Evaluation of Chloride Ion Attack in Self-Compacting Concrete Using Recycled Construction and Demolition Waste Aggregates

Lorena K. S. Peixoto 1,4, Marcos A. S. dos Anjos 2, Evilane C. de Farias 3 and Fernando G. Branco 4

Abstract: Construction and demolition waste (CDW) destined for recycling companies has great potential for use in civil construction, since it gives rise to recycled aggregates of different particle sizes that can be used in concrete. However, there is a lack of studies on the durability of concrete produced with recycled aggregates from CDW. This study analyzed the influence of incorporating recycled aggregates from CDW, sand, and gravel on the durability parameters of SCC mixtures, with and without the addition of metakaolin (MK), when subjected to two exposure conditions: outdoors and in cycles of attack by chloride ions. Five mixtures were produced: reference SCC, with natural sand and gravel; SCC with recycled sand and gravel; SCC with recycled sand and gravel and the addition of 10% MK; SAC with recycled sand, natural gravel, and the addition of 10% MK; and SCC with natural sand, recycled gravel and the addition of 10% MK. The water/binder ratio was kept constant for all mixtures and the additive dosage was adjusted according to the variation in the use of aggregates. The mechanical and durability properties were assessed using axial compressive strength; ultrasonic pulse velocity; chloride penetration; chloride ion diffusion; and electrical resistivity tests. The results showed the feasibility of using recycled aggregates from CDW in SCC. The addition of MK significantly improved the performance of SCC using these aggregates. The mixtures with added MK showed a low risk of corrosion and high resistance to chloride ion penetration, and, under highly aggressive attack conditions, it was observed that the chloride ions did not exceed the minimum cover thickness recommended for reinforced concrete structures. The addition of MK to the mix with recycled aggregates caused an 84.6% reduction in the Cl⁻ diffusion coefficient, there was also a 40.3% reduction in Cl⁻ penetration and an increase of up to 156.14% in electrical resistivity compared to the mix with recycled aggregates without the addition of MK. The SCC mix with recycled sand and metakaolin stood out positively compared to the others, achieving an axial compressive strength similar to the reference mix (55.10 MPa). We, therefore, conclude that it is possible to produce such a mix with acceptable performance and ensure good behavior under aggressive environmental conditions.

Keywords: self-compacting concrete; recycled aggregates; metakaolin; mechanical properties; ultrasonic pulse velocity; durability; chloride penetration; chloride ion diffusion; electrical resistivity

1. Introduction

Comprehensively, sustainability actions such as the recycling of construction and demolition waste (CDW) have been of interest worldwide. Statistics have shown that
countries such as the United States, France, China, and Germany are the largest generators of CDW, accounting for 48%, 62%, 40%, and 86%, respectively, of the recycling of this waste [1]. Brazil recycles only 6% of the total CDW it generates [2].

The construction industry is one of the sectors that consumes the most natural resources and generates solid waste in the world, making it responsible for significant environmental impacts. The global production of natural aggregates increased by 58% over a 10–year period (2007 to 2017), and it is estimated to increase by 16.7% in the next 10 years [3]. Considering the trends of population growth and modernization, there is clear evidence of an increase in the generation of CDW. As economic development drives the accelerated pace of construction, it is known to project a global environmental crisis as a result of the waste of natural resources from non-renewable sources. This leads to a search for alternatives through which to reuse CDW in civil construction. In this context, recycling the mineral fraction of CDWs as aggregates for concrete production is considered an effective alternative to mitigate the environmental impacts caused by civil construction.

The use of concrete with recycled aggregates has grown in recent years, and is supported by a wealth of scientific research. While it is true that concrete properties are compromised when using recycled aggregates, it has been proven that recycled concrete aggregate can be used up to 100% in concrete, including structural elements [4,5]. However, concrete containing recycled aggregates of mixed origin, from both construction and demolition waste, tends to exhibit reduced properties [6–9], primarily due to the typical heterogeneity of construction waste. Recycled aggregates from construction waste can include ceramic materials, old mortar, wood, and glass.

Although some researchers have reported positive results using recycled aggregates in concrete, many building codes restrict their use due to their inferior properties. The presence of an old adhered mortar layer is one of the factors responsible for weakening the Interfacial Transition Zone (ITZ). In recycled concrete, three ITZs are identified: (1) the transition layer between the old and new mortar, (2) the transition layer between the aggregates and the old mortar, and (3) the transition layer between the recycled aggregate and the new mortar [10]. The use of recycled aggregates in concrete generally results in compressive strength reduction, lower density, and higher water absorption, which can negatively impact the concrete’s durability [1,3,10–14]. However, the extent of these effects depends on the source and variability of recycled aggregates.

