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Circular Aggregates – Crushed Concrete Aggregates for Concrete Applications

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ABSTRACT
Concrete waste is utilized in Sweden mostly for backfilling in road applications and building landfills. The techniques for recycling concrete to replace natural aggregates are in place and makes it possible to produce circular and climate reduced concrete. This paper explores **concrete crushed aggregates** (CCA) from rest concrete, produced using industrial crushing methods. Also, the regulatory framework supporting recycling has been discussed. The Swedish concrete standard is implementing to a lower grade the use of CCA in new concrete in comparison to other European standards specially regarding the use of fine CCA fractions. Results for CCA water absorption and apparent density from lab scale and industrial crushing are shown. The CCA fulfills claims for aggregates for indoor concrete. With further improvements in the crushing process, CCA is fit for applications in outdoor concrete.

Keywords: Crushed concrete aggregates, Industrial upscaling, Recycling, Sustainability, Circularity.

1. INTRODUCTION

Concrete waste poses significant environmental challenges due to CO_2 emissions during cement production. Most of our concrete waste is sourced from ready-mixed concrete or demolition objects near the urban area. Concrete relies heavily on natural aggregates, leading to resource depletion in the existing quarries around the metropolitan areas. Utilizing CCA along with supplementary cementitious materials (SCM) is a technique to produce circular and climate-reduced **concrete**. Circularity reduces climate impact and brings financial benefits, in the case of aggregate production and transportation. In Sweden, the construction industry accounts for 21% of greenhouse gas emissions and 40% of total waste [1].**The waste framework directive** 2008/98/EC aimed to have at least 70% by weight of construction and demolition waste (CDW) recycled by 2020 [2]. Concrete being one of the heaviest building materials, by recycling concrete, enables Sweden to come nearer to achieving this goal.

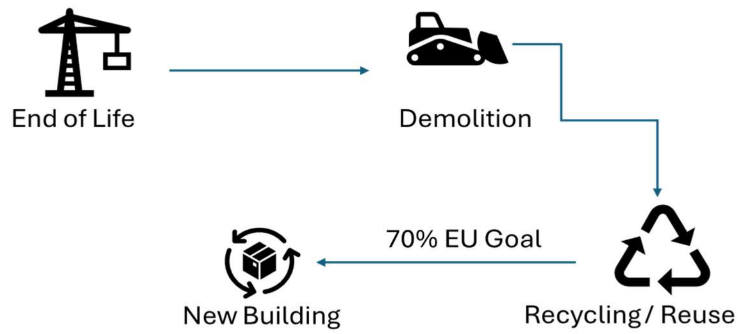

Figure 1 - European waste recycling goal by 2020

Sweden is one of the countries that did not reach this goal, with the recycling rate still under 60%. This goal had been prolonged until 2025 [3]. The EU Commission has a climate target of **net zero** greenhouse gas emissions by the year 2050, which has been adopted by the Swedish concrete industry starting by reducing emissions by 55% at least in 2030 [4] [5]. The European Commission also has an environmental accountability policy, where companies must disclose sustainability performance; the corporate sustainability reporting directive **(CSRD)**. This includes a plan for lowering CO_2 emissions, which will help in evaluating companies sustainability performance according to the EU Green Deal [6].

This article investigates using CCA as a replacement for natural aggregates in concrete and, thus, increasing its circularity. Through a literature review, the recyclability of CDW is analyzed across different demolition techniques with the intent to receive clean concrete waste to produce recycled aggregates. Different recycled aggregate treatment methods from literature are analyzed for improvements to recycled aggregate quality to meet standard requirements for concrete.

The article includes experimental work demonstrating crushing of CCA using lab and industrial crushing infrastructure. The resulting aggregates are compared for physical properties such as particle grading, density and water absorption. It reviews different crushing methods for improving CCA quality and predicts the CCA quality of different concrete sources in accordance with primary and secondary crushing.

2. CONCRETE WASTE STATISTICS

Concrete waste in Sweden comes from **three main sources**: reclaimed concrete; hardened or fresh condition, prefabrication rejects, and demolition debris. Reclaimed concrete includes excess concrete from ready-mixed and site leftovers. Prefabrication rejects arise from failing quality requirements, like dimensional inaccuracies or surface defects. Reclaimed concrete waste in unhardened condition can also be washed to recover natural aggregates for reuse.

