided cube, f_{ck}.

Results

Compressive strengths after 28 days are summarized below.

Table 0-13 Compressive Strengths; freeze thaw resistant concrete

		Entrained Air	**28 day comp. strength**	**Density**
		(%)	MPa	kg/m^3
REF	REF (iv)	5.2	59.8	2350
SLEEPERS 0-4mm				
	F_S5-0-4mm	6.0	55.2	2350
	F_S11-0-4mm	5.8	57.1	2360
	F_S22-0-4mm	5.0	59.1	2370
	F_S33-0-4mm	5.8	58.0	2360
	F_S66-0-4mm	4.8	65.3	2370
	F_S100-0-4mm	7.5	53.5	2280
HCS 0-4mm				
	F_H5-0-4mm	5.4	58.4	2300
	F_H11-0-4mm	5.2	61.1	2370
	F_H22-0-4mm	4.8	62.5	2380
	F_H33-0-4mm	4.7	60.3	2370
	F_H66-0-4mm	5.2	59.9	2350
	F_H100-0-4mm	4.3	62.5	2340
SLEEPERS 4-8mm				
	F_S50-4-8mm	4.5	63.6	2390
	F_S100-4-8mm	7.0	49.9	2260
HCS 4-8mm				
	F_H50-4-8mm	5.0	62.6	2363
	F_H100-4-8mm	4.5	62.0	2400
SLEEPERS 8-16mm				
	F_S50-8-16mm	5.2	57.7	2370
	F_S100-8-16mm	4.5	58.2	2310

HCS 8-16mm				
	F_H50-8-16mm	5.2	55.5	2320
	F_H100-8-16mm	4.5	64.7	2360

Discussion

The compressive strengths are dependent on the air content that was entrained during mixing. As a rule of thumb, for every extra 1% of entrained air, a drop of 5% in compressive strength is observed. The F_S100-0-4mm was the exception in terms of keeping within the limit (7.0%) and the compressive strength reflected this. It is difficult to compare exactly between the series and even within the series due to this variation in air content.

Conclusion

Entrained air was able to be mixed into the RCA concretes and an acceptable 28 day compressive strength was obtained. The 100% replacement of 0-4mm Sleepers was difficult to mix and the amount of air-entrainer required was the highest of all mixes (0.42 kg/m^3).

Freeze thaw resistance

Method

All air entrained concretes were tested for freeze thaw resistance. Two sample areas from two 150mm sided cubes were used for testing and was carried out according to SS 13 72 44:2015 (Swedish Standards Institute, 2005) method A in a 3% NaCl solution.

Results

Table 0-14 Freeze-thaw resistance results; w/c 0.4

		Entrained air	**Scaling after 56 freeze thaw cycles**
		(%)	kg/m^2
REF		5.2	< 0.01
SLEEPERS 0-4mm			
	F_S5-0-4mm	6.0	0.01
	F_S11-0-4mm	5.8	0.01
	F_S22-0-4mm	5.0	< 0.01
	F_S33-0-4mm	5.8	0.01
	F_S66-0-4mm	4.8	0.02
	F_S100-0-4mm	7.5	0.02
HCS 0-4mm			
	F_H5-0-4mm	5.4	0.03
	F_H11-0-4mm	5.2	< 0.01
	F_H22-0-4mm	4.8	< 0.01
	F_H33-0-4mm	4.7	0.01
	F_H66-0-4mm	5.2	0.02
	F_H100-0-4mm	4.3	0.02
SLEEPERS 4-8mm			
	F_S50-4-8mm	4.5	0.01
	F_S100-4-8mm	7.0	0.02
HCS 4-8mm			
	F_H50-4-8mm	5.0	0.01
	F_H100-4-8mm	4.5	0.01
HCS 8-16mm			
	F_S50-8-16mm	5.2	0.05
	F_S100-8-16mm	4.5	0.04
HCS 8-16mm			
	F_H50-8-16mm	5.2	0.02
	F_H100-8-16mm	4.5	0.03

Discussion

The results show very little variation in the scaling measurements. At most, 0.05 kg/m^2 were obtained but this is within measurement uncertainty levels. Values below 0.1 kg/m^2 are deemed to have very good freeze thaw resistance properties. The reclaimed concrete aggregates from the sleepers and the hollow core slabs did not contain entrained air. According to the standards (Swedish Standards Institute, 2015) these would not have been allowed to be used in a XD3 or XF4 environment according to SS 137003 (Swedish Standards Institute, 2015) but the low w/c of these RCAs and the entrained air in the new concrete was sufficient to resist the expansion effects of freezing and thawing the cement paste.