The durability of a structure is closely related to the resistance of porous materials to infiltration by aggressive agents [3]. Some durability indicators, such as permeability and water diffusivity, are highly and strongly dependent on the material’s porous network, connectivity, and water content [15]. Recent studies have indicated that the durability of recycled concrete decreases when exposed to aggressive conditions, such as attack by chloride ions [15,16]. Incorporating recycled aggregates into concrete causes a drop in resistance to chloride penetration; therefore, the likelihood of corrosion increases [17,18]. However, Zega et al. [19] reported satisfactory durability results for concrete produced with 75% recycled aggregates.

Self-compacting concrete (SCC) mixtures can be considered good receptors suitable for recycled aggregates because, when compared to normal vibrated concrete, SCC mixtures generally typically exhibit greater durability. This can be attributed to the increase in the fines content in SCC, which refines the microstructure by densifying the material’s pore network, contributing to the reduction in concrete’s permeability [20,21].

Table 1 summarizes the fresh and mechanical properties of SCC with total and partial use of recycled concrete aggregates reported in the literature. These studies were successful in terms of the fresh properties and evaluated the reduction in axial compressive strength.
Table 1. A summary of the properties of SCC using recycled concrete aggregates.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Mixtures</th>
<th>w/b</th>
<th>Slump Flow (mm)</th>
<th>Accordance with EF-NARC Guidelines</th>
<th>Reduction in Axial Compressive Strength at 28 Days Compared to the Reference Mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sasanipour et al. [1]</td>
<td>100% recycled fine and coarse aggregates</td>
<td>0.40</td>
<td>570</td>
<td>yes</td>
<td>27.0%</td>
</tr>
<tr>
<td>Cuesta et al. [11]</td>
<td>100% recycled fine and coarse aggregates</td>
<td>0.53</td>
<td>755</td>
<td>yes</td>
<td>26.0%</td>
</tr>
<tr>
<td>Kapoor et al. [13]</td>
<td>100% recycled coarse aggregate</td>
<td>0.45</td>
<td>700</td>
<td>yes</td>
<td>13.4%</td>
</tr>
<tr>
<td>Bahrami et al. [22]</td>
<td>100% recycled fine aggregate</td>
<td>0.41</td>
<td>600</td>
<td>yes</td>
<td>36.4%</td>
</tr>
<tr>
<td>Sasanipour et al. [23]</td>
<td>100% recycled coarse aggregate</td>
<td>0.40</td>
<td>610</td>
<td>yes</td>
<td>40.0%</td>
</tr>
<tr>
<td>Singh et al. [24]</td>
<td>100% recycled coarse aggregate</td>
<td>0.45</td>
<td>680</td>
<td>yes</td>
<td>17.3%</td>
</tr>
</tbody>
</table>

Sasanipour et al. [1] stated that the durability of SCC is reduced with the use of recycled concrete aggregates as the water absorption and void ratio increase. They also reported that there is a significant reduction in the electrical resistivity of concrete with the incorporation of recycled fine aggregates.

On the other hand, there are a limited number of studies on the use of recycled construction and demolition aggregates (RCD) in SCC, which may be linked to the greater negative effect of using these aggregates due to the variability of their composition (mixed origin). Duan et al. [25], for example, incorporated recycled powder and recycled coarse aggregates from CDW and reported a weakening of the compressive strength and greater chloride penetration.

To improve the durability of concrete using CDW, it is essential to ensure that its microstructure is improved. It is possible to produce SCC with recycled aggregates by controlling the water/cement ratio, using chemical and mineral additives, and preparing these aggregates before use. Supplementary cementitious materials (SCMs), such as fly ash, metakaolin, silica fume, and granulated blast furnace slag, can play the role of microfillers, contributing to increased concrete compactness and decreased porosity [12,26]. Most SCMs react with calcium hydroxide, which is formed during cement hydration, creating additional cementitious products that modify the concrete structure and leading to its mechanical development and improved durability properties [10,13,15].

SCC with full incorporation of recycled RCC aggregates (fine and coarse) has not yet been widely studied, and there are no relevant data on its long-term behavior and/or exposure to aggressive environments. In view of this, this study contributes by analyzing the performance of SCC with total replacement of natural aggregates by recycled aggregates from CDW, with and without the addition of metakaolin, through accelerated exposure to wetting and drying cycles in saline solution, which simulated a chloride ion (Cl\^-) attack, as well as in natural outdoor exposure conditions.

2. Materials and Methods

2.1. Materials

For the production of self-compacti ng concrete SCC, type V Portland cement with high initial strength [27] (corresponding to ASTM C 150 type III Ordinary Portland Cement (OPC) [28] and EN-197-1 CEM I [29]), metakaolin (MK) as a mineral addition, natural aggregates, and recycled aggregates from CDW from a recycling plant were used. Water and a polycarboxylic ether-based superplasticizing additive based on polycarboxylic ether were also used.