Demolition and construction of new structures occur very often for many reasons like expensive renovation, change of purpose, expanding cities or living areas, relocating industrial areas, expanding roads, etc. In the last 10 years, China, the United States, and the European Union have generated about 3.8 billion tons of construction demolishing waste, of which most of it was concrete waste [7]. In Sweden, the CDW generated in 2018 was 12.4 million tons, which increased to 14.6 million tons, accounting for 40% of the total waste excluding mining waste in 2020. In 2022, this decreased to 13.6 million tons, of which some were treated, and others were landfilled [8-10]. The CDW comprises of different construction materials out of which mineral waste is looked at in the study. Statistics in Figure 1 show four application areas of mineral waste where conventional recycling stands for recycling for the same application to demonstrate closed loop recycling. This includes recycling concrete waste into new concrete. The share of conventional recycling has been increasing over the years, but it needs more attention as landfilling is still high. The reduced construction activities during the 2020 pandemic affected all aspects of mineral waste reuse and recycling. A major share of the waste, 0.71 million tons, was used in construction of road subbases, an application which achieves high recyclability rates because the claims are less strict than for bound applications.

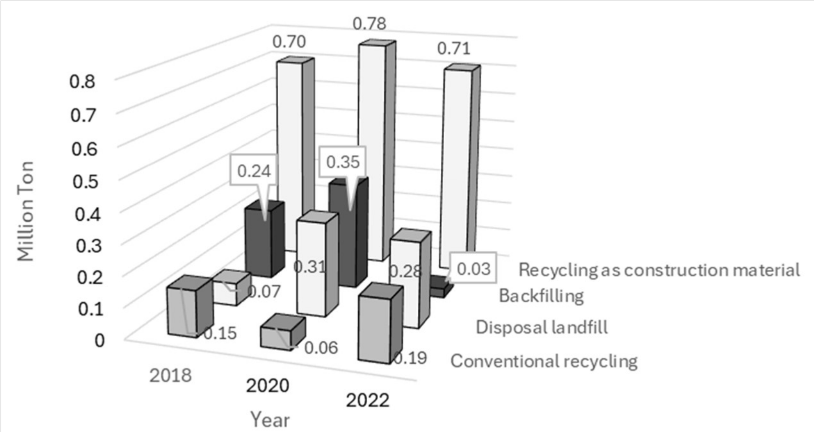

Figure 2 – Application areas for mineral waste fractions in Sweden in million-tons [8-10].

The Swedish Environmental Protection Agency has **restricted the extraction of natural sand aggregates** through limits on the extracted amount and taxation [11]. Aggregate producers have specific permits with a limited time on stone extraction. Hence, a new product has to be adopted for companies to proceed with production [12]. Aggregates form ca 67-70% of concrete's volume; for this reason, a substitute can have a substantial impact on circularity and consequently the climate. This allows for the integration of a large amount of suitable concrete waste into new concrete. By recycling, the technical life of concrete can be prolonged in new concrete, and thus, the climate impact of concrete is distributed through two technical service lives.

Conventional demolition CCA quality is inconsistent as, besides concrete, it will contain materials such as bricks and tiles, resulting in a type B recycled aggregate. Thus requiring more treatment processes to include the aggregate in new concrete.

Selective demolishing results in CCA with low variation in quality and is executable for structures with load-bearing frames. It also enhances the possibility of recycling other materials and components from the building, distributing the selective demolition process costs across several reused and recycled components [13]. The carbon footprint of a selective demolition has been verified to be lower if recycling happens in the same location as demolition in new construction, in comparison to conventional demolition [14]. Selective demolition has been demonstrated to enable reclaiming of bricks from an existing building to be used in new construction in Borås, Sweden [14]. Figure 3 shows different structural elements to be disassembled, such as a frame consisting of prefabricated concrete columns with brick walls in between and prefabricated beams. Buildings following this typology are easier to disassemble by selective demolition; the bricks and concrete elements can be reclaimed for reuse in new buildings [15, 16]. Selective demolition provides cleaner waste compared to conventional demolition, which may be recycled in place using mobile crushing equipment.

