ABSTRACT

Sweden’s concrete waste is recycled for use in low-utility purposes such as in the construction of sub-bases in roads but hardly as aggregates in new concrete. To analyse the potential for high-utility recycling, a literature study was conducted on the regulatory instruments, building standards, production and properties of recycled concrete aggregates and the recycled aggregate concrete for Sweden and European countries. Results urge statistics to quantify recycled concrete; regulations like source sorting of waste and selective demolition could potentially optimize recycled aggregate production. Also, the compressive strength of recycled concrete aggregate’s parent concrete influences the properties of the new concrete.

**Key words:** Recycled concrete aggregate, Structural applications, Closed-loop recycling, Sustainability
1. BACKGROUND

Recycled Concrete Aggregates (RCA) are aggregates produced from the crushing and recycling of only concrete or concrete combined with mineral waste sourced from demolition waste, rejects from prefabrication and concrete spill. RCA is useful in road construction and as aggregates in new concrete. The new concrete produced using RCA or a combination of RCA and other aggregates is called Recycled Aggregate Concrete (RAC) [1]. The production of RAC is being implemented in certain European countries for example Spain, where coarse fractions of RCA was used in structural RAC in housing near Madrid [2]. Similarly in Germany, RAC formed about 4% of the total precast concrete products and ready-mixed concrete produced in 2004 [3]. Sweden on the other hand uses RCA in low-grade construction applications. This can be confirmed by national statistics which estimated that Sweden in 2014 used 670,000 ton of crushed concrete and mineral waste for road sub-base construction while disposing 510,000 ton in the landfills [4].

In Sweden, the inclusion of RCA as aggregates in structural concrete is acknowledged by sustainability and environmental certification systems in their methods of assessment [5, 6]. Besides the certification systems, the European standard for concrete EN 206 has proposed regulations for the inclusion of RCA in new concrete. This is to help producers of ready-mixed and prefabricated concrete realize a closed loop recycling by using the waste concrete for the same application as its parent concrete [7].

Generally, the introduction of RCA in the production process of concrete as a replacement for natural aggregates is investment intensive [8], however, environmental benefits can be made from prolonging the life cycle of the parent concrete as aggregates and un-hydrated cement in the new concrete. This also creates opportunity for internal recycling of waste as a raw material in production. Furthermore, if the production of RCA in included in the concrete production (in-house production) it could potentially eliminate transportation costs related with the delivery of natural aggregates to the industry.

This article attempts to list and analyse examples of the regulatory instruments, building standards and production infrastructure for RCA suitable for use in structural and non-structural RAC. Such examples are drawn from European countries that are forerunners in RAC production and are compared with corresponding Swedish examples.

Together with this, relatable examples from the extensive RCA research from Europe and China are presented and critically analysed regarding the influence of RCA in the mechanical, deformational properties and durability of RAC. It is to note that, except for a single research study in Sweden [9] there were no other published attempts relating to RAC produced from RCA.

The comparative analysis with examples are presented as a sequence starting with the production of RCA from concrete waste and finally ending with the properties of RAC produced from such RCA.

2 CONCRETE WASTE TO RCA

The concrete waste received as hardened spill or mixed demolition waste is recycled into RCA by Construction and Demolition Waste (CDW) recycling plants in Germany, Italy, Spain, and
Belgium. Figure 1 is a simplified representation of the treatment processes for RCA production in a CDW plant.