Natural river sand (NS) and recycled CDW sand (RS) were used as fine aggregates, both with a maximum diameter of 2.4 mm. The coarse aggregates used were granite gravel (NG) and recycled CDW gravel (RG), both with a maximum diameter of 12.5 mm. The recycled aggregates were collected from a construction waste recycling plant located in the metropolitan region of Natal-RN, as depicted in Figure 1.
Table 2 shows the chemical analysis of powders and recycled aggregates, and Table 3 shows the physical properties of natural and recycled aggregates. Figure 2a,b shows the particle size distributions of the aggregates and powders, respectively.

**Table 2.** Chemical analysis of Portland cement (C), metakaolin (MK), recycled sand (RS), and recycled gravel (RG).

<table>
<thead>
<tr>
<th>Composition</th>
<th>C (%)</th>
<th>MK (%)</th>
<th>RS (%)</th>
<th>RG (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>70.10</td>
<td>0.12</td>
<td>53.6</td>
<td>43.9</td>
</tr>
<tr>
<td>SiO₂</td>
<td>13.80</td>
<td>55.34</td>
<td>29.16</td>
<td>32.47</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>7.60</td>
<td>7.14</td>
<td>8.86</td>
<td>11.28</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>4.00</td>
<td>33.55</td>
<td>3.74</td>
<td>2.97</td>
</tr>
<tr>
<td>SO₃</td>
<td>3.32</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.49</td>
<td>0.84</td>
<td>2.53</td>
<td>4.93</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.27</td>
<td>1.32</td>
<td>1.76</td>
<td>1.66</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>-</td>
<td>0.27</td>
<td>-</td>
<td>2.62</td>
</tr>
<tr>
<td>Others (&lt;1%)</td>
<td>0.42</td>
<td>1.42</td>
<td>0.35</td>
<td>0.17</td>
</tr>
</tbody>
</table>

**Table 3.** Physical properties of natural sand (NS), recycled sand, natural gravel (NG), and recycled gravel.

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>Standard</th>
<th>NS</th>
<th>RS</th>
<th>NG</th>
<th>RG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum diameter (mm)</td>
<td>NBR NM 248 [30]</td>
<td>2.40</td>
<td>2.40</td>
<td>12.50</td>
<td>12.50</td>
</tr>
<tr>
<td>Fineness modulus</td>
<td>NBR NM 248 [30]</td>
<td>1.79</td>
<td>1.94</td>
<td>5.86</td>
<td>5.79</td>
</tr>
<tr>
<td>Specific gravity (g/cm³)</td>
<td>NBR NM 52 [31]</td>
<td>NBR NM 53 [32]</td>
<td>2.61</td>
<td>2.49</td>
<td>2.58</td>
</tr>
<tr>
<td>Water absorption (%)</td>
<td>-</td>
<td>-</td>
<td>14.00</td>
<td>-</td>
<td>11.00</td>
</tr>
<tr>
<td>Permeable voids (%)</td>
<td>NBR 16,972 [33]</td>
<td>-</td>
<td>38.55</td>
<td>-</td>
<td>42.75</td>
</tr>
<tr>
<td>Powder content (%) &lt; 75 μm</td>
<td>NBR NM 46 [34]</td>
<td>-</td>
<td>14.55</td>
<td>-</td>
<td>4.81</td>
</tr>
<tr>
<td>Adhered mortar content (%)</td>
<td>-</td>
<td>-</td>
<td>11.00</td>
<td>-</td>
<td>17.00</td>
</tr>
</tbody>
</table>
2.2. Mixture Proportions

An SCC mixture was produced with the total replacement of natural aggregates with recycled RCD aggregates in order to evaluate the effects caused by the combined use of recycled aggregates (fine and coarse). Furthermore, the same mixture mentioned above was produced with the addition of 10% MK for the purpose of evaluating the compensation of the use of MK in the properties of SCC with the use of recycled aggregates. Understanding that there was an improvement in the performance of the CAA with the use of MK, two other CAA mixtures were also produced with 10% MK and the individual replacement of natural aggregates with recycled aggregates, fine and coarse, respectively. Thus, we evaluated the individual effects of the use of recycled CDW aggregates in SCC.

In total, five mixtures were produced: (1) reference SCC, with natural sand (NS), natural gravel (NG), and a cement consumption of 440 kg/m³, referred to as NS_NG*; (2) SCC with sand (RS) and gravel (RG) from CDW, called RS_RG; (3) SCC with sand and gravel from CDW and the addition of 10% metakaolin, called RS_RG (MK); (4) SCC with recycled sand (RS) and natural gravel (NG) and the addition of 10% metakaolin, called RS_NG (MK); and (5) SCC with natural sand (NS) and recycled gravel (RG) and the addition of 10% metakaolin, called NS_RG (MK). The water/binder ratio (w/b) was kept constant for all the mixes, and the dosage of superplasticizing admixture was adjusted according to the variation in the use of aggregates to guarantee the self-compactability of the concrete. In mixtures containing recycled aggregates, there was a need to add more water due to their absorption. Table 4 shows the mixture proportions required to produce 1 m³ of SCC in this study and provides a comparison with the parameters suggested by the European Federation for Specialist Construction Chemicals and Concrete Systems (EFNARC).