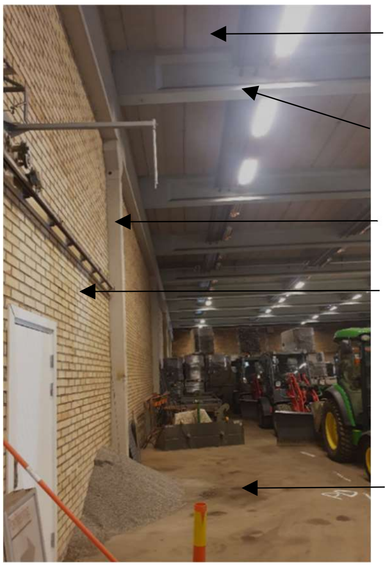

Figure 3: An example of a frame structure building to be demolished selectively in Borås, Sweden.

3. CRUSHED CONCRETE AGGREGATES

CCA can be produced from any of these sources and used as a substitute for natural aggregates in concrete, both fine and coarse fractions [17]. There are various applications in the form of concrete block systems, such as retaining walls, warehouse walls, and infrastructure applications. These can be considered as applications for recycled concrete, as it uses concrete leftovers [18]. Reclaimed concrete and prefabrication rejects are sources of homogenous concrete waste with many recycling trials underway [19]. Demolition waste shows more composition variations, making the recycling process more challenging [20].

3.1 Standard claims on CCA

The Swedish standard SS 137003 [21] and SS-EN 206 [22]The Swedish standard acknowledges the replacement percentage for CCA sourced from demolition and classifies it into type A and B. Reclaim concrete satisfies the requirements in the same table, but since the quality of the waste is better and more uniform, this should be revised.

Swedish standard

The Swedish concrete application standard SS-EN 206 [22] gives the allowable replacement percentages of coarse recycled aggregates in different concrete exposure classes based on aggregate composition types A and B, see Table 1. For full replacement in concrete, aggregates need to fulfill the requirements of aggregate standard SS-EN 12620 [23] based on exposure class. The type A and type B recycled aggregates consist of more than 90% and 75% of concrete or concrete and stones, respectively. These have been considered as high and moderate-quality recycled aggregates according to the European commission report [24]. These aggregates can be used directly in new concrete without fulfilling requirements of aggregates standard, SS-EN 12620. For example, claims of frost resistance on CCA need to be fulfilled when CCA replacement is within 30% of coarse aggregate content in outdoor concrete with exposure classes XF. This is the most common exposure class in Nordic countries, making frost resistance governing property for CCA.

For reclaimed concrete, the allowed percentage of recycling is 5%, independent of exposure class. With techniques found in a recent VINNOVA project for circular and climate-reduced concrete element, this percentage of reclaimed concrete can be increased. The VINNOVA project involves stakeholders from a crew of concrete supply chain to investigate industrial upscaling of concrete recycling [25].

Table 1 - Combination of maximum percentage of coarse aggregates according to SS-EN 206 integrated with demanding classes according to [24]

Aggregate	Type A: concrete or concrete + stones (>90%)		
Concrete exposure classes, percentage replacement	Non-demanding: X0-50% replacement	Low-demanding: XC1, XC2- 30% replacement	Demanding: XC3, XC4, XF1, XA1, XD1- 30% replacement
Aggregate	Type B: concrete or concrete + stones (>75%)		
Concrete exposure classes, percentage replacement	Non-demanding: X0 - 50% replacement	Low-demanding: XC1, XC2- 20% replacement	

Recycling of concrete in European countries

Table 2 compares the use of CCA among different European countries by three distinct categories corresponding to exposure class. Non-demanding - X0, low demanding - XC1 and XC2 and demanding - XC3 and XC4. A noticeable feature is that Denmark and Germany allow even the replacement of fines in low-demanding concre

Table 2 - European countries standards for the use of CCA [24]