The processes which are a sequence of crushing, separation of impurities and screening [2, 10] aim to produce RCA free from contaminants and adhered cement mortar that adversely affect the RAC’s properties. Examples of such contaminants are unwanted blended CDW fractions such as wood, plastic, paper and gypsum from plaster boards that cause harmful internal expansion in concrete [11]. Fine fractions of gypsum, autoclaved aerated concrete and organic materials can be separated by complex methods such as X-ray transmission [12] and Near Infrared Sorting [13]. The separation processes are, however, not entirely successful in separating the cement mortar adhered to the RCA; which if developed could make possible larger RCA replacements in the RAC [14]. The cement mortar from the parent concrete adhered to the RCA increases the RCA’s porosity thereby negatively influencing the mechanical properties and durability of the RAC [15]. Novel thermo-mechanical separation methods include the “closed cycle construction” from Netherlands [12], microwave-assisted technique [16], ADR dry classification technology [17]. These methods have been successful in separating contamination and adhered cement mortar from the finer fractions of RCA that are more susceptible to contamination [18].

The RCA used mainly in un-bound road applications in Sweden is produced in waste treatment facilities following largely the processes shown in Figure 1, however, the separation processes involved are less advanced in comparison with the aforementioned CDW plants. The equipment in the most advanced of Swedish facilities can separate non-ferrous materials and fines in addition to mobile crushers, ferrous metal separation and screening operations [19, 20]. These plants are, however, not tried and tested for producing RCA that could substitute natural aggregates in concrete.

Currently, there exist only few instances of high-utility concrete recycling conducted internally by Swedish concrete producers; as is reported in their product declarations [21, 22]. These instances are however missing from the national statistics along with the information on the amount of RCA produced in treatment facilities to be used in low-grade recycling.

For it to be economically feasible to produce purer RCA fractions suitable for RAC using complex separation methods, a continuous supply of considerably uncontaminated waste is required [23]. According to industrial actors even the intermittent supply of concrete waste to produce RCA is challenged by the long transportation distances resulting from the extensive land area in Sweden. This leads to the accumulation of crushed concrete waste in intermediate storage facilities until a considerable amount is collected to justify the establishment of mobile recycling equipment in the facility. Logistical challenges of this nature reduce the availability of waste for recycling, but can potentially be resolved by alternatives like the establishment of
localized sorting, storage facilities and the creation of material or waste exchange opportunities between industrial clusters [24].

The Swedish waste regulations aim to increase the concrete waste available for recycling but fall short in initiating its use in high-utility applications. Also, certain aspects of the waste regulations seem to indirectly cause landfilling to be a more viable option.

2.1 Regulatory instruments to aid in recycling of concrete waste

**Landfill tax** in Sweden is charged at SEK 435/ton (approx. EUR 47) as of 2006 with no-fee exceptions for materials useable in landfill construction [25]. Additionally, the quantities of concrete waste and other mineral fraction used in landfill construction is considered recovered by the Swedish Environmental Protection Agency [26]. The use of recovered waste to enhance landfill capacity justifies the claim by the European Environmental Agency that landfill tax is not an efficient driver for recycling. Landfill taxes have, however, increased recycling rates when coupled with mandates such as recycling targets and source-sorting of waste in Germany and Denmark [27].

Mandatory **source-sorting** along with landfill tax in Denmark, Germany and the Netherlands has been effective in reaching high recycling rates for concrete waste. Concrete waste in Denmark is sorted separately as 1 out of 10 waste fractions which has increased the recycling rate in Denmark to 90% [28]. Mandatory source-sorting in Portugal has also helped to create cost savings in the separation processes for the production of RCA free of contaminants [29] and on-site production of RCA in Brazil [30]. However, recycling concrete waste to contaminant-free RCA is challenging in Sweden because source-sorting is not mandatory. But even when such sorting is implemented, the Swedish branch-normative guidelines recommend concrete waste to be sorted as a mineral fraction combined with bricks, stones and asphalt which only increases the chances of contamination [31].

Regulatory measures such as **selective demolition** have been identified in facilitating better recycling and production of lesser contaminated RCA [12, 32] that could potentially be used in RAC. Selective demolition is, however, difficult to implement because of the need of sufficient space on-site for sorting; the cost of which exceeds the costs of processing CDW [33]. For example the Danish Construction Federation’s guidelines NMK 96, formulated towards separating hazardous components from CDW has been remarked as ineffective [34]. Additionally, the environmental benefits arising from the increased recycling in selective demolition [35] could in a few cases be lost to increased transportation needs [36]. This could lead to decisions made in favour of conventional demolition.

