Progress in Developing Self-Consolidating Concrete (SCC) Constituting Recycled Concrete

Aggregates: A Review

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Abstract

Recycled concrete aggregate (RCA) derived from demolition waste has been widely explored for use in civil engineering applications. One of the promising strategies globally is to utilize RCA in concrete products. However, the use of RCA in high performance concrete such as self-consolidating concrete (SCC) has only been studied in the past decade. This paper summarizes recent publications on the use of coarse and/or fine RCA in SCC. The high-water absorption and porous structure of RCA, as expected, have been a challenge to produce high fluidity mixture. According to the analysis of published data, a lower strength reduction (within 23% regardless of coarse RCA content) is noticed in SCC as compared with vibrated concrete, possibly attributed to the higher paste content in the SCC matrix which enhances...
the weak surface layer of RCA and interfacial transition zone. Similarly, SCC tends to become less
durable with RCA substitution, though the deterioration can be minimized by using treated RCA through
removal and strengthening the adhered mortar. To date, the information reported on the role of RCA on
the long-term performance of SCC is still limited, hence a wide range of studies are needed to
demonstrate the feasibility of RCA-SCC in field applications.

**Keywords:** Self-consolidating concrete; Construction and demolition waste; Recycled concrete
aggregate (RCA); Durability, Properties enhancement.

1. Introduction

Due to the explosive growth of global economic and development, a significant amount of wastes derived
from construction and demolition activities is produced every year. In 2016, the annual production of
construction and demolition (C&D) waste was more than 800 million tons in Europe [1]. In the United
States of America alone, the average amount of generated C&D waste was over 540 million tons in 2015
[2]. As for China, annual production of 1.5 billion tons of C&D waste is reported [3]. At present,
landfilling is still a major approach to dispose of C&D waste [4, 5], but this raises concern on the
environmental impact. To minimize the destruction of landscape and disturbance to the ecological
balance, recycled concrete aggregate (RCA) has widely been studied to produce new concrete. In
addition, this may reduce the burden of extraction of natural aggregate (~50 billion tons worldwide per
year) [6], solving the issue of scarcity in some countries at the same time.
To produce high quality concrete with recycled aggregate, the adhered old-mortar is the main concern. RCA has a rougher surface, porous structure and higher water absorption capacity than natural aggregate (NA) due to the presence of adhered mortar [7]. The properties of RCA are mainly governed by the strength of the parent concrete [8], crushing process [9] and grading size [4]. Therefore, it is expected that the RCA derived from high strength concrete may exhibit better intrinsic properties and lower water absorption [8,9], thus minimizing the concrete deficiency. Compared with coarse recycled concrete aggregate (CRCA), fine recycled concrete aggregate (FRCA) usually contains more adhered mortar and weaker porous structure.

Self-consolidating concrete (SCC) which was first invented in the 1980s, is gaining wide acceptance in the construction industry across the world. This is because SCC possesses superior flowability and ability to fill in areas with congested reinforcement bars without undergoing any excessive segregation [10]. To achieve such self-consolidating features (i.e. high fluidity, passing ability and viscosity), mixture requires a relatively high amount of powder content and superplasticizer (SP) and a lower amount of coarse aggregate [11]. In other words, the overall material cost of SCC is higher than conventional vibrated concrete, and thus the incorporation of RCA could balance the cost of SCC production [12]. Moreover, SCC mixture usually possesses a better intrinsic quality of mortar paste [13] which can compensate concrete for the compromised quality induced by RCA.

Compared to conventional vibrated concrete, utilization of RCA in SCC is relatively new and only being explored in the past 10 years according to globally sourced literature [14, 15]. This paper presents an
overview of the feasibility and challenges of utilizing coarse and/or fine RCAs in the production of SCC.

A detailed discussion concerning the properties of RCAs and mixing approaches to produce self-consolidating recycled concrete (SCRC) was reported. Analysis and interpretation of the published data concerning the RCA effects (i.e. content, particle size, etc.) and enhancement methods (on RCA or the concrete matrix) on altering the fresh, hardened and durability properties of SCRC are also presented.

2. Characterization of RCAs and the mix design of SCRC

RCA is obtained by crushing C&D waste and the properties may vary depending on the crushing processes and the strength grade of original concrete. To reuse RCA in concrete, the density and water absorption are the two fundamental properties and have been specified as performance control criterion in most standards/specifications worldwide [16]. Silva et al. [17] performed a statistical analysis of the relationship between oven dried density and water absorption of 589 recycled aggregates sourced from 116 publications and found a good polynomial correlation between these two factors (fig. 1a). A performance-based classification was then proposed (fig. 1b) and is effective in predicting the compressive strength and modulus of elasticity of recycled aggregate concrete [18, 19].
Fig. 1. (a) Properties of different types of recycled aggregate [17] and (b) Classification of RA based on oven dried density and water absorption. (RMA: Recycled masonry aggregate; MRA: Mixed recycled aggregate contains RCA and waste rubber; CDRA: Construction and demolition recycled aggregates)

Table 1 summarizes the basic properties of RCAs used in SCC based on published literature. As indicated, the specific gravity of CRCA (10 mm~20 mm) and FRCA (≤5 mm) can range from 2.10 to 2.63, approximately 7%~15% lower than that of used NA. The crushing and impact resistance of CRCA is 5%~14% lower than NA owing to the existence of the adhered paste, micro-cracks and weak interfacial transition zone (ITZ) between the old mortar and core aggregate [4]. Moreover, RCAs exhibit higher water absorption values (about 5%~7% for CRCA and 10%~13% for FRCA), which can absorb a higher amount of free water and reduce the fluidity of the SCC mixtures considerably [4, 20, 21]. According to the categorization proposed by Silva et al. [17], CRCAs and FRCAs analyzed in this paper are classified as grade B and C, respectively.
Table 1. Details of RCAs properties reported in SCC studies