Country	Standard	Fraction	Quality of CCA	Use
Denmark	DS 2426	Coarse and fine	High-quality	Low to moderate exposure class: fine 30% (C30/37), coarse 100% (max C40/50)
			Moderate quality	Low exposure class: fine 20%, coarse 100%
Norway	NS-EN 206	Coarse and fine	High-quality	Up to 10% fine, up to 30% coarse (max C25/30)
				20% coarse type A (max C45/55)
			Moderate quality	5% fine, 10% coarse (max C20/25)
France	NF EN 206-1/CN	Coarse	High-quality concrete waste	Up to 30% low demanding exposure class
		Coarse	High-quality	Up to 15% low demanding exposure class
		Coarse	Moderate quality	Up to 5% low demanding exposure class
		Fine	High-quality	Up to 5% low demanding exposure class
Germany	DIN 1045-2	Coarse	High quality-concrete waste	Low demand & carbonation-related exposure class: 45% fine + coarse
				Chloride-related exposure class: 35% fine + coarse
				Chemical-related exposure class: not allowed
			High-quality	Low demand & carbonation related exposure class: 35% fine + coarse
				Chloride related exposure class: 25% fine + coarse
				Chemical related exposure class: not allowed

3.2 Integrating CCA in new concrete

The most important factors that slow the integration of CCA in industrial concrete production include, among others, the composition of CCA and the lack of devoted testing methods for recycled aggregates. Also, the acceptable limit on CCA properties, such as WA is at 1%, a value based on the WA of natural aggregates. There is no specialized standard for recycled aggregates for concrete, on the contrary CCA is validated according to virgin aggregate standard SS-EN 12620. Advanced crushing and separation techniques are cost-intensive and must be examined for their climate impact. Due to the somewhat lower density of CCA, and thus less energy-claiming crushing processes and more efficient transports, it is beneficial to study the climate impact of CCA and try to show that the circularity of concrete brings about climate benefits [26]. The use of CCA in new concrete is still emerging in the Swedish concrete industry.

3.2.1 Adhered mortar

CCA comprises natural aggregate parts and hardened cement mortar remaining from the parent concrete. The adhered cement mortar is more porous than the aggregate part and contributes to a higher water absorption (WA) value than natural aggregates. This has shown a reduction in workability and the mechanical properties of concrete [27, 28], and also needs to be addressed with strict claims for frost resistance. There is no standard method to measure the attached mortar in recycled aggregates; usually, there are chemical and thermal treatments used to remove mortar and weigh it separately. However, the results of mortar content vary significantly based on the test: 25–70% for chemical treatment (hydrochloric acid solution) and 40–55% for thermal treatment [29]. Chemical and thermal methods have been used to improve CCA quality along with mechanical preprocessing techniques, which remove the mortar and cubisize CCA.

Mechanical processing is used to separate adhered mortar (AM) from CCA using an autogenous mill. It is found that AM and water absorption have decreased with the increase in pre-processing duration [30, 31]. Similar effects of cleansing CCA from adhered mortar can come from crushed rock manufacturing infrastructure [32] and are easier to upscale in Sweden. Removing the adhered mortar has resulted in improved WA and shape, which manifests as enhanced strength and workability in concrete. Without mechanical preprocessing or other ways of cleansing adhered mortar, CCA aggregate will need more cement to give the same compressive strength as a reference concrete with virgin aggregates [33]. It has been demonstrated at the University of Borås that it is possible to achieve the control concrete strength and workability without increasing the cement content [19] and is also the focus of the ongoing VINNOVA project.

Methods used for removing and densifying AM have shown to improve the quality of CCA [19]. Although the literature shows two different terminologies as shown in Figure 4, where both densifying and removing adhered mortar shows improvement in CCA properties such as density and WA. One exception maybe the densification of AM by carbonation instead of AM removal.
An additional process that is currently often used in climate-reduced concrete is the incorporation of SCM, which has been shown to densify the adhered mortar [34].