3. RCA AS AGGREGATES IN RAC

The suitability of RCA for use in RAC depends on likeness of the properties of RCA with the properties of natural aggregates [37]. The RCA properties such as the physical and chemical properties are in turn influenced by the adhered mortar and CDW contaminants that the RCA is composed of [38].
3.1 Constituents of RCA

The constituents and properties of the RCA can vary depending on the waste source, methods of demolition and waste sorting, and the quantities sampled to determine its composition [39, 40]. RCA’s constituents also depend on the treatment process; namely the crushing operation that varies the cement-mortar content [41, 42].

Classification of RCA based on its constituents

To ensure quality despite such variation, standards and specifications such as the RILEM, EHE 08 from Spain and the PTV 406 from Belgium include a classification of recycled aggregates especially RCA. This classification delimits the content of certain constituents in coarse RCA [43]. The delimited constituents are those that negatively affect the properties of RAC such as glass, plastic, organic material and light-weight material content [44].

Similarly, the Swedish standard SS 137003:2015 which is the application of EN 206 in Sweden delimits the constituents of coarse RCA and determines the extent of using RCA in RAC. The RCA’s constituents are defined by the harmonized European standard SS EN 12620+A1:2008 aggregates for concrete. This definition has resulted in SS 137003:2015 classifying RCA into categories A and B based on their constitution. For coarse RCA to qualify as Type A, 95% of the constituents must originate from concrete and natural aggregates; whereas in Type B the content of similar constituents is reduced to 70%.

Table 1 shows the maximum allowable mass percentage of coarse natural aggregates that could be replaced with Type A and B coarse RCA; as prescribed by SS 137003:2015.

Table 1 – Maximum permissible mass percentages of RCA
(adapted from Table 6, SS 137003:2015)

<table>
<thead>
<tr>
<th>RCA type</th>
<th>Exposure classes</th>
<th>Other exposure classes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X0</td>
<td>XC1, XC2</td>
</tr>
<tr>
<td>Type A</td>
<td>50%</td>
<td>30%</td>
</tr>
<tr>
<td>Type B</td>
<td>50%</td>
<td>20%</td>
</tr>
</tbody>
</table>

From Table 1 it can be inferred that the maximum RCA replacement percentage permitted by the standard is 50% for use in non-reinforced RAC in an indoor environment (X0). The permitted mass percentages are based on the constituents of RCA, the physical properties of the RCA and the resulting properties of the RAC.

Table 2 presents a classification of RCA and compares the allowable content of concrete, natural aggregate, masonry, bitumen, and lightweight materials from standards and specifications from different countries in Europe. Most of the classification stated in this table is derived from the European Standard EN 933-11 of 2009 [38].

The existing information from [38] was updated with the allowable content for constituents from the Swedish standard. The recycled aggregate classifications in the table are considered as RCA by researchers based on the high content of concrete in the aggregate and its suitability in RAC recommended by the respective standard.
### Table 2 – Classification of RCA and the allowable content of its constituents (Adapted from Martin-Morales, Zamorano et al. [38])