<table>
<thead>
<tr>
<th>Literature</th>
<th>Resource</th>
<th>Parent concrete strength</th>
<th>Types</th>
<th>Size/mm</th>
<th>Impact value/%</th>
<th>Crushing Value/%</th>
<th>SSD specific gravity</th>
<th>24h Water absorption/ wt%</th>
<th>Oven dried density/ (Kg·m^3)</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tang et al. [12]</td>
<td>Commercially produced RCA Concrete specimen; jaw crushed</td>
<td>-</td>
<td>Coarse</td>
<td>&lt;10</td>
<td>-</td>
<td>-</td>
<td>2.45</td>
<td>7.75</td>
<td>2260</td>
<td>BIII</td>
</tr>
<tr>
<td>Singh et al. [22]</td>
<td>Concrete specimen; jaw crushed</td>
<td>-</td>
<td>Coarse</td>
<td>5-12.5</td>
<td>22.14</td>
<td>23.87</td>
<td>2.48</td>
<td>3.92</td>
<td>2382</td>
<td>BI</td>
</tr>
<tr>
<td>Tuyan et al. [23]</td>
<td>Lab specimens</td>
<td>-</td>
<td>Coarse</td>
<td>4-16</td>
<td>-</td>
<td>-</td>
<td>2.48</td>
<td>4.8</td>
<td>2361</td>
<td>BI</td>
</tr>
<tr>
<td>Modani and Mohitkar [24]</td>
<td>Lab specimens</td>
<td>-</td>
<td>Coarse</td>
<td>&lt;12</td>
<td>17.36</td>
<td>-</td>
<td>2.27</td>
<td>5.6</td>
<td>2143</td>
<td>BIII</td>
</tr>
<tr>
<td>Kapoor et al. [25]</td>
<td>Lab specimens</td>
<td>-</td>
<td>Coarse</td>
<td>&lt;10</td>
<td>30.43</td>
<td>25.6</td>
<td>2.46</td>
<td>5.35</td>
<td>2328</td>
<td>BII</td>
</tr>
<tr>
<td>Revathi et al. [26]</td>
<td>35-year old building; manually crushed</td>
<td>-</td>
<td>Coarse</td>
<td>5-20</td>
<td>29</td>
<td>34</td>
<td>2.55</td>
<td>4.73</td>
<td>2429</td>
<td>B1</td>
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<td>Assaad and Harb [27]</td>
<td>Returned concrete from ready-mixed plants</td>
<td>-</td>
<td>Coarse</td>
<td>&lt;12.5</td>
<td>-</td>
<td>23.1</td>
<td>2.43</td>
<td>7.04</td>
<td>2259</td>
<td>BIII</td>
</tr>
<tr>
<td>Li et al. [28]</td>
<td>Lab specimen</td>
<td>55 MPa</td>
<td>Coarse</td>
<td>5-10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.95 / 6.78</td>
<td>BII/BIII</td>
</tr>
<tr>
<td>Rajhans et al. [29,30]</td>
<td>30-year old building</td>
<td>-</td>
<td>Coarse</td>
<td>5-20</td>
<td>28</td>
<td>33</td>
<td>2.6</td>
<td>4.78</td>
<td>2476</td>
<td>BI</td>
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<tr>
<td>Kapoor et al. [31]</td>
<td>Lab concrete blocks</td>
<td>-</td>
<td>Fine</td>
<td>0-5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Kapoor et al. [31]</td>
<td>Lab concrete blocks</td>
<td>-</td>
<td>Coarse</td>
<td>5-10</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Velay-Lizancos et al. [32]</td>
<td>Rejected precast element</td>
<td>&gt;40 MPa</td>
<td>Mixed</td>
<td>0-12</td>
<td>-</td>
<td>-</td>
<td>2.35</td>
<td>6.06</td>
<td>2210</td>
<td>BII</td>
</tr>
<tr>
<td>Gonzalez-Taboada et al. [33,34]</td>
<td>Structural concrete debris</td>
<td>-</td>
<td>Coarse</td>
<td>4-11</td>
<td>-</td>
<td>-</td>
<td>2.34</td>
<td>6.96</td>
<td>2177</td>
<td>BIII</td>
</tr>
<tr>
<td>Güneyisi et al.</td>
<td>Lab specimens,</td>
<td>C20</td>
<td>Fine</td>
<td>0-4</td>
<td>-</td>
<td>-</td>
<td>2.26</td>
<td>12.80</td>
<td>1970</td>
<td>CII</td>
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<tr>
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<td>Type</td>
<td>Material</td>
<td>Size</td>
<td>Cohesion (kPa)</td>
<td>Dilation (°)</td>
<td>Plasticity Index</td>
<td>ID</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>[35]</td>
<td>jaw and cone crushed</td>
<td>Designed specimen</td>
<td>4-16</td>
<td>2.4</td>
<td>7.00</td>
<td>2232</td>
<td>BIII</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Gesoglu et al. [36]</td>
<td>Coarse</td>
<td>20 MPa</td>
<td>Fine</td>
<td>0-4</td>
<td>-</td>
<td>2.1</td>
<td>10.94</td>
<td>1870</td>
<td>CII</td>
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<tr>
<td>Vinay Kumar et al. [37]</td>
<td>Coarse</td>
<td>30 MPa</td>
<td>Fine</td>
<td>0-4.75</td>
<td>-</td>
<td>2.2</td>
<td>10.40</td>
<td>1971</td>
<td>CI</td>
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</tr>
<tr>
<td>Kebaili et al. [38]</td>
<td>Lab concrete</td>
<td>Old building, lab crushed</td>
<td>Coarse</td>
<td>4.75-12.5</td>
<td>-</td>
<td>2.4</td>
<td>6.10</td>
<td>2254</td>
<td>BII</td>
<td></td>
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<tr>
<td>Grdic et al. [39]</td>
<td>C&amp;D waste recycling facility</td>
<td>C37/45</td>
<td>Coarse</td>
<td>4-8</td>
<td>-</td>
<td>-</td>
<td>5.88</td>
<td>-</td>
<td>BII</td>
<td></td>
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<tr>
<td>Carro-Lopez et al. [40, 41]</td>
<td>C&amp;D waste recycling facility</td>
<td>&lt;9.5</td>
<td>Fine</td>
<td>5-10</td>
<td>-</td>
<td>2.3</td>
<td>9.3</td>
<td>2100</td>
<td>CI</td>
<td></td>
</tr>
<tr>
<td>Pereira-de-Oliveira et al. [42]</td>
<td>C&amp;D waste recycling facility</td>
<td>&lt;19</td>
<td>Coarse</td>
<td>4.75-10</td>
<td>-</td>
<td>2.51</td>
<td>4.1</td>
<td>2407</td>
<td>BII</td>
<td></td>
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<tr>
<td>Singh and Singh [43, 44]</td>
<td>Lab specimens</td>
<td>&lt;10</td>
<td>Coarse</td>
<td>5-20</td>
<td>-</td>
<td>2.64</td>
<td>5.35</td>
<td>2498</td>
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<tr>
<td>Wang [45]</td>
<td>Lab specimens</td>
<td>30.43</td>
<td>Coarse</td>
<td>5-20</td>
<td>-</td>
<td>2.48</td>
<td>6.6</td>
<td>2316</td>
<td>BIII</td>
<td></td>
</tr>
<tr>
<td>Singh et al. [46]</td>
<td>20-year old building</td>
<td>Lab specimens</td>
<td>Coarse</td>
<td>5-20</td>
<td>-</td>
<td>18.7</td>
<td>2.41</td>
<td>7.2</td>
<td>2236</td>
<td>BIII</td>
</tr>
<tr>
<td>Omrane et al. [47]</td>
<td>Lab concrete slabs</td>
<td>Coarse</td>
<td>3-8</td>
<td>24.72</td>
<td>4.23</td>
<td>6.5</td>
<td>2281</td>
<td>BII</td>
<td></td>
<td></td>
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<tr>
<td>Señas et al. [48]</td>
<td>Field concrete waste</td>
<td>Fine</td>
<td>&lt;12.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