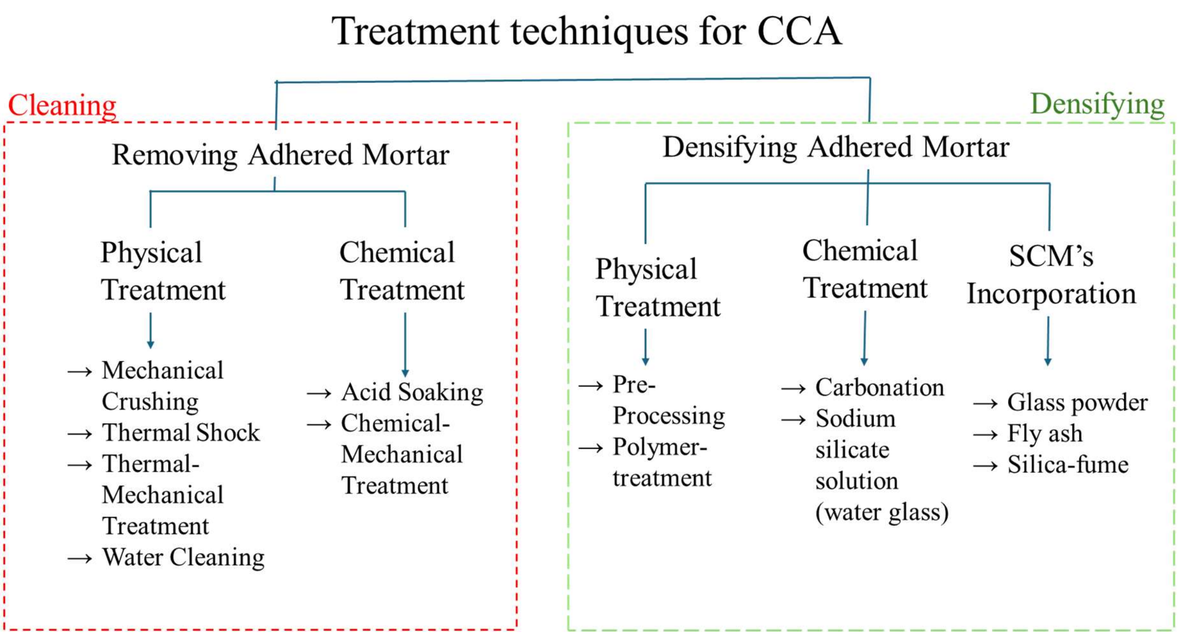

Figure 3 - Different treatment techniques for CCA [35]

The efficiency of the quality improvement methods on the properties of the CCA is shown in Table 3. It can be seen that crushing processes with a combination of jaw and cone crushers give the best fit for the particle grading fitting concrete applications compared to natural aggregate. Subject to the fitting of particle grading, check is made on the aggregate WA. Therefore the most important property to be fulfilled is the particle grading of the aggregate. The crushing trials with the best WA also result in concrete with higher compressive strength. For example it can be seen that with a secondary crushing trial, a reduction of 50% in WA is achieved with a 39% increase in compressive strength for the particle grading best suiting concrete production [36].

Table 3 - Improvement in WA and compressive strength upon applying different treatment methods (AM removal)

Treatment methods	**W.A improvement %**	**Compressive strength improvement %**	**Note**	**REF**
Traditional Heating	-10%	-	More energy (CO_2) Not available on an industrial scale. Time consuming.	[35]
Microwave Heating	-33%	+27%	More energy (CO_2) Not available on an industrial scale. Time consuming.	[35]
Secondary Crushing	-50%	+39%	Possible with available crushing infrastructure Particle grading fitting con	[36]
Thermal-mechanical Treatment	-55%	+18%	More energy (CO_2) Disposal of fine particles.	[35]
Washing	-10%	-		HB LAB
Autogenous	-21%	+15%	Special machine needed.	[31]

3.2.2 Testing methods for CCA

To reuse CCA in new concrete, it must fulfill the claims of SS-EN 12620, the standard for natural aggregates for concrete. CCA is different from natural aggregates; it is a stone and cement paste composite. Investigating the physical properties of aggregates involves oven drying to 105 °C, such as in the testing for WA and frost resistance. Oven drying CCA to 105 °C gives rise to evaporation of bound water from AM, leading to material loss, therefore influencing weights of test quantities. Oven drying CCA at 70 to 80 °C maybe seen as a favorable alternative [37].