### Table 4. Mixture proportions and EFNARC parameters [35].

<table>
<thead>
<tr>
<th>Materials</th>
<th>EFNARC [35]</th>
<th>NS_NG*</th>
<th>RS_RG</th>
<th>RS_RG (MK)</th>
<th>RS_NG (MK)</th>
<th>NS_RG (MK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM</td>
<td>-</td>
<td>440.45</td>
<td>432.39</td>
<td>416.65</td>
<td>418.23</td>
<td>422.50</td>
</tr>
<tr>
<td>MK</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NS</td>
<td>-</td>
<td>792.82</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>760.49</td>
</tr>
<tr>
<td>RS</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NG</td>
<td>750–1000</td>
<td>880.90</td>
<td>778.30</td>
<td>749.96</td>
<td>752.82</td>
<td>-</td>
</tr>
<tr>
<td>RG</td>
<td>750–1000</td>
<td>-</td>
<td>-</td>
<td>864.77</td>
<td>833.29</td>
<td>-</td>
</tr>
<tr>
<td>Water</td>
<td>150–200</td>
<td>213.18</td>
<td>209.27</td>
<td>221.66</td>
<td>222.5</td>
<td>224.77</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>EFNARC [35]</th>
<th>NS_NG*</th>
<th>RS_RG</th>
<th>RS_RG (MK)</th>
<th>RS_NG (MK)</th>
<th>NS_RG (MK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% SP to fines</td>
<td>-</td>
<td>1.44%</td>
<td>1.45%</td>
<td>2.00%</td>
<td>1.71%</td>
<td>1.62%</td>
</tr>
<tr>
<td>Water/binder (kg/kg)</td>
<td>-</td>
<td>0.484</td>
<td>0.484</td>
<td>0.484</td>
<td>0.484</td>
<td>0.484</td>
</tr>
<tr>
<td>Binders (kg/m³)</td>
<td>380–600</td>
<td>440.45</td>
<td>433.39</td>
<td>458.31</td>
<td>460.06</td>
<td>464.75</td>
</tr>
</tbody>
</table>

![Figure 2. Particle size distribution: (a) aggregates and (b) powders.](image-url)
Based on the consumption of the materials, the volume fraction of each component of the mixture was calculated, and then, using the chemical analysis in Table 2, the Al2O3 content of each SCC composition was estimated, as shown in Table 5.

**Table 5. Al2O3 content in SCC mixtures.**

<table>
<thead>
<tr>
<th></th>
<th>NS_NG</th>
<th>RS_RG</th>
<th>RS_RG (MK)</th>
<th>RS_NG (MK)</th>
<th>NS_RG (MK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.57</td>
<td>2.73</td>
<td>3.18</td>
<td>2.22</td>
<td>2.09</td>
<td></td>
</tr>
</tbody>
</table>

2.3. Mix Preparation and Sample Molding

The concrete was produced in a 150 L inclined shaft mixer with a 1/3 HP (horsepower) motor. The mixing process followed the following sequence:
- (1st) Add 100% coarse aggregate and 30% water, and mix for 30 s;
- (2nd) Add 50% sand and 20% water, and mix for 30 s;
- (3rd) Add 100% cement, 50% sand, and 40% water, and mix for 2 min;
- (4th) Add 50% admixture and mix for 2 min;
- (5th) Add 100% metakaolin, 10% water, and 50% admixture, and mix for 3 min.

For the mixtures that used recycled aggregates, the absorption water from the recycled sand was added together with the water from the SCC mixture. The absorption water from the CDW was added to the RG, as a kind of pre-soaking, for 20 min to approach the saturated surface dry (SSD) condition. For each SCC mixture, 25 cylindrical specimens were molded, with dimensions of 10 × 20 cm, to carry out tests on the SCC in the hardened state, such as axial compressive strength, ultrasonic pulse velocity, electrical resistivity, chloride ion diffusion, and physical indices. Four cubic specimens with 10 cm edges were also molded to carry out the chloride penetration depth test.

2.4. Properties of Fresh SCC

The fresh SCC tests were carried out immediately after the mixing process. The flow parameters were assessed using the Slump Flow and T500 Flow Time tests, standardized by NBR 15823-2 [36]. The passing ability of the SCC was assessed using the J-ring method, according to NBR 15823-3 [37], and the L-box method, according to NBR 15823-4 [38]. Viscosity was assessed using the V funnel method, standardized by NBR 15823-5 [39].