a: Class of RCA are determined based on Silva et al. [17]
Table 2. Mix design of SCRC reported in literature

<table>
<thead>
<tr>
<th>Literature</th>
<th>Mixing strategy</th>
<th>W/P</th>
<th>RCA CRCA</th>
<th>RCA FRCA</th>
<th>SCMs</th>
<th>SP</th>
<th>VM</th>
</tr>
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<tr>
<td>Tang et al. [12]</td>
<td></td>
<td>0.35</td>
<td>0-100%</td>
<td>×</td>
<td>25% FA, 5% SF</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>Singh et al. [22]</td>
<td></td>
<td>0.34</td>
<td>0-100%</td>
<td>×</td>
<td>25-50% FA, 5% MK, 5% SF</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Tuyan et al. [23]</td>
<td></td>
<td>0.43, 0.48, 0.53</td>
<td>0-60%</td>
<td>×</td>
<td>30% FA</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>Modani and Mohitkar [24]</td>
<td>RCA immersed in water for 24 hours/SSD condition</td>
<td>0.45</td>
<td>0-100%</td>
<td>×</td>
<td>20-30% FA, 10% MK, 10% SF</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>Kapoor et al. [25]</td>
<td>RCA immersed in water for 24 hours/SSD condition</td>
<td>0.45</td>
<td>0-100%</td>
<td>×</td>
<td>36% FA</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>Assaad and Harb [27]</td>
<td></td>
<td>0.38, 0.44, 0.50</td>
<td>0-100%</td>
<td>×</td>
<td>25% GGBS, 5% SF</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Li et al. [28]</td>
<td></td>
<td>0.45</td>
<td>0-100%</td>
<td>×</td>
<td>×</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>Rajhans et al. [29,30]</td>
<td></td>
<td>0.45</td>
<td>0-100%</td>
<td>×</td>
<td>30% FA</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>Kapoor et al. [31]</td>
<td></td>
<td>0.45</td>
<td>0-30%</td>
<td>0-50%</td>
<td>30% FA</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>Velay-Lizancos et al. [32]</td>
<td></td>
<td>0.5</td>
<td>0-30%</td>
<td>0-20%</td>
<td>49% LF</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>González-Taboada et al. [33,34]</td>
<td>RCA immersed in water for 10 mins</td>
<td>0.32</td>
<td>0-100%</td>
<td>×</td>
<td>31% LF</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>Güneyisi et al. [35]</td>
<td>RCA immersed in water for 30 mins</td>
<td>0.32</td>
<td>0-100%</td>
<td>0-100%</td>
<td>20% FA</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>Gesoglu et al. [36]</td>
<td></td>
<td>0.3, 0.43</td>
<td>0-100%</td>
<td>0-100%</td>
<td>25% GGBS, 10% SF</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Vinay Kumar et al. [37]</td>
<td>SSD CRCA, Dry FRCA</td>
<td>0.36</td>
<td>0-20%</td>
<td>0-20%</td>
<td>25% FA</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Kebaïli et al. [38]</td>
<td>Extra water, 24-h aggregate absorption</td>
<td>0.37</td>
<td>0-100%</td>
<td>×</td>
<td>24% LF</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>Grđic et al. [39]</td>
<td>Extra water 16kg/m³</td>
<td>0.25</td>
<td>0-100%</td>
<td>×</td>
<td>39% LF</td>
<td>√</td>
<td>×</td>
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<tr>
<td>González-Taboada et al. [33,34]</td>
<td>10-min aggregate absorption</td>
<td>0.32</td>
<td>0-100%</td>
<td>×</td>
<td>31 LF%</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>Carro-López et al. [40, 41]</td>
<td>Extra water 53.12kg/m³</td>
<td>0.32</td>
<td>0-100%</td>
<td>×</td>
<td>31 LF%</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>Kou and Poon [15]</td>
<td>Extra water 62 kg/m³, 24h</td>
<td>0.35, 0.40, 0.44, 0.53</td>
<td>0-100%</td>
<td>0-100%</td>
<td>37% f-FA, 11% r-FA</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Author(s)</td>
<td>Dosage of SP (superplasticizer)</td>
<td>Dosage of VMA (viscosity modifying agent)</td>
<td>Admixtures</td>
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<tr>
<td>Pereira-de-Oliveira et al. [42]</td>
<td>0.25</td>
<td></td>
<td>56% LF</td>
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<tr>
<td>Singh and Singh [43, 44]</td>
<td>0.45</td>
<td></td>