Water absorption of aggregates is determined by the pycnometer method and has been modified for testing CCA using vacuum filtration to drain wet aggregates to saturated surface dry (SSD) condition [38]. Specifically for fine natural aggregates, cone is used to determine the SSD by ocular assessment, while this is not applicable for CCA. The modified pycnometer method suggests the use of vacuum filtration to assess the SSD condition [38]. New research is showing that other methods maybe used, such as rapid testing methods, including microwave drying, which uses the change in drying rate to differentiate loss of free water and pore water. The SSD is said to be reached when the pore water starts to evaporate [39]. Moisture content in aggregates influences thermal properties such that the thermal conductivity which increases with moisture content. This technique has been used in infrastructure applications such as aggregates for conduction beds of underground electric cables [37]. Techniques investigating thermal properties can be applied to investigate the moisture content of aggregates in SSD; to be investigated in future studies.

4. AGGREGATE CRUSHING INFRASTRUCTURE FOR CCA PRODUCTION

As of today, many Swedish aggregate producers use mobile crushers to produce CCA for infrastructure applications such as road filling. The stationary crushing infrastructure from quarries and aggregate production sites of virgin aggregate products maybe used for CCA.

Existing aggregate crushing infrastructure in Sweden involves the subsequent crushing of primary, secondary, and even tertiary crushing stages. Primary crushing is usually done using a jaw crusher or a hammer mill crusher for size reduction. The secondary crushing is done with cone and impact crushers for desirable shape and grading fitting natural aggregates. In the case of fine crushed rock aggregates, vertical shaft impact (VSI) crushers are used for cubisizing the flaky aggregates as a tertiary crusher. Laboratory investigations of mechanical pre-processing emulate VSI crushers reducing adhered mortar from CCA, resulting in reduced WA [40, 41].

4.1 Lab investigations for CCA as coarse aggregates in concrete

In Sweden, industrial upscaling trials have been made on stationary crushing infrastructure to crush reclaimed concrete waste to produce CCA within the VINNOVA project "circular and climate reduced concrete in new elements" [36]. The industrial upscaling happened at an aggregate crushing facility with a jaw crusher for primary, followed by a spindle and cone crushers for secondary crushing, respectively. Laboratory investigations have been conducted on particle grading, water absorption, and apparent density of fine and coarse CCA fractions; see Figure 5 and Table 4. In comparison, results from repeated jaw crushing at the laboratory are shown. A combination of different crushers within stationary crushing facilities shows better results for WA and apparent density. This is because the jaw crushers are effective in reducing size, while cone crushers are useful in cubicizing and reducing adhered mortar [42, 43]. The effectiveness of the crushing will be verified by a rapid WA test method based on thermal conductivity in future research. Figure 3 shows that replacing 8/16 crushed rocks with 8/16 CCA gives a suitable aggregate grading for concrete use, compared to a natural aggregate NA (0/8 sand and 8/16 crushed rocks), an ideal grading curve for a specific industrially produced concrete recipe. A grading envelope between 0 to 8 mm has earlier been used as a branch norm but nowadays concrete producers have their own ideal combined curve.

Table 4 - A lab crushed and industrial crushed CCA properties

	Repeated jaw crushing		Industrial crushes Primary + Secondary	
	0/8	8/16	0/8	8/16
Water absorption (%)	6,24	2,5	3,5	2,07
Apparent Density (kg/m^3)	2,55	2,52	2,52	2,5

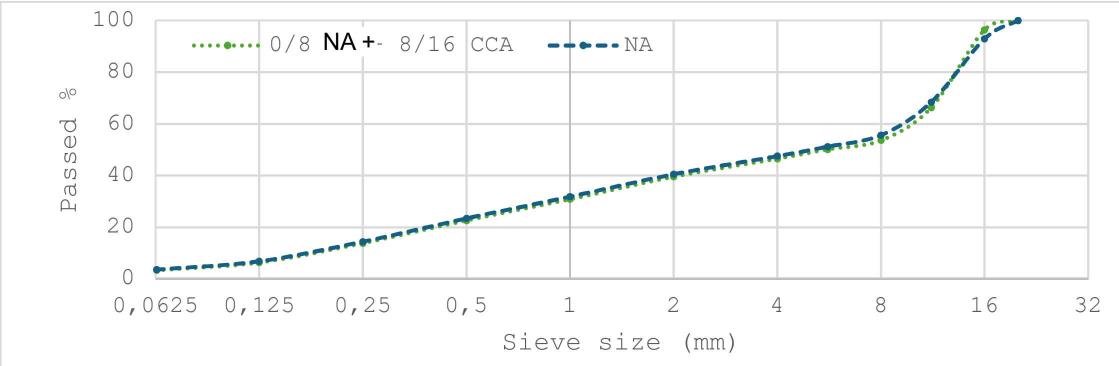

Figure 5 - Combined particle size distribution for coarse 8/16 CCA and 0/8 NA versus all-NA