2.5. Properties of SCC in the Hardened State

After evaluating the fresh properties of SCC, the specimens were molded to investigate the mechanical and durability properties. The specimens were demolded after 24 h and then cured in water at room temperature (23 ± 2 °C) until the test date. After 28 days of curing, some of the samples were exposed to air in a laboratory environment, and the others were subjected to cycles of soaking in chloride water and drying to simulate the attack of chloride ions on concrete exposed to aggressive environments. Each cycle comprised three phases: (1) drying in an oven at 60 °C for two days, (2) attack by chloride ions through immersion in chloride water for four days, and (3) exposure to air in the laboratory for another four days. The samples went through nine cycles (see Figure 3). The chloride water was prepared with a concentrated 15% NaCl solution, based on the study carried out by Montemor et al. [40], to accelerate the attack and obtain insights into the quality of the concrete in a shorter timeframe than under real conditions.
Mechanical and durability properties were assessed using non-destructive tests (electrical resistivity and ultrasonic pulse velocity) and destructive tests (axial compressive strength, chloride penetration depth, chloride ion diffusion, and physical indices). The non-destructive tests were carried out at 7 and 28 days of submerged curing and the end of each cycle (Figure 3). Destructive tests were also carried out at 7 and 28 days of submerged curing and the end of the last cycle, except for the chloride penetration depth test, which was also conducted at the end of the 3rd and the 6th cycles. Figure 3 illustrates a schematic flowchart summarizing all the tests carried out on the SCC mixtures under study, their respective ages, and their deterioration cycles.

![Flowchart](image)

**Figure 3.** Flowchart of the tests carried out on the SCC mixtures.

### 2.5.1. Compressive Strength

According to the recommendations of the NBR 5739 standard [41], three cylindrical samples were tested for each age at 7 and 28 days for wet curing and at 118 days, with and without a wetting and drying cycle, in chloride water. The results were obtained by averaging the strengths of the three samples.

### 2.5.2. Ultrasonic Pulse Velocity (UPV)

The measurement of the ultrasonic pulse velocity (UPV) in concrete was carried out according to the NBR 8802 standard [42] with the assistance of Pundit Lab+ equipment, manufactured by Proceq SA, using two 54 kHz ultrasonic wave transducers with 0.1 μs resolution. The test was conducted on cylindrical samples (Type A test specimens) at 7 and 28 days of age and at the end of each exposure cycle. The test was conducted on both the samples exposed to the air and the samples subjected to Cl⁻ attack. The results were obtained by averaging the readings from three samples of each SCC mixture.

### 2.5.3. Chloride Penetration under Wetting and Drying Cycles

The cubic SCC specimens (Type B test specimens) were submerged in water for 28 days and then exposed to the aggressive cycles. After the cycles, at the ages indicated in the flowchart (see Figure 3), the specimens were broken transversely in the direction of...
the open faces. Afterwards, a 0.1 M silver nitrate (AgNO₃) solution was sprayed onto the specimen’s surface. Chloride ions present in the specimens react in the presence of silver nitrate, forming a precipitate of silver chloride (AgCl). The precipitation appears as a white region when it is wet and turns purple after the solution dries (Figure 4). With the aid of a digital caliper, it was possible to measure the depth of chloride ion penetration for each specimen.

![Figure 4](image-url)

**Figure 4.** Precipitation of silver chloride in the test specimen.

### 2.5.4. Chloride Ion Diffusion

Determination of the chloride ion diffusion coefficient was carried out in accordance with NT BUILD 492 [43] (Figure 5), also specified by E-463 [44]. Specimens with heights of 50 ± 5 mm and diameters of 100 ± 2 mm were prepared, extracted from the cylindrical test specimens (Type A). Before conducting the test, the specimens were subjected to vacuum treatment and immersion in a saturated Ca(OH)₂ solution to ensure that chloride ingress into the samples would occur predominantly by diffusion. The diffusion coefficient was obtained as the average result from three specimens subjected to the same exposure condition. Upon completion of the test, the specimens were broken, the depth of chloride ion penetration was measured using the method described in Section 2.5.3, and the diffusion coefficient was calculated.

![Figure 5](image-url)

**Figure 5.** Chloride ion diffusion test by the method described in NT BUILD 492 [43].
2.5.5. Electrical Resistivity

The electrical resistivity of the concrete specimens under study was measured using the four-electrode method with a Wenner probe (Figure 6), according to G57 [45] and RILEM TC 154 [46]. The equipment used was the Proceq Resipod, with a probe spacing of 50 mm, manufactured by the company Proceq SA, located in Schwerzenbach, Switzerland. The test specimens used for this test were the same as those used in the ultrasonic test, and the results were obtained by averaging the readings from three samples of each SCC mixture.

![Image of Electrical resistivity test](Figure 6)

2.5.6. Water Absorption and Void Index

The water absorption by immersion and the void index were determined according to NBR 9778 [47] guidelines. The tests were conducted on two cylindrical samples (Type A test specimens) from each mixture, at 28 days and 118 days, under both exposure conditions.