Conclusion

The use of high quality RCA from a known source did not cause the air entrained concrete with a w/c = 0.4 to have a deteriorated resistance to freeze thaw action.

Chloride migration

Method

A select number of air entrained concretes were chosen to be tested for chloride ion ingress. The ones chosen were related to their applicability in a concrete factory environment. The testing was carried out according to Nordtest Method NT BUILD 492 (NordTest Method, 1999). The results are given in terms of a coefficient, D_{NTB492}, a low value indicates a high resistance to chloride migration. The concretes tested were at least 90 days old and had been stored in a climate room (20°C and RH 98 ±2%). The testing was carried out by CBI , Borås.

Results

Table 0-15 Chloride Migration testing results

		Entrained Air	**D_{NTB492}**
		(%)	10^{-12} m^2/s
REF (iv)		5.2	6.9
SLEEPERS 0-4mm			
	F_S33-0-4mm	5.8	6.6
	F_S66-0-4mm	4.8	6.6
HCS 0-4mm			
	F_H33-0-4mm	4.7	7.1
	F_H66-0-4mm	5.2	7.1
SLEEPERS 8-16mm			
	F_S50-8-16mm	5.2	6.8
	F_S100-8-16mm	4.5	7.3
HCS 8-16mm			
	F_H50-8-16mm	5.2	7.1
	F_H100-8-16mm	4.5	6.6

Measurement uncertainty in this method is: ± 0.2 x10-12 m^2/s

Discussion

The chloride migration testing showed that there is a slight difference between the two materials but the results lie approximately within the measurement uncertainty range between the reference concrete and the two materials. The similar results show that the concrete was compacted in a good manner.

From a CBI report (Pettersson, 1994) the use of entraining air had no significant effect on the chloride diffusion in a concrete with a w/c = 0.4 and slump of 75mm. The chloride diffusion was reported to be 30 x 10^{-12} m^2/s, significantly higher than that obtained in the experiments. Further reading into the effects of w/c or w/b can be read in (Sandberg, 1995). At a w/b of 0.4 the chloride diffusion was slightly under 10 x 10^{-12} m^2/s (Tang & Sørensen, 1998).

Conclusion

No significant difference could be detected in the chloride ion ingress by using the RCA from either source material. Good results were obtained from all tested specimens.

Conclusion

The use of RCAs from two different sources was successfully incorporated into two types of concrete. The high quality of these RCAs from railway sleepers (S) and hollow core slabs (HCS) resulted in very good hardened properties compared to the reference concrete. The effects of using the RCAs in size fraction 0-4mm can be problematic if used in large volume replacements. The rheological properties of the concrete change and affect the plastic viscosity the most. The (S) material didn't have the same impact on this property, even though earlier mortar trials showed a reversed relationship, i.e. the (S) 0-4mm had by far the highest plastic viscosity and yield stress of the materials tested.

A 100% replacement of NA caused a drop in compressive strengths, (HCS) -5% & (S) -15% in the 0-4mm size fraction, and an increased dry shrinkage (HCS) +15% & (S) +15% was observed. This increased drying shrinkage was also observed in the100% replacement in the 8-16mm size fraction (HCS) +10% & (S) +20% and however an increase in the compressive strengths (HCS) +18% & (S) +12% was observed.

The freeze thaw resistant concretes using RCAs from (HCS) & (S) had similar properties as the as the reference concrete at all replacement levels. Chloride migration tests on selected air entrained concrete recipes also showed very similar results, regardless of the size fraction. The 4-8mm size fraction wasn't tested due to its low volume impact (12% of total aggregate volume).

The grading of the crushed concrete aggregates into the three size fractions improved the CO_2 diffusion into the cement pastes. The main portion of the cement paste accumulated in the 0-4mm size fraction and also experienced the highest carbonation amount. This though was only experienced in the outer layers of the RCA pile. The centre layers carbonated at a lower rate and amount due to the higher diffusion resistance created by the finer particles. In the size fractions 4-8 and 8-16mm less gas diffusion resistance was experienced and the carbonation rates and levels were similar throughout the whole pile. The RCAs need to be kept dry in order to reduce the internal humidity and hence increase the rate of CO_2 gas diffusion into the cement paste. This though would increase the cost of handling the RCA material.