The stationary aggregate crushing infrastructure already gives CCA fitting nondemanding concrete class, that is, exposure class X0 indoor concrete. The concrete waste investigated is reclaimed concrete comprised of 100% stone and concrete, surpassing standard type A recycled aggregate.

4.2 Results from literature for CCA as coarse aggregates in concrete

Table 5 presents an overview of CCA produced from reclaimed concrete from prefabricated concrete industries, used in concrete as 100% replacement of coarse aggregates [44, 45]. It surpasses a type A aggregate with stone and concrete composition higher than 95%, i.e. high quality CCA.

Table 5 - Comparison of CCA performance on compressive strength of different source concrete from literature.

Aggregate quality	Application	Parent concrete waste (MPa)	New concrete compressive strength	REF
High quality	New concrete	100 MPa prefab rejects	Comparable to the reference concrete	[38, 44]
		40 MPa prefab rejects	Comparable to the reference concrete	
High quality	New concrete	30 MPa ready-mix rest concrete	Decrease in strength	[45]
		50 MPa ready-mix rest concrete	Comparable or equal to reference concrete	

5. CONCLUSIONS

The conclusion of this article is based on ready-mixed concrete waste, resulting in type A recycled aggregates for recycling in new concrete. If demolition waste is accounted, cleaner aggregates can be derived from selective demolition.

5.1 Findings from literature

- Selective demolition can produce better-quality CCA than conventional demolition. If reused in the same place in a new building, it will result in lower CO_2 emissions. Frame structures are more suitable for selective demolition, and they promote the recycling and reuse of several elements from the building's load-bearing structure.
- Coarse CCA produced from ready-mixed concrete waste shows higher WA than virgin aggregates yet comply with the standards for virgin aggregates for concrete for indoor applications.
- Testing methods for characterizing CCA aggregates suit coarse aggregates better than fine aggregates fractions. For example, WA method and determining saturated surface dry state for aggregates.
- Modified pycnometer method is suggested for WA assessment of CCA.
- Tertiary crushing steps using a VSI crusher, results in fine aggregates particle grading that fits concrete application, requires to be checked only for WA.
- CCA can replace up to 100% coarse aggregates in new concrete for the same strength as concrete with virgin aggregates, Table 5.
- Recycling concrete waste into new aggregates for concrete is the closest way to closed-loop recycling and the most value-preserving process for concrete waste.

5.2 Findings from lab experiments and industrial upscaling in Sweden

- The existing infrastructure of stone crushing can be used to crush concrete into coarse CCA recycled aggregates; the CCA fraction 8/16 combined with natural sand 0/8 shows perfect agreement with particle grading for concrete application, Figure 5.
- Primary crushing combined with secondary is necessary for getting particle grading suitable for aggregates for concrete. WA and adhered mortar are tested subsequently after particle grading fitting, Table 4.
- The latest industrial upscaling with existing rock crushing infrastructure gives aggregates fit for indoor concrete.
- Preliminary upscaling trials with improved aggregate processing and existing infrastructure show that the aggregates produced can be suitable for external concrete applications.
- Using rock crushing infrastructure, CCA can be produced suiting different application areas. As CCA has been tested and found fit for indoor concrete, with strictest claims, CCA maybe used for other applications such as road construction material or backfilling based on the need.

Further research planned in relation to this study

- Integration of fine and coarse CCA aggregates into new concrete.

- Rapid test methods for particle grading, WA, and frost resistance feasible for industrial environment.
- Refined crushing processes to produce CCA on an industrial level.
- Using CCA aggregates in bound and un-bound applications to achieve more narrow material loops, thus reducing climate impact.

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