<table>
<thead>
<tr>
<th>Country/Standard</th>
<th>Standard</th>
<th>Concrete (in %)</th>
<th>Masonry (in %)</th>
<th>Natural aggregate (in %)</th>
<th>Lightweight materials (in %)</th>
<th>Bituminous materials (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>PTV406</td>
<td>&gt;90</td>
<td>&lt;10</td>
<td>n.a.</td>
<td>n.a.</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Denmark</td>
<td>DS 2426</td>
<td>&gt;95</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>Germany</td>
<td>DIN 4226-100 Type 1</td>
<td>&gt;90</td>
<td>&lt;10</td>
<td>n.a.</td>
<td>n.a.</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>DIN 4226-100 Type 2</td>
<td>&gt;70</td>
<td>&lt;30</td>
<td>n.a.</td>
<td>n.a.</td>
<td>1</td>
</tr>
<tr>
<td>Netherlands</td>
<td>CUR</td>
<td>&gt;95</td>
<td>&lt;5</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>NEN 5905</td>
<td>&lt;80</td>
<td>n.a.</td>
<td>&lt;20</td>
<td>0.1</td>
<td>n.a.</td>
</tr>
<tr>
<td>Norway</td>
<td>NB 26</td>
<td>&gt;94</td>
<td>&lt;5</td>
<td>b</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>Portugal</td>
<td>LNEC E 471 Type 1</td>
<td>&gt;90</td>
<td>&lt;10</td>
<td>b</td>
<td>1</td>
<td>&lt;5</td>
</tr>
<tr>
<td></td>
<td>LNEC E 471 Type 2</td>
<td>&gt;70</td>
<td>&lt;30</td>
<td>b</td>
<td>1</td>
<td>&lt;5</td>
</tr>
<tr>
<td>RILEM [43]</td>
<td>Type II</td>
<td>&lt;100</td>
<td>n.a.</td>
<td>n.a.</td>
<td>0.5</td>
<td>1a</td>
</tr>
<tr>
<td></td>
<td>Type III</td>
<td>&lt;20</td>
<td>&lt;10</td>
<td>&gt;80</td>
<td>0.5</td>
<td>1a</td>
</tr>
<tr>
<td>Sweden</td>
<td>SS 137003 Type A</td>
<td>≥90</td>
<td>≤10</td>
<td>b</td>
<td>≤2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>SS 137003 Type B</td>
<td>≥50</td>
<td>≤30</td>
<td>b</td>
<td>≤2</td>
<td>1</td>
</tr>
</tbody>
</table>

b included in the crushed concrete content  
[a] includes metals, glass, soft material and bitumen  
n.a. no limit values reported by the standard

**Adhered cement mortar content in RCA**

RCA basically comprises the original aggregate surrounded by adhered cement mortar that is physically attached to the surface of the aggregate [45]. The adhered mortar is a remnant of the from the RCA’s parent concrete that has undergone crushing. This adhered mortar as a result of its porosity has been identified to negatively affect the physical properties of RCA such as lowering its density and abrasion resistance, increasing the water absorption. The sulphate content in the adhered mortar can also increase the sulphate content of the RCA [46].
The porosity of the RCA due to the adhered mortar affects subsequently the mechanical properties of the RAC such as the drying shrinkage [15].

The adhered mortar content in the RCA has been identified to vary with RCA particle size fractions [32, 46, 47]. Padmini, Ramamurthy et al. [48] reasoned that smaller sized aggregates contained a higher adhered mortar content due to the higher surface area available for equal volume of aggregate. Juan and Gutiérrez [46] investigated the adhered mortar content in 15 RCA samples of sizes 4/8 mm and 8/16 mm by thermal treatment. They reported that 4/8 mm size fraction contained between 33-55% and the 8/16 mm between 23-44% adhered mortar.

They also deduced from literature, a tendency for the adhered mortar content to increase with decreasing RCA size fractions. Unable to obtain a significant regression they concluded that there were other factors that influenced the adhered mortar content.

The Building Contractors Society of Japan (BCSJ) determined the adhered cement mortar content in RCA acquired from parent concretes of medium-high compressive strengths [1]. The investigation by dissolution in hydrochloric acid yielded results of the adhered cement mortar content as weight percentages of RCA and is shown in Figure 2. Where the coarser fractions (20-30 mm) contained 20% adhered mortar compared to finer fractions that contained 40-60%; thereby confirming the size-adhered mortar relation. Additionally, the result also shows that RCA of identical size fractions can have different adhered cement mortar contents depending on the strength of the parent concrete, as is seen for RCA of size 0.3 mm.