Further Research

- Mixing Techniques; Drum mixers vs. counter current pan mixers. The effect of grinding on the RCAs due to the power dissipation of different mixing conditions such as ready mix concrete (drum mixer) and precast concrete mixing conditions (counter current pan mixers) should be investigated. An experimental plan to evaluate the crushing conditions and how this effects the RCA in both tensile and compressive strengths with relation to the following equations:

$$E = C \log \frac{X_F}{X_P} \qquad \text{(Kick, 1885)}$$

$$E = 100E_i \left(\frac{1}{\sqrt{X_P}} - \frac{1}{\sqrt{X_F}}\right) \qquad \text{(Bond, 1952)}$$

Where E is the work done(or mixing conditions) , C is constant , X_F and X_P are the size of the particle (Feed and Product) and E_i is the Bond Work Index

- The effects of initial dry mixing and effects on RCA originated with different aggregate types, i.e. crushed and natural aggregates.
- Produce an optimized “greener” concrete, i.e. reduce cement paste content with 5-10% volume and still obtain reference concrete strengths.

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Appendix

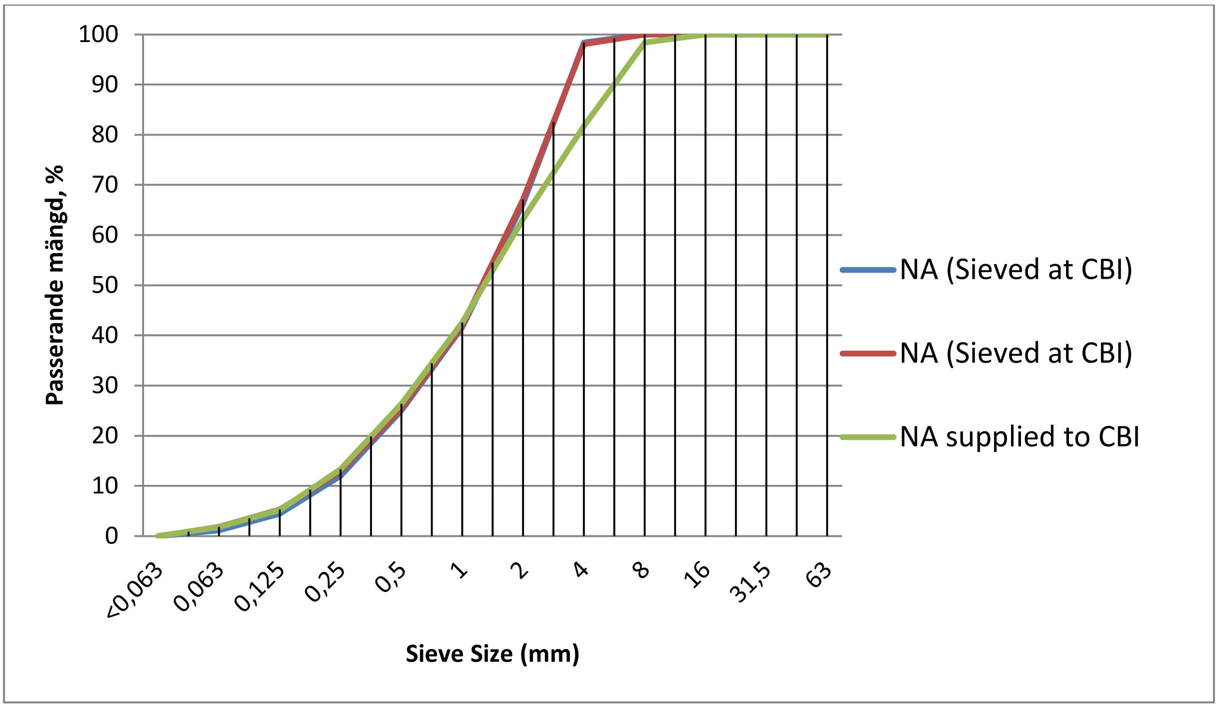

Figure 51 Sieving Curve of natural aggregates (NA) 0-4mm (sieved at CBI) and 0-8mm supplied to CBI Stockholm