3. Results and Discussion

3.1. Fresh Properties of SCC

The fresh properties of SCC are presented in Table 6. SCC classification is carried out in accordance using NBR 15823 instructions, parts 2 to 5 [36–39]. All mixtures exhibited self-compacting properties. All mixtures incorporating recycled aggregates showed lower spread than the reference mixture, even with the addition of the absorbed water from the recycled aggregates and the increased amount of SP admixture. This behavior can be attributed to the high absorption capacity and greater surface roughness of the recycled aggregates [11,48,49]. The flow classification for the NS_NG* and RS_RG (MK) mixtures was SF3, while the other mixtures were classified as SF2. Through visual analysis of the flow of all SCC mixtures, no signs of segregation or bleeding were detected, as a uniform distribution of particles in the mixtures was observed (Figure 7).

<table>
<thead>
<tr>
<th>Mixtures</th>
<th>Slump Flow</th>
<th>J-Ring</th>
<th>V-Funnel</th>
<th>L Box</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T&lt;sub&gt;500&lt;/sub&gt; (s)</td>
<td>Slump Flow (mm)</td>
<td>T&lt;sub&gt;500&lt;/sub&gt; (s)</td>
<td>J-Ring (mm)</td>
<td>Time (s)</td>
</tr>
<tr>
<td>NS_NG*</td>
<td>2.03</td>
<td>773.33</td>
<td>3.50</td>
<td>763.33</td>
<td>6.00</td>
</tr>
<tr>
<td>RS_RG</td>
<td>2.28</td>
<td>730.00</td>
<td>2.92</td>
<td>710.00</td>
<td>7.50</td>
</tr>
<tr>
<td>RS_RG (MK)</td>
<td>2.10</td>
<td>763.33</td>
<td>4.53</td>
<td>740.00</td>
<td>8.22</td>
</tr>
<tr>
<td>RS_NG (MK)</td>
<td>1.97</td>
<td>716.67</td>
<td>3.15</td>
<td>716.67</td>
<td>5.50</td>
</tr>
<tr>
<td>NS_RG (MK)</td>
<td>1.60</td>
<td>740.00</td>
<td>2.87</td>
<td>740.00</td>
<td>6.63</td>
</tr>
</tbody>
</table>
3.2. Properties of SCC in Hardened State

3.2.1. Axial Compressive Strength

Figure 8 shows the evolution of the axial compressive strength of the studied SCC mixtures. When comparing the RS_RG mixture with the reference mixture (NS_NG*), the compressive strength was reduced by 18.8% at 7 days, 14.9% at 28 days, and 21% at 118 days. This reduction has been widely reported in the literature [1,3,10–12,14,15,19,21], since the CDW aggregate exhibits greater fragility and heterogeneity, and the layer of old mortar adhered to the grains of the recycled aggregates (RS and RG), increasing the porosity of the concrete. Furthermore, there is a greater network of pores in the microstructure of the recycled aggregates, and their use in concrete weakens the bond between the old interfacial transition zone (ITZ) and the new ITZ, leading to a compromise in the mechanical properties of the concrete. The compressive strength reduction attributed to the use of recycled aggregates is compensated for by the filler effect and pozzolanic reaction of MK. Previous studies have shown that the addition of MK helps to compensate for the loss of strength in SCC with the incorporation of recycled aggregates from construction waste [24,50]. Although the recycled CDW aggregate is more porous than the natural aggregate, when concrete containing recycled aggregates is prepared using MK, there is an improvement in the bonding of the ITZ between the paste and the aggregates [50]. The NS_RG (MK) mixture achieved a compressive strength similar to the RS_RG (MK) mixture, while the RS_NG (MK) mixture exhibited a compressive strength similar to the reference (NS_NG*), reaching 55.10 MPa at 118 days of age. This may be associated with the filling of the SCC’s pores, which occurred due to both the addition of MK and the content of powdered material present in the RS.
3.2.2. Ultrasound Pulse Velocity (UPV)

As shown in the graph in Figure 9, the ultrasonic pulse velocity (UPV) decreased with the incorporation of recycled aggregates into the SCC, albeit insignificantly. When comparing the RS_RG mixture with the reference mixture (NS_NG*) under submerged curing at 28 days and exposure to air in the following days, the UPV decreased by approximately 13.9%, considering the low variation in results over time. The reduction in UPV in the RS_RG mixture, similar to what happened with mechanical strength, occurred because of the increased porosity of the SCC with CDW aggregates due to the layer of mortar adhering to the grains and the greater porosity of the recycled coarse aggregate. Similar results were observed in other studies [1,11,23,49]. In addition to porosity, Kapoor et al. [49] stated that other parameters can affect UPV, such as the water–cement ratio and the concrete saturation level during testing. The UPV results for the RS_RG, RS_RG (MK) and NS_RG (MK) mixtures were similar at all ages. The RS_NG (MK) mixture achieved results similar to the reference mixture (NS_NG*), as shown in Figure 9. This highlight was also observed in the compressive strength result mentioned earlier, demonstrating that the porosity of the coarse aggregate was primarily responsible for the decrease in strength, as all SCCs with recycled CDW gravel showed the same UPV.