<td>25-30% FA, 5% MK</td>
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<td>Wang [45]</td>
<td>0.27</td>
<td></td>
<td>39% FA</td>
<td></td>
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<td>Singh et al. [46]</td>
<td>0.45</td>
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<td>20-30% FA, 10% MK, 10% CBA</td>
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<td>Omrane et al. [47]</td>
<td>0.42</td>
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<td>5-25% NP</td>
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<tr>
<td>Señas et al. [48]</td>
<td>0.4</td>
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<td>LF, WCP</td>
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<td></td>
</tr>
</tbody>
</table>

*: the dosage of SP (superplasticizer) and VMA (viscosity modifying agent) is varied.

Abbreviations: FA: fly ash (f type<45 μm; r type>45 μm); MK: metakaolin; LF: limestone filler; SF: silica fume; GGBS: ground granulated blast slag; CBA: Coal bottom ash; NP: natural pozzolan; WCP: waste cement powder.
Table 2 provides an overview of SCRC mix designs. Normally, 25%-50% of supplementary cementitious materials (SCMs, including fly ash limestone filler, ground granulated blast slag, etc.) were used as filler to achieve high paste content and required flowability of self-consolidating concrete.

Considering the high water absorption of RCAs, practical approaches have been proposed in SCC studies to compensate SCRC for reduced workability by (i) immersing RCA in water bath prior mixing [12, 22-36]; (ii) adding corresponding extra water during concrete mixing [15, 38-41] and (iii) adding extra high range water-reducing admixture [42-48].

3. Effects of RCAs on fresh and rheological properties of SCC

3.1. Fresh properties

One of the superior advantages of SCC over conventional concrete is the high flowability characteristics, which allows the mixture to flow and fill formwork without any vibration and undergoing excessive segregation. Various methods have been used to examine the characteristics of SCC at fresh state including the flowability, filling and passing abilities, with respect to the EFNARC guidelines [48] as indicated in table 3.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Test method</th>
<th>Measured value</th>
<th>Accepted range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flowability/filling ability</td>
<td>Slump flow</td>
<td>Total spread/mm</td>
<td>650–800</td>
</tr>
<tr>
<td></td>
<td>T_{500}</td>
<td>Flow time/s</td>
<td>2–5</td>
</tr>
<tr>
<td>Viscosity/filling ability</td>
<td>V-funnel</td>
<td>Flow time/s</td>
<td>6–12</td>
</tr>
<tr>
<td></td>
<td>L-box</td>
<td>Passing ratio</td>
<td>0.8–1</td>
</tr>
<tr>
<td>Passing ability</td>
<td>U-box</td>
<td>Height difference/mm</td>
<td>0–30</td>
</tr>
<tr>
<td></td>
<td>J-ring</td>
<td>Step height, total flow/mm</td>
<td>0–10</td>
</tr>
</tbody>
</table>
Grdíc et al. [39] have demonstrated that NA in the SCC can be partly or fully replaced by RCA, and the addition of 4.7% and 9.4% extra water in the SCC mixtures can compensate the flowability loss associated with 50% and 100% CRCA substitution levels, respectively. Arabi et al. [50] indicated that NCA can be fully replaced by CRCA with extra water to compensate 10-min water absorption of RCA, the slump flow, $T_{500}$ slump flow time and L-box ratio remained similar. However, total replacement of fine and coarse NA by RCA is not advisable since it failed to satisfy both the requirement of slump flow (610 mm) and L-box ratio (0.2). Kou and Poon [15] reported that adding extra water maintained or even increased the slump flow values of SCRC containing 100% CRCA and FRCA. This was because during the first 10 min of mixing process, RCA was only able to absorb about 51% of 24h absorption capacity [15], and part of the extra water added to compensate the absorption would help to increase the workability.