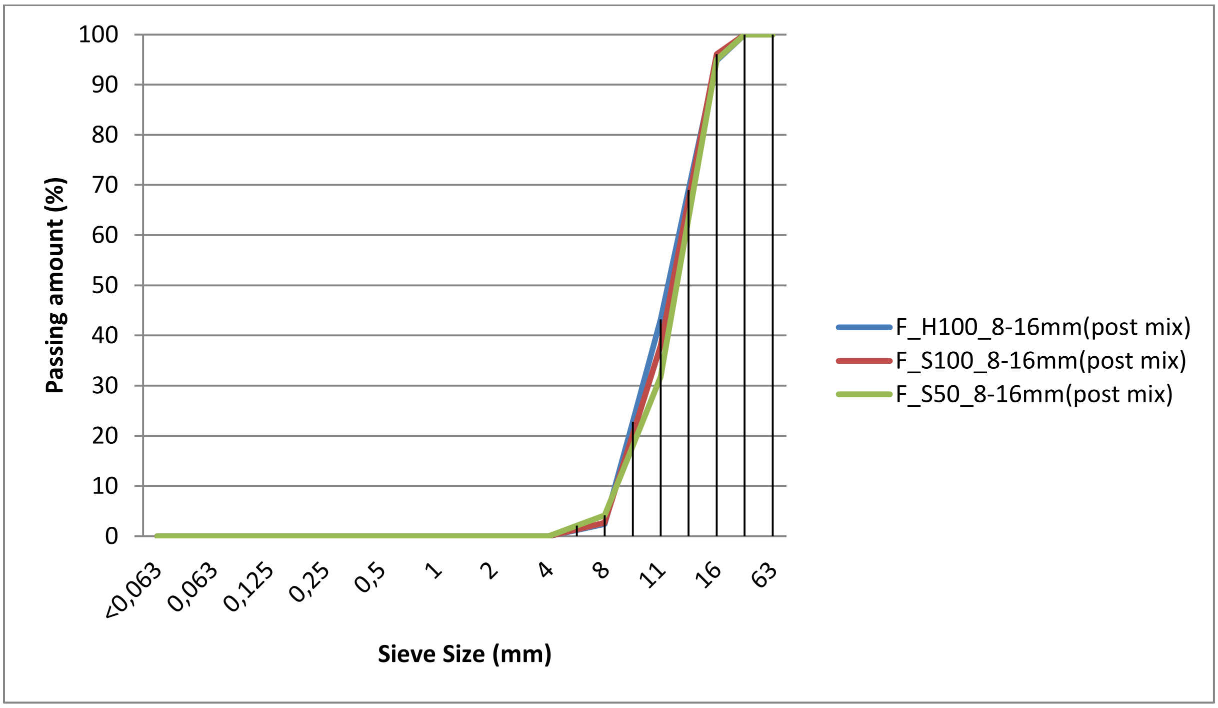

Figure 52 Sieving Curve; Aggregates Collected after freeze thaw batching

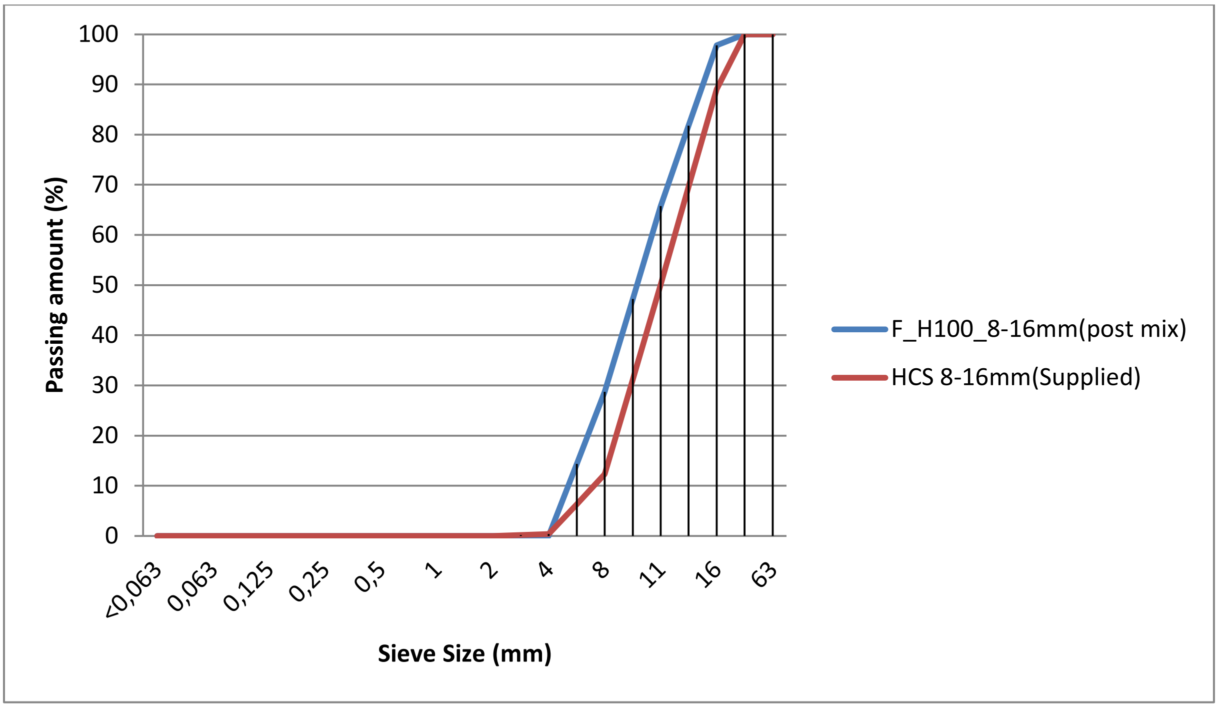