Figure 8. Axial compressive strength for SCC mixtures at 7, 28, and 118 days.

Figure 9. Ultrasonic pulse velocity (UPV) of SCC mixtures exposed to the air.
3.2.3. Chloride Penetration by Wetting and Drying Cycle, Chloride Ion Diffusion, and Electrical Resistivity

The chart in Figure 10 shows the results of chloride ion penetration depths in the SCC mixtures after being subjected to wetting and drying cycles in saline solution. Before exposure to the cycles, the mixtures did not have a penetration front. It is evident that, in all mixtures, there was a tendency for the Cl⁻ penetration depth to increase with age, which was related to the increased number of aggressive cycles.

When comparing the behavior of each mixture against an attack by Cl⁻, we observed a greater depth of penetration in mixtures without the addition of MK. It is clear that the presence of MK allows for significant control of the discovery of Cl⁻ in concrete; this fact has been observed by other authors [13,51–53]. The RS_RG (MK) mixture achieved a 40.3% reduction in Cl⁻ penetration compared to the NS_NG* (reference) and RS_RG mixtures after the aggressive cycles. Kapoor et al. [13] reported that the penetration of chloride ions in SCC made with full use of recycled aggregate and addition of 10% metakaolin was significantly lower than the reference SCC (with natural aggregates) without the use of mineral additions.

It can be observed that the presence of MK allows for significant control of Cl⁻ penetration in the concrete. SCC mixtures with recycled aggregates and MK addition had shallower Cl⁻ penetration depths when compared to the reference mixture (Figure 10). This was due to the refinement of the pore structure with the production of additional CSH (calcium silicate hydrate), C₂ASH₈ (stratlingite), and C₆AH₁₃ (calcium aluminate hydrate) through pozzolanic reactions of MK [54,55], as well as the formation of Friedel’s salt [52,53,56].

Materials rich in alumina, such as MK, produce Friedel’s salt, which chemically binds to chloride ions [57]. The amount of Friedel’s salt formed is directly proportional to the alumina (Al₂O₃) content in the pozzolanic material [58].

![Figure 10](image)

Figure 10. Chloride penetration depth in the SCC mixtures subjected to Cl⁻ attack cycles.

Figure 11 shows the chloride ion diffusion coefficients in SCC mixtures exposed to the open air at 28 and 118 days. With advancing age, there was a reduction in Cl⁻ diffusion, attributed to the filling of pores with the formation of more hydration products, except for the RS_RG mixture, which increased Cl⁻ diffusion due to its greater porosity compared to the other mixtures. At 28 days, the NS_NG* and RS_RG mixtures exhibited similar results. The addition of MK resulted in a decrease in Cl⁻ diffusion, as can be observed in Figure 11. At 118 days, the RS_RG (MK) mixture reduced the diffusion by 84.6% compared to the RS_RG mixture. The use of MK reduces chloride diffusion and increases the percentage of Cl⁻ ions dissolved in the interstitial water. The chloride diffusion coefficients of the RS_NG (MK) and NS_RG (MK) mixtures were similar to those of the RS_RG (MK) mixture. The isolated or combined use of recycled sand and recycled coarse aggregate (RS and RG) did not have a significant effect on Cl⁻ diffusion when using MK.
The electrical resistivity results of the SCC mixtures are shown in Figure 12. An increase in electrical resistivity could be observed as age increased, which was directly related to the development of more hydration products as the concrete aged, allowing for voids to be filled. The NS_NG* and RS_RG mixtures obtained similar electrical resistivity results at early ages (7, 28, and 58 days). It is worth noting the increase in the electrical resistivity of the RS_RG mixture when compared to the reference mixture (NS_NG*), which reached 31.4% at 88 days and 31.90% at 118 days.