Some studies [12, 22-36] adopted the approach of immersing RCA in water to achieve saturated surface dry (SSD) prior mixing in SCC. SSD-RCA gave a slight decrease in flowability and passing ability, and making the concrete mixture more viscous [24, 26, 27]. Tang et al. [12] noticed that the increased viscosity of SCRC mixture could resist the segregation, which was associated with the higher inter friction and rough surface texture of RCA. At lower w/c ratio, SCRC exhibited greater segregation resistance with no slump flow change [27]. Güneyisi et al. [35] pre-soaked CRCA and FRCA for 30 min prior mixing (about 87% of water absorbed by RCAs for 24h) and found the utilization of FRCA increased the slump flow value and L-box ratio, as well as decreased the V-funnel time and $T_{500}$ slump flow time. On the contrary, the use of 50% CRCA alone increased the slump flow and L-box ratio.
whereas higher replacement of CRCA provided less increase in flowability and passing ability due to the higher inter friction caused by the angular shape and rough surface of CRCA.

Other studies [12, 23] suggested that the passing ability was governed by the SP more than CRCA. Singh and Singh [43, 44] used additional chemical admixtures in order to meet the fresh properties requirement of SCRC containing 100% of CRCA. In the study, SP (1.72 kg/m³-2.15 kg/m³) and viscosity modifying agent (VMA, 1.72 kg/m³-1.93 kg/m³) were used to maintain the slump flow, T₅₀₀ and V-funnel times within the range of 680 mm-690 mm, 1.8 s~2.5 s and 5.8 s~7 s, respectively. Omrane et al. [47] used SP (Ether polycarboxylates) to compensate for the absorption of coarse and fine RCAs (both at 0%, 50%, 75% and 100%). Results indicated that although the slump flow of all 4 mixtures was kept within the targeted value of 710 mm~750 mm, the V-funnel and J-ring failed to meet the EFNARC requirements [49] when RCAs replacement was above 50%. In addition, through optimization of aggregate gradation and mix proportion, Hu et al. [51] successfully produced eco-SCC with 100% of CRCA and 15% less binder content.

In terms of workability retention, Assaad and Harb [27] reported that after 1h of mixing, slump flow decreased significantly with the increase of CRCA content. For instance, 28% slump flow reduction was observed when NA was fully replaced by CRCA [27]. Also, the filling ability and passing ability of SCRC decreased after 1h of concrete mixing due to the continuous water absorption of RCA [12]. As for FRCA, Carro-López et al. [41] found that when FRCA was used more than 20% in SCRC, the slump flow and blocking ratio reduced, and the T₅₀₀ and V-funnel time increased significantly with the elapse of time. In addition, the concrete mixture tends to lose its self-consolidating ability at 45 min. However,
Kou and Poon [15] reported that the slump loss of SCRC after 1h is not significant (within 10%). One difference that should be emphasized between both studies is that the content of extra water introduced was different, which may result in the different observation of workability reduction over time.

3.2. Rheological properties

Rheology is a powerful tool to characterize the flow-behavior, shear thickening, and workability loss of fresh cementitious materials [52]. Fresh SCC can be simulated as a viscoelastic suspension with a model that relates to the shear stress (τ) and shear rate (γ). Normally, SCRC can be modeled using Hershel-Bulkley model, \( \tau = \tau_0 + \mu \gamma^n \) or Modified Bingham model, \( \tau = \tau_0 + \mu \gamma + c \gamma^2 \), to account for the shear-thickening behavior [22, 35, 53], in which \( \tau_0 \) is yield stress, the minimum stress to initialize flow; \( \mu \) is the plastic viscosity; \( n \) is the flow index; and \( c \) is the second order constant.

Limited studies have shown that the rheological properties of SCRC varied, which may be affected by RCA replacement, the shape of aggregate, aggregate moisture state, water compensation method of RCA and SCM utilization. Some studies [33, 54] found that the yield stress and plastic viscosity increased significantly with the replacement of CRCA. Kebaïli et al. [38] demonstrated that the yield stress of SCRC increased dramatically with the use of more than 60 wt% dried CRCA although added water satisfied the 24h absorption capacity of recycled aggregate, possibly because the suction of water generated capillary tensions within the paste and cause a higher required initial stress. Similarly, Carro-López et al. [40] reported an increase in both static yield stress and plastic viscosity over time with dried FRCA and extra water. In contrast, Güneyisi et al. [35] presoaked aggregates for 30 mins and found that
the yield stress and shear thickening behavior of SCRC were clearly reduced with the replacement of FRCA. González-Taboada et al. [55] reported that the yield stress after resting for up to 30 mins increased with higher replacement of CRCA. While the thixotropy, which describes the reversible and time-dependent reduction of viscosity, showed slight differences among SCRCs with different CRCA replacement level due to the water absorbed by recycled aggregates.