![Figure 2](image2.png)

*Figure 2 – Adhered cement mortar content varying with RCA size fraction and water/cement ratio of the parent concrete (adapted from Hansen [1]).*

### 3.2 Physical properties of RCA

**Density and water absorption**

The density of RCA is lesser than that of natural aggregate because of the adhered cement mortar that is relatively less dense. It is the porosity of the adhered cement mortar that reduces the density and increases the water absorption of the RCA [46]. The relationship between the density and water absorption of RCA has been described as a linear relationship [49]. The
factors that could vary the adhered mortar content and thereby influencing the RCA’s density include:

- Different stages of crushing [41, 50]
- Compressive strength of the parent concrete [48, 51]

The effects of primary crushing and primary combined with secondary crushing were investigated on the density of coarse RCA prepared from precast and lab concrete rejects. Primary crushing entailed the use of jaw crusher while the combined crushing included the use of the jaw crusher and the impact crusher. It was observed that the primary combined with secondary crushing produced RCA of higher density. The RCA fractions that underwent primary and secondary crushing demanded lesser water for workability of the RAC mix implying that they had reduced water absorption compared to the RCA produced only from primary crushing [41]. The lesser water absorbed by the RCA can be attributed to the reduction in the mortar content with successive crushing.

Padmini, Ramamurthy et al attempted to investigate the influence of the compressive strength of the parent concrete on the physical properties of coarse RCA [48]. They investigated the water absorption and density for fractions of 10, 20 and 40 mm obtained from low, medium and high strength concrete. The results of the particle density and water absorption for the 20 mm RCA for the respective parent concretes are shown in Table 3; also included is a 20 mm crushed granite aggregate used as a benchmark by the authors themselves. The results show higher densities and lower water absorption values for RCA from lower strength parent concrete. The authors observed this to be due to lesser mortar adhered to RCA acquired from a parent concrete of lower strength. Thus they deduced that the adhered mortar content was an outcome of the bond strength between the mortar phases and aggregate which increased with increasing strength of the parent concrete. Therefore RCA from parent concretes of lesser strength, in this case 37 MPa, were easier to separate from the RCA when compared to stronger parent concretes.

<table>
<thead>
<tr>
<th>20mm sized aggregate obtained from parent concrete of strength</th>
<th>Water absorption (% weight in 24 hours)</th>
<th>Particle Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>37 MPa</td>
<td>3.65</td>
<td>2520</td>
</tr>
<tr>
<td>50 MPa</td>
<td>4.1</td>
<td>2510</td>
</tr>
<tr>
<td>58 MPa</td>
<td>4.86</td>
<td>2480</td>
</tr>
<tr>
<td>Fresh crushed granite</td>
<td>0.3</td>
<td>2800</td>
</tr>
</tbody>
</table>

4. PROPERTIES OF RAC

The amount of RCA included and its properties, such as porosity have been observed to influence the fresh properties, especially the workability of the RAC. The porosity of the RCA, the RCA content and the adhered cement mortar quality have a large influence on the hardened properties of RAC such as compressive strength, elastic modulus and shrinkage.
4.1 Fresh properties of RAC - Workability

RAC has a reduced workability compared to conventional concrete from natural aggregates. This is largely due to the porosity of the cement mortar adhered to the RCA causing it to rapidly absorb the free water from the mixture [49, 52]. The water absorption capacity of the RCA would depend on the moisture content in the RCA at the instance of mixing. The RCA’s moisture content during the time of mixing is determined between the differences in mass at the situation of mixing and dry state. Similar to natural aggregates, RCA at oven-dry and air dry state are known to absorb more mixing water than at a saturated state; moreover the absorption increases with the increased content of RCA [53]. Therefore, to reduce their water absorption capacity and moreover maintain constant water/cement ratio, the RCA is pre-wetted or pre-saturated before its inclusion in the concrete mix [54]. In this case, adjustments to the amount of water added to the mix is based on the amount of RCA and the difference between the RCA’s absorption value and moisture content during mixing.