Figure 53 Sieving Curve; Aggregates pre and post mixing 8-16mm (freeze thaw batching)

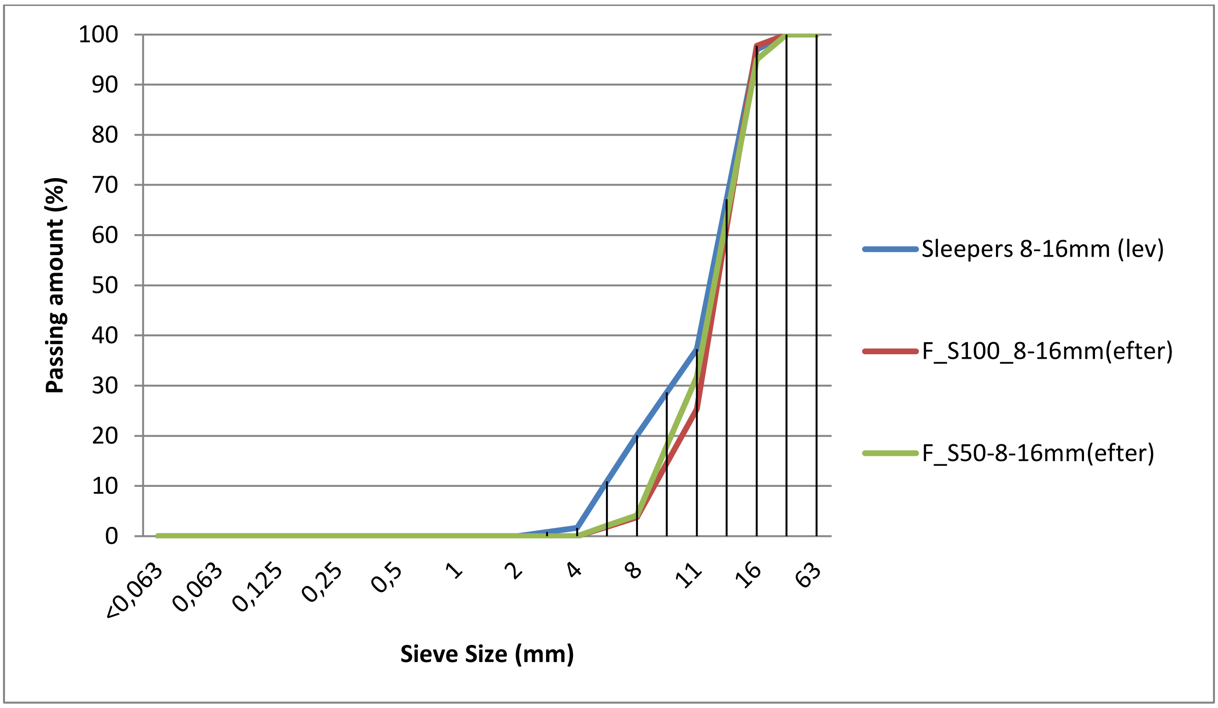

Figure 54 Sieving Curve; Aggregates pre and post mixing(freeze thaw batches)