Moreover, Singh and Singh [53] indicated that the incorporation of SCMs significantly altered the shear thickening behavior of SCRC, as demonstrated in Fig. 2. It can be seen that with the use of 60 wt% fly ash, the flow index n of SCRC by Hershel-Bulkley model decreased from 1.51 to 1.12, indicating a reduced shear thickening behavior. Moreover, the index n of other SCRC mixes (25 wt% fly ash+5 wt% silica fume and 15 wt% silica fume) is below 1 which suggesting a shear thinning behavior. Similar finding is reported in [22] that the incorporation of metakaolin and silica fume clearly reduced the shear thickening behavior.
4. Effects of RCAs on hardened properties SCC

4.1. Compressive strength

Similar to that of conventional vibrated concrete (VC), the compressive strength of SCC with RCA is greatly dependent on water to binder (w/b) ratio, water compensation method, RCA replacement level as well as the physical and mechanical properties of RCA [23, 27]. The influence of CRCA replacement on 28d compressive strength of SCRC reported by 11 different studies is summarized in fig. 3. It is noticed that the 28d compressive strength of SCRC decreased proportionally with CRCA content [24, 26 28, 42, 45]. The strength loss may be related to the increase of porosity and the presence of weak ITZ in
the concrete matrix. Since the ITZ is commonly regarded as the weakest region in concrete, the existence of old ITZ may further weaken the microstructure of concrete matrix [43, 44, 56].

**Fig. 3.** 28d relative compressive strength with increasing CRCA content.

On the contrary, several authors [12, 23, 27] reported a comparable or slightly higher 28d compressive strength when part of the NA was replaced by CRCA. The possible reasons are related to i) roughness surface of CRCA which improved the bonding between the cement matrix and aggregate; and ii) absorbed water by CRCA could lower the effective w/b ratio, and therefore inhibited the crystal growth during hydration and promote a denser microstructure [23, 57].

Furthermore, a statistic analysis is performed based on strength data of SCRC with CRCA inclusion. Regression line and 95% prediction bond are plotted, as shown in fig. 4a, which shows the predicted maximum strength reduction is about 23%. Compared with the analysis conducted by Silva et al. [18], one interesting notification is that the maximum predicted strength loss of SCRC is 15% lower than that
of normal vibrated concrete produced with grade B CRCA, as indicated in fig. 4b. One possible explanation could be that the higher paste content in SCC strengthens RCA and enhance the weak region of ITZs [58-60]. Another possible reason might be related to the lower amount of coarse RCA used in SCC [61], which makes the negative effect of CRCA on strength in SCRC become less pronounced [42].

Fig. 4.  (a) Relative 28d compressive strength of SCRC (95% prediction bond) with increasing CRCA content; (b) Relative compressive strength of RAC mixes produced with increasing coarse RA of different quality classes [18].

As for the effect of FRCA content, Carro-López et al. [40, 41] reported an 8% and 47% decrease of compressive strength when 20% and 100% of FRCA were used in SCRC, respectively. Santos et al. [62] revealed that FRCA would cause additional 3%~10% strength loss than CRCA did, possibly due to the more porous structure of FRCA. Gesoglu et al. [36] observed as much as 30.9% reduction in strength at 56 days when coarse and fine recycled aggregates were used as 100% replacement. Señas et al. [48] reported a moderate (6%~11%) effect on strength reduction when 50% CRCA or/and 20% FRCA were used to replace NA. Interestingly, when 20% FRCA was used in dry condition, the compressive strength increased by about 11% [37], possibly attributed to the absorption of free water by FRCA which causes
the reduction in effective w/c ratio. Hu et al. [63] compared the effect of FRCA on the compressive strength of SCRC prepared with two different binder contents. For the higher binder content group, the use of FRCA up to 75% content could give a positive effect on compressive strength, whereas for the case of lower binder content group, the optimum content of FRCA was at 25%. Possible reasons for this phenomenon may be because the higher binder content could enhance the outer surface of FRCA and thus improved the mechanical performance of the SCRC. Kou and Poon [15] introduced extra water (equal quantity of absorbed water of RCAs at 24 h) in the mix and observed that the compressive strength reduction was not significant even 100% CRCA and FRCA were used as aggregates substitution in SCRC. While Arabi et al. [50] found that the 28d compressive strength reduction of SCRC was about 23% with 100% CRCA and FRCA replacements and extra water added based on the 10-min water absorption of RCAs.

4.2. Split tensile strength

The split tensile strength of SCRC derived from literature studies are given in fig.5. In general, split tensile strength decreases with an increase in CRCA replacement, and the reduction rate is more obvious than the compressive strength results. Some studies [24, 26] reported 37% and 58% reduction in split tensile strength for SCC with 100% CRCA substitution. However, others [12, 39] indicated that the strength reduction was kept within 15%. Tuyan et al. [23] reported that the strength loss is higher in SCRC mixtures with higher w/c ratio. Moreover, Wang [45] mentioned that the SCC using higher strength CRCA (as indicated by lower aggregate crushing value) suffered lower split tensile strength reduction.
Limited information is available with regards to the effect of FRCA alone, but in general the reduction trend is similar to that observed in CRCA results. Señas et al. [48] noticed an 11%–17% decrease in 28d split tensile strength with the use of 20% FRCA and 50% CRCA as aggregate replacement. Gesoglu et al. [36] reported that the split tensile strength of SCRC with 100% FRCA at 56 days decreased by 26% and 28% for w/c ratios of 0.3 and 0.43, respectively. Kou and Poon [15] indicated that the maximum reduction of 28d split tensile strength was about 13% when coarse and fine RCAs were used as 100% aggregates in SCRC. In contrast, Vinay Kumar et al. [37] noticed that using 20% dry FRCA increased the split tensile strength of SCRC by 18%, similar to their reported results of compressive strength, possibly attributed to the decrease of free water and effective w/c ratio, making the microstructure denser.