Exteberria et al. investigated the workability of RAC while substituting the coarse natural aggregates of size 4/10 mm, 10/16 mm and 16/25 mm entirely with RCA of the same size fractions [54]. Aiming to achieve the required workability for RAC and reducing the water absorption capacity of the coarse RCA, they pre-saturated the RCA until it had reached 80% of its absorption capacity. The RCA was wetted with a sprinkler and stored under a plastic sheet for 24 hours to maintain the high humidity level. In this manner they were able to receive the desired slump value of 8-10 cm while maintaining the effective water/cement ratio. However the additive content was increased to 2% for RAC in place of the 1.28% for the reference conventional concrete.

Rogers, Fridh et al., prepared two sets of self-compacted RAC samples with a water/cement ratio of 0.5 with coarse and fine RCA sourced from both railway sleepers (S) and crushed hollow-core slabs (HCS) [9]. The authors concluded that the workability of the RAC was affected most by the fine RCA sized 0-4 mm. They attributed this to the fine RCA’s large specific surface area and its larger share in the total aggregate volume.

4.2 Hardened properties of RAC

Compressive Strength

Due to the porosity and lowered density of the RCA, it is speculated that the compressive strength of RAC would decrease with increased replacement percentage of RCA. Chakradhara Rao, Bhattacharyya et al. [55] by means of a literature review and experimental investigation reported that there was no significant reduction in the compressive strength up to a coarse RCA replacement of 25%. The authors however did not communicate how significant the reduction was.
Hansen and Narud conducted an investigation to determine the influence of the water/cement ratios of the RCA’s parent concrete on the compressive strength of the RAC [1]. They prepared nine different combinations of high, medium and low strength RAC using RCA derived from parent concretes of high, medium and low strength; with same mixed proportions and curing conditions. They observed that the compressive strength of high-strength RAC produced from RCA of a lower-strength parent concrete was 39% lower than the compressive strength of the same RAC produced from high-strength parent concrete.

In this manner, they deduced that the compressive strength of RAC depended not only on its water/cement ratio but also on the strength of the RCA’s parent concrete namely its water/cement ratio. This relationship between the compressive strength of the RAC and the RCA’s parent concrete is influenced by the porosity of the RCA’s interfacial transition zone which in turn depends on the compressive strength of the parent concrete [45].

Li investigated the 28 day compressive strength for RACs of six different water/cement ratios relating to low, medium and high strength concrete [56]. These RACs were prepared at 30, 50, 70 and 100% RCA replacement ratios. His results, shown in Figure 3, indicate a steady decline of compressive strength with the increasing water/cement ratio for the 30, 70 and 100% replacements of RCA. However at 50% replacement of RCA, the largest compressive strength of about 37 MPa is recorded at 0.47 water/cement ratio; and the lowest value of 28 MPa at 0.35 when compared to 30,70 and 100% replacements at the same water/cement ratios. Poon, Shui et al. [53] have also observed different behavior for the 28 day compressive strength for RAC at 50% replacement of RCA. They noticed the compression strength to have reduced to 40 MPa at 50% from 44 MPa at 20% replacement and further increased to 45 MPa at 100% replacement. The factors affecting the behavior of RAC at 50% RCA replacement have to be further investigated.

![Figure 3– Relation between water/cement ratios, RCA replacement percentages and the compressive strength of RAC (adapted from Li [56]).](image-url)
**Elastic Modulus**

The elastic modulus of RAC is always lower than that of conventional concrete due to the low elasticity modulus of the adhered mortar in the RCA [1]. Implying that as the RCA content increases, the elastic modulus of the RAC would decrease.