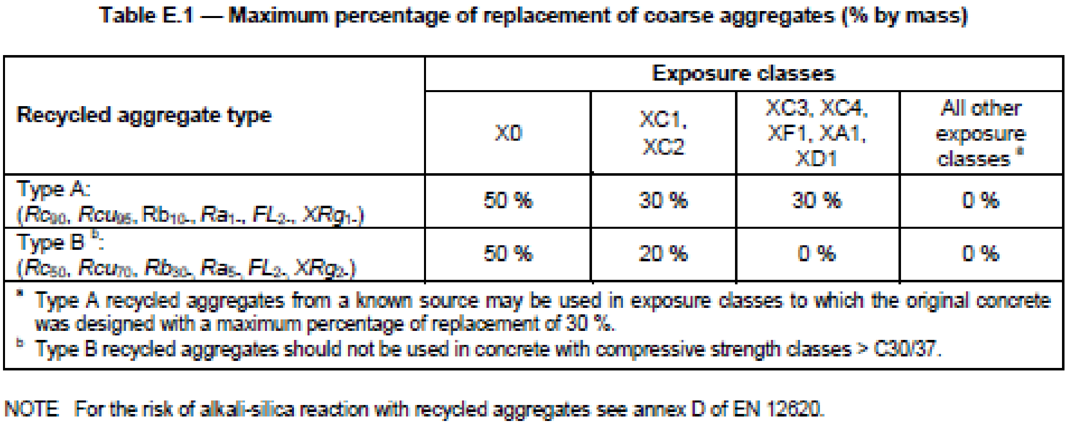

Table E.1 — Maximum percentage of replacement of coarse aggregates (% by mass)

Recycled aggregate type	**Exposure classes**			
	X0	XC1, XC2	XC3, XC4, XF1, XA1, XD1	All other exposure classes [a]
Type A: (Rc_{90}, Rcu_{95}, Rb_{10-}, Ra_{1-}, FL_{2-}, XRg_{1-})	50 %	30 %	30 %	0 %
Type B [b]: (Rc_{50}, Rcu_{70}, Rb_{30-}, Ra_{5-}, FL_{2-}, XRg_{2-})	50 %	20 %	0 %	0 %

[a] Type A recycled aggregates from a known source may be used in exposure classes to which the original concrete was designed with a maximum percentage of replacement of 30 %.

[b] Type B recycled aggregates should not be used in concrete with compressive strength classes > C30/37.

NOTE For the risk of alkali-silica reaction with recycled aggregates see annex D of EN 12620.