4.3. Elastic modulus

The elastic modulus of concrete is known to be greatly affected by the aggregate [64]. Since RCAs exhibit higher porosity and lower stiffness, the presence of RCAs in the SCRC may not be favorable for
the elastic modulus properties of concrete. Tang et al. [12] reported a 22% reduction in elastic modulus when NA was fully replaced by CRCA. A similar observation was also reported by Gesoglu et al. [36]. The effect of FRCA on SCRC elasticity modulus is more significant than CRCA, which corroborates the observation that the FRCA is weaker than CRCA [36]. Pereira-de-Oliveira et al. [43] reported that the dynamic modulus of elasticity reduced by 7.5% when CRCA was 100% substituted by NA.

4.4. Fracture properties

Fracture properties can provide more predictable information with regards to potential load-carrying capacity and post-peak behavior of concrete. Tang et al. [12] noticed a 30% reduction in fracture energy and characteristic length of SCRC when CRCA was incorporated. Similar results were also reported by Gesoglu et al. [36] as the fracture energy and characteristic length reduced by 28.6%-56.7% and 29.1%-40.7%, respectively, for the replacement of 100% CRCA and/or FRCA. The reason for the reduction may be associated with the inferior properties of RCAs which allow easy development of cracks through the ITZ areas. Besides that, it has been reported that the increase in strength resulted in lower characteristic length, indicating that the SCRC with lower w/b ratio became more brittle. This is because when cement paste and ITZs are strengthened, cracks tend to travel through aggregates which may cause a lower fractal dimension [65].

5. Effects of RCAs on durability properties of SCC

Durability is an important consideration for the practical application of concrete structure. The durability properties such as permeability or transport properties as well as the integrity of concrete against
aggressive substances and hazardous environment (i.e. CO$_2$, chloride ion, acid, freeze-thaw cycling) are of major interest for new alternative material in concrete structure.

The permeability of SCRC is one of the essential factors since it determines the transportation of substances between the inner and outer environment of concrete. Basically, the water permeability of SCRC is higher than SCC made with natural aggregate. The initial rate of surface absorption and water penetration depth of SCRC increased with CRCA content, and a maximum increase of about 40% was recorded [25]. Similarly, the water absorption capability of 100% CRCA-SCRC was found to be 40% higher than the control SCC [24]. Kapoor et al. [31, 66] found that the partial replacement of FRCA could mitigate the higher permeability induced by CRCA. This might be attributed to the grading size effect and better cementing property of unhydrated cement grains within the FRCA.

Similarly, the chloride penetration resistance of SCRC is also expected to be lower than the control SCC. Kapoor et al. [25] reported an increase of 6% and 13% in chloride-ion permeability, when CRCA was used to replace 50% and 100% of NA, respectively. Tuyan et al. [23] revealed that the chloride penetration of SCRC could be minimized by adopting lower w/b ratio. Gesoglu et al. [67] indicated that either 100% CRCA or FRCA had increased the chloride-ion permeability by almost two times. However, very fine particles (<300 µm) of FRCA can act as “effective fillers” in densifying the microstructure of concrete and provide better resistance to chloride intrusion [15]. In terms of carbonation resistance, Singh and Singh [43] reported a 63% increase in carbonation depth of SCRC prepared with RCA, and the negative effect can be minimized by incorporating 10% metakaolin (MK) to densify the microstructure.
RCA showed a positive effect on the sulfate resistance of SCRC. Omrane et al. [47] found that the mass loss of SCRC after 3 months of 5% $\text{H}_2\text{SO}_4$ immersion, reduced by 23% with the use of 50% CRCA and FRCA. Boudali et al. [68] did not find visible defects or suffer from significant mass loss after SCRC samples were immersed in 5% $\text{Na}_2\text{SO}_4$ for 12 months. The reason for this observation is that the sulfate attack mainly results in the formation of gypsum and ettringite, which causes an internal expansion leading to cracking and deterioration. The use of RCAs could increase the porosity of SCRC and allows some room for expansion and prevent the induced cracks due to excessive expansion.

Tuyan et al. [23] reported that after 300 freeze-thaw cycles, the SCRC made with 100% CRCA suffered more severe cracks than the corresponding control SCC sample, probably due to the higher porosity induced by the RCA. Li et al. [28] reported that the incorporation of RCA could have both positive and negative effects when subjected to freeze-thaw cycles: The positive effect of the more porous RCA is due to its ability to dissipate the hydraulic pressures exerted by frozen water [69]; but the negative effect of poor mechanical properties of RCA could cause the concrete to be less durable against the freeze-thaw cycles [28].

To date, there is still limited information reported in terms of durability performance of SCC with RCAs, especially the use of FRCA. Thus, more studies are needed in this aspect to fill this gap and fully identify the durability performance before the RCAs can be introduced to the SCC industry.

6. Enhancement methods of RCA incorporated SCC
Considering the drawbacks of using RCAs in SCC, various enhancement approaches have been adopted based on basic principles of: a) improving the quality of RCA; b) adding supplementary cementitious materials; or c) altering the SCC mixing process.

6.1. Improving the quality of RCA

As discussed in earlier sections, the inferior properties of RCA and high-water absorption capability are the major challenges to achieve the desired mechanical and durability properties in SCRC. One of the effective ways to improve the quality of CRCA is removing the old mortar (i.e. HCl immersion) or strengthening the adhered mortar via different treatment methods (i.e. water glass treatment, carbonation).