Xiao investigated the relation between the elastic modulus of the RAC and the RCA content by finding the elastic modulus at different RCA replacement percentages [57]. He expressed these results in terms of a relative elastic modulus defined as the ratio between the elastic modulus of the RAC and the reference concrete produced using natural aggregates. Figure 4 shows that when RCA substitutes 30% natural aggregates by mass in RAC, the elastic modulus of the RAC is 40% lesser than the reference concrete. The elastic modulus of RAC is seen to be nearly constant at RCA replacement percentages higher than 30%.

![Figure 4– The elastic modulus of RAC as a function of RCA content (adapted from Xiao, Poon et al. [57]).](image)

**Drying Shrinkage**

The drying shrinkage observed in RAC is higher than in conventional concrete made of natural aggregates. Researchers attribute this to the increase in cementitious material due to the old mortar adhered to RCA [15, 57] and the lower restraining capacity of the RCA when compared to natural aggregates [49].

Limbachiya, Leelawat et al., investigated the effect of the water/cement ratio and RCA content on the drying shrinkage of the RAC [15]. Test samples of high-performance RAC of design strength 60 and 70 MPa were prepared for each coarse RCA replacement of 30, 50 and 100%. From the drying shrinkage results which are shown in Figure 5 it can be inferred that:

- 70 MPa RAC and reference concrete have higher shrinkage values when compared to their 60 MPa counterparts.
- It is also seen that on replacing natural aggregates entirely with RCA, the 60 MPa has a higher shrinkage increase of 9.3% from its reference concrete compared to the 70 MPa that has increased by 6.3%.
Figure 5– Drying shrinkage of RAC for different RCA content and RAC water/cement ratio (diagram based on information acquired from Limbachiya, Leelawat et al. [15]).

The results of the test for drying shrinkage performed by Rogers, Fridh et al. [9] for the 100% replacement of the coarse 8-16 mm RCA at 224 days showed that the RAC(S) had increased drying shrinkage from the reference concrete by 20%. The strain value for the RAC(HCS) was larger than the reference concrete by 12%. Given that the percentage replacement of RCA and water/cement ratio is the same for both RAC groups; it could be reasonable to assume that the difference in the drying shrinkage values could be due to larger adhered mortar content in the RAC(S).

4.3 Durability of RAC

The durability aspects are critical to investigate for RAC so as to enable its use in structural applications and for different exposure conditions. The durability of the RAC is influenced to a great extent by the physical properties of the included RCA such as its low density, high water absorption and low abrasion resistance [57]. Moreover it is the porosity of the RCA that makes the RAC vulnerable to the ingress and further transport of water, carbon dioxide as well as chlorides and other harmful chemicals which leads to cracking in concrete and corrosion of the reinforcement.

Freeze-Thaw Resistance

The freeze-thaw resistance of RAC is assumed low because of the porosity of the old cement mortar adhered to the RCA having higher absorption compared to natural aggregates. However, Nixon [58] reviewed the results from two separate investigations on accelerated freeze-thaw cycling and the flexural strength measurements after the period of freeze-thaw cycling of RAC. The tests concluded that resistance of RAC was similar to that of conventional concrete.

Limbachiya et al. investigated the freeze-thaw resistance of RAC consisting of RCA derived from precast rejects. The tests were performed according to the procedure described in ASTM C666, Procedure A: freezing and thawing in water [15]. RAC samples containing 5.5% entrained air were prepared with RCA percentage replacements of 20, 40, 60, 80 and 100%. The
durability factor calculated at the failure criterion for 100% RCA replacement surpassed the 90% limit thereby proving that the RAC had considerable freeze-thaw resistance.

Similarly, the Swedish researchers Rogers et al. designed their RAC samples with different RCA replacements, a water/cement ratio of 0.4 and 4.5% air-entrainment [9]. The scaling tests to identify the freeze-thaw resistance were carried in accordance with the Swedish standard SS 137244:2015. The test results were well within the threshold value of 0.1 kg/m$^2$ proving that the RAC was freeze-thaw resistant.