Figure 55 Table extracted from SS 13 70 03 :2015

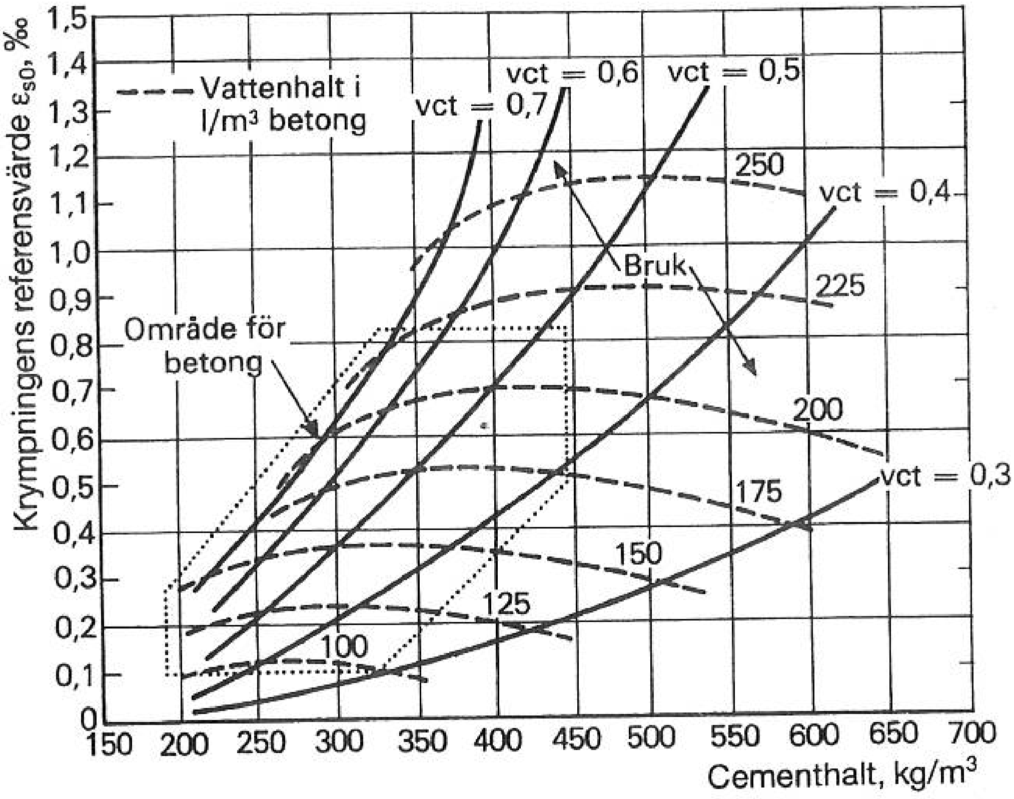

Figure 56 Drying Shrinkage diagram taken from Betonghandbok Material Figure 15.5:2 (AB Svensk Byggtjänst, 2013)

Grinding effect during concrete production

After the air entrainment testing (8l) for F_H100-8-16mm (i.e. no RCA under 8mm) was collected. All materials above 4mm were collected washed and dried. Note all materials below 8mm were natural aggregates (initially). The mixing process affected the size distribution of these materials.

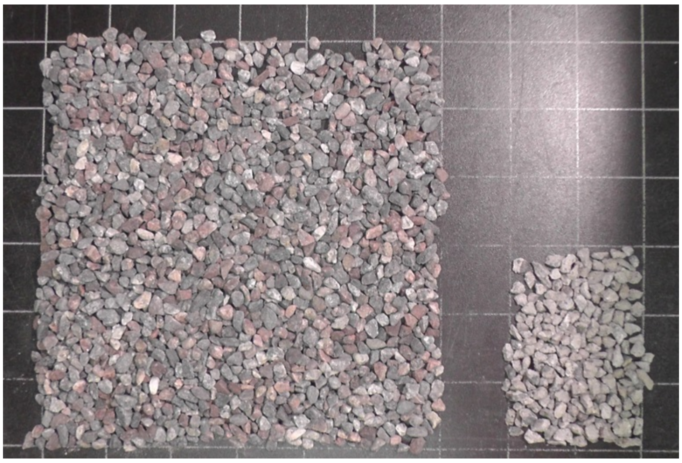

Figure 57 Material collected on 4-5,6mm sieve (from F-H100-8-16mm);NA (left) HCS (right)

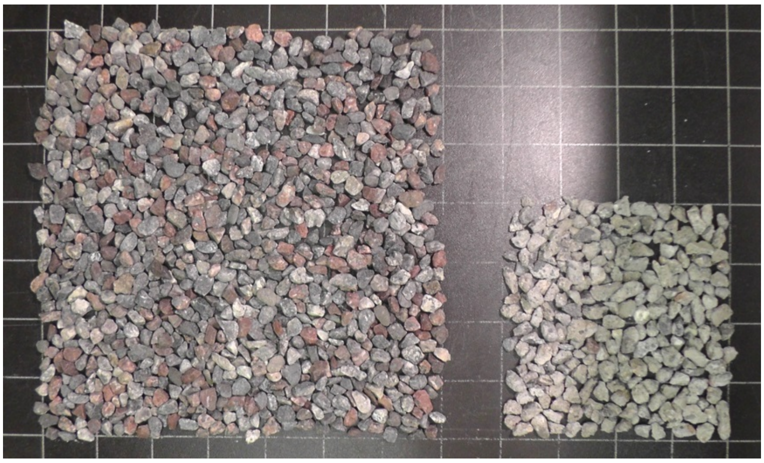

Figure 58 Material collected on 5,6-8mm sieve (from F-H100-8-16mm);NA (left) HCS (right)