Table 4 summarizes the information of treatment methods and the resulting properties of treated CRCA. Among these methods, water glass treatment is found to be the most effective in reducing the water absorption capacity (~75%) because water glass generates a smooth coating around the porous surface of CRCA (fig.6b). While treatments of HCl immersion and accelerated carbonation show reasonable positive effect in reducing the water absorption of CRCA (20%~38%), immersing RCAs in cement-silica fume slurry was observed to be the least effective method (~5%) possibly due to the coated layer having high contents of macro and micro pores (fig.6a).

<table>
<thead>
<tr>
<th>Authors</th>
<th>Notation</th>
<th>Methodology</th>
<th>Size</th>
<th>24h-Water absorption /wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Güneyisi et al. [70]</td>
<td>RCA-</td>
<td>Control</td>
<td>4–8</td>
<td>8.72</td>
</tr>
<tr>
<td></td>
<td>RCA-HCl</td>
<td>Submerge RCA in HCl solution at 0.1 molarity</td>
<td>4–8</td>
<td>6.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8–16</td>
<td>7.66</td>
</tr>
</tbody>
</table>
Fig. 6. SEM images of RCA treated by (a) cement-silica fume and (b) water glass [70].

As for the effect of using different treated RCAs on the properties of SCRC, the compressive and split tensile strengths were enhanced except for the case of cement-silica fume slurry treated-CRCA [70].
Wang [45] found a 15%~18% improvement in the compressive strength and 12%~15% increase in the tensile strength for SCRC mixed with the HCl treated-CRCA. Regarding the carbonation treatment method, Li et al. [28] found that carbonated CRCA was beneficial to the compressive strength and frost resistance of SCRC. In addition, incorporation of carbonated CRCA increased the number of micropores and reduced the number of larger pores, resulting in a 5.7%~7.1% improvement in residual compressive strength of SCRC after 300 freeze-thaw cycles.

6.2. Adding supplementary cementitious materials

Supplementary cementitious materials (SCM) such as fly ash, silica fume, metakaolin, etc. are found to be effective in improving the mechanical and durability performances of SCRC. Kou and Poon [15] used fine fly ash (<45µm) to improve strength development and mitigate the drying shrinkage. Incorporating 10% of SF improved the strength (3%~25%) and modulus of elasticity (~7%) of SCRC [36]. Omrane et al. [47] reported that up to 20% natural pozzolan as cement replacement can enhance the chloride resistance and sulphuric acid tolerance by 68% and 15%, respectively. It has been mentioned that 10% of SF and MK compensated for the strength loss of SCRC prepared with 50% of CRCA, and improved the impermeability and chloride resistance [25]. In general, the possible roles of mineral admixtures in the SCRC are: a) pores filling and reduces the porosity of concrete, and b) formation of secondary C-S-H and densified the microstructure [4, 71-73], as shown in fig. 7.
6.3. Altering SCC mixing process

Güneyisi et al. [70] suggested a two-stage mixing method to combat the mechanical strength loss of SCC mixed with CRCA, and the effect was found to be 40% better than using water glass pre-treated CRCA. In the study of Rajhans et al. [29], SCRC were prepared by three different mixing methods, including normal mixing approach (NMA), two-stage mixing approach (TSMA) and two-stage mixing approach with extra silica slurry (TSMA\textsubscript{sf}), as illustrated in fig. 8. SCRC mixed by TSMA and TSMA\textsubscript{sf} exhibited higher compressive strength than mixes prepared by NMA, while the effect of TSMA\textsubscript{sf} was better than TSMA [29, 30]. Moreover, these modified mixing approaches could enhance the impermeability, chloride and carbonation resistance of SCRC, due to the formation of denser microstructures (fig. 9). They related this effect to the formation of a thin layer of cement slurry around RCA through the TSMA.
process, to strengthen the ITZs between RCA and new mortar paste [58]. As for TSMA$_{scp}$, the added silica fume in the pre-mixing procedure could further densify the microstructure of RCA surface layer and thus enhance the new ITZ regions. The high specific surface area of silica fume is highly reactive and possess good nucleation effect to facilitate pozzolanic reaction [74, 75].

**Fig. 8.** Modified mixing approaches adopted by Rajhans et al. [29].
Fig. 9. SEM-BSE image of SCRC prepared with (a) NMA, (b) TSMA and (c) TSMA_{sfc} [29].

7. Conclusions

(1) Approaches compensating high water absorption of RCA are promising to produce SCRC with desired properties at initial fresh stage, and RCA incorporated mixture results in a lower workability retention.

(2) The rheological properties of SCRC are affected by RCA content, shape and moisture content as well as water compensation method. Use of pozzolans can reduce the shear thickening behavior.

(3) The reduction of compressive strength due to use CRCA in SCC is much lower (< 23%) than that found in vibrated concrete, probably due to higher paste content helps in strengthening the weak surface layer of RCA and thus can provide a denser ITZ.
(4) High RCA replacement can result in increased porosity of SCRC, which is not favorable for permeability, chloride and carbonation resistance. However, larger pore structures could help in resisting excessive expansion caused by sulfate attack and freeze-thaw cycles.

(5) Among different treatment methods, CO\textsubscript{2} treated RCA is found to be a simple and efficient method to enhance the mechanical and durability performance of SCRC. Incorporation of mineral admixtures and modification of concrete mixing process also can enhance the overall performance of SCRC.

In summary, RCA generally can be incorporated in SCC as coarse or fine fraction aggregates which eventually can provide a sustainable solution to the major solid waste derived from C&D activities. However, there is still remaining questions especially related to the durability of SCRC which should be further investigated.

Acknowledgment

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References