Limbachiya et al.[15] and Rogers et al.[9] concluded that RCA sourced from precast rejects produced RAC with suitable freeze-thaw resistance.

**Chloride Ingress:**
The ingress of chloride is damaging to the concrete as it causes corrosion of reinforcement; the risk of chloride ingress is furthered in RAC due to the porosity of RCA. Similar to conventional concrete, the chloride ingress in RAC occurs from its exposure to sea water or de-icing salts. RCA exposed to the aforementioned chloride sources before its inclusion in the RAC could also cause chloride ingress.

Xiao J., Poon et al. have reasoned that the chloride resistance of RAC is influenced by quality of the interface between the aggregate portion and adhered cement mortar in the RCA [57]. Cracks along this interface caused during the RCA production increases RAC’s vulnerability for chloride ingress.

Kou and Poon conducted chloride penetrability tests according to ASTM C 1202 for their self-compacted RAC with varied percentage replacements of fine RCA of sizes less than 5 mm [52]. A total of three series of mixes containing fine RCA were prepared, with fine fly ash (< 45-µm) as part binder and rejected flyash (> 45-µm) as a filler in two series; and only rejected flyash in the third. They observed that the resistance to chloride ion penetration increased with increased fine RCA content especially for the series containing fly ash as binder. The authors attributed the resistance to chloride ion penetration to a filler effect caused by the inclusion of fine RCA fractions lesser than 0.3 mm in size.

**Carbonation:**
Carbonation is the reduction in alkalinity (neutralization) that occurs in concrete when CO$_2$ from air or water reacts with the products of hydration to produce carbonate and other products. The permeation of CO$_2$ in RAC can result from the porosity of the concrete, cement mortar or aggregate. RCA is very porous compared to natural aggregates and increases carbonation risk in RAC. Carbonation is highly dependent on the relative humidity in the concrete pores and diffusion of CO$_2$ occurs at a relative humidity between 50 and 70% [59].

The BCSJ standard of 1977 reported that the extent of carbonation in RAC increases by 65% with the inclusion of RCA that has already suffered carbonation and causes the reinforcement to rust [53]. BCSJ also recommended that the risk of corrosion can be reduced with reducing the water/cement ratio in RAC.
Katz noted the depth of carbonation of the RACs to be 1.3-2.5 times greater than the reference concrete [42]. However he noticed higher carbonation in the RACs with ordinary Portland cement compared to the ones with white Portland cement.

5. CONCLUSIONS

- Statistics relating to concrete waste recycling published by the Swedish Environmental Protection Agency estimates only the quantities of mineral waste fractions including concrete waste collected and subsequently the percentage recycled. However, a more timely and precise reporting of concrete waste from prefabrication industries could help create a continuous supply of RCA. Creating in this way, a market potential for RCA and subsequently RAC suitable for high-utility applications.
- The continuous and intermittently supply of concrete waste for recycling is challenged by the large transportation distances. Transportation distances could be minimized by the establishment of intermediate storage facilities and waste exchange between industrial clusters.
- Regulatory instruments such as selective demolition and source-sorting when applied to demolished concrete waste could help produce RCA of consistent quality suitable for RAC in high-utility applications. Additionally, these instruments reduce the costs arising from contaminant separation and thereby optimize the production cost of RCA.
- The adhered cement mortar content in RCA is central in determining the mechanical properties and durability aspects of RAC. Also, the adhered cement mortar in RCA derived from high strength parent concrete potentially contains more un-hydrated cement whose effect on the RAC’s properties could be interesting to investigate.
- The compressive strength of RAC does not change significantly up till an RCA replacement of 25%. The compressive strength of the RCA’s parent concrete has an influence on the RAC’s compressive strength. Studies have shown that RACs of low water/cement ratio could show compressive strengths higher than their target strength with RCA derived from high-strength parent concrete.

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