Borg et al. [58] reported that the electrical resistivity of concrete with recycled aggregate did not show a significant difference when compared to reference mixture at 28 nor at 56 days. These results oppose the findings of some authors [1,10,23,24,59] who reported a reduction in electrical resistivity in concrete with increased levels of natural aggregate replacement by recycled aggregates. The satisfactory electrical resistivity results in the RS_RG mixture can be attributed to the content of powdery material present in the recycled aggregates (RS and RG) and the presence of AlO3 in the chemical composition of these aggregates, which led to a denser microstructure in the SCC. The RS_RG (MK) mixture achieved higher electrical resistivity results when compared to the RS_RG mixture, with increases of 97.56%, 156.14%, 120.74%, 77.50%, and 91.00% at 7, 28, 58, 88, and 118 days, respectively (Figure 12). This is due to the reactivity of MK, as its pozzolanic activity enables the filling of pores in the interfacial transition zone (ITZ) and consequently increases the concrete density. It can be observed in Figure 12 that the electrical resistivity of the RS_RG (MK) and RS_NG (MK) mixtures stood out positively when compared to the NS_RG (MK) mixture, indicating a lower risk of corrosion. As mentioned earlier, this can be attributed to the high content of powdery material in AR, which refines the pores, in addition to the effect of MK.
Figure 13 depicts the electrical resistivity results for the SCC mixtures at 118 days under two exposure conditions: air and after nine cycles of chloride attack. Clearly, there was a reduction in electrical resistivity for all mixtures after being subjected to the chloride attack cycles. This decline can be attributed to the presence of chloride ions in the pores of the studied mixtures, which increases electrical conductivity and, consequently, decreases electrical resistivity. When comparing the electrical resistivity performance of all mixtures subjected to the cycles of aggression, it is evident that the trends were similar to those observed in mixtures exposed to the air (Figure 12). Despite the decrease in resistivity, the RS_RG (MK) mixture maintained relatively higher electrical resistivity (23.58 kΩ·cm), remaining within the range of moderate corrosion risk.

This reduction in electrical resistivity is expected when concrete is exposed to chloride ions. Even though the electrical resistivity decreases after chloride exposure, the addition of metakaolin (MK) has a positive effect in terms of mitigating this decline, as evidenced by the RS_RG (MK) mixture’s comparatively higher resistivity, which indicates a lower risk of corrosion compared to the other mixtures.

![Figure 13](image1.png)

**Figure 13.** Electrical resistivity of SCC mixtures exposed to air and chloride attack.

Figure 14 summarizes three durability indices of SCC mixtures (chloride ion penetration depth, chloride ion diffusion coefficient, and electrical resistivity). It can be observed that these indices are directly correlated. The RS_RG (MK), RS_NG (MK), and NS_RG (MK) mixtures showed low risks of corrosion in terms of electrical resistivity, high resistance to chloride ion penetration (6.80, 5.97, and $3.99 \times 10^{-12}$ m²/s, respectively), and under these highly aggressive conditions, chloride ions do not penetrate beyond the minimum cover thickness (20 mm) for reinforced concrete structures.

![Figure 14](image2.png)

**Figure 14.** Correlation of durability indices in SCC mixtures (chloride ion penetration depth, chloride ion diffusion coefficient, and electrical resistivity).
3.2.4. Water Absorption and Void Index

Figure 15 presents the results of water absorption by immersion and void index for SCC mixtures at 118 days when exposed to air and subjected to chloride attack cycles. There was a considerable increase in water absorption (174%) and in the void index (138%) for the RS_RG mixture when compared to the reference mixture (NS_NG*). This increase was expected, as the porous structure of the recycled aggregates (RS and RG) promotes increased water absorption in concrete. With the addition of 10% MK to RS_RG mixture, there was a 10.5% reduction in water absorption, and the void index decreased by 10.92% when compared to RS_RG mixture, both at 118 days of exposure to open air. The benefit of using MK in concrete durability properties can be attributed to the filler effect. The particles of MK are smaller than cement particles, thus filling the voids in the concrete microstructure and making it more impermeable.

Comparing the water absorption and void indices of the RS_NG (MK) and NS_RG (MK) mixtures with RS_RG (MK) mixture in Figure 15, it is evident that recycled sand (RS) performed better than recycled gravel (RG). While the water absorption of the NS_RG (MK) mixture decreased by 7.70% after 118 days of exposure to air, the water absorption of RS_NG (MK) mixture decreased by 55.00% under the same conditions. This was due to the greater porosity of the coarse aggregate when compared to the fine aggregate, as mentioned earlier.

In Figure 15, a trend of decreased water absorption in all mixtures after being subjected to cycles of chloride attack is also noticeable. As chloride ions penetrated the concrete, the porosity of the concrete tended to decrease due to the formation of Friedel’s salt.

![Figure 15. Water absorption by immersion and the void index of the SCC mixtures exposed to air and under chloride attack.](image)

Figure 16 displays the correlation between the chloride ion diffusion coefficients, Al₂O₃ contents, water absorption, and void indices of the studied SCC mixtures. The content of alumina (Al₂O₃) in the mixtures mainly came from metakaolin and the recycled aggregates, but the portion from metakaolin consisted of reactive alumina. In addition to the direct correlation between water absorption and void index, it can be observed that the higher the amount of reactive alumina in the mixture, the lower the chloride ion diffusion, as seen in the results of the RS_RG (MK), RS_NG (MK), and NS_RG (MK) mixtures.

The RS_RG mixture had a higher void index and exhibited higher water absorption, indicating that its diffusion coefficient was the highest when compared to the other mixtures. The alumina content in this mixture originated from the recycled aggregates, meaning it was not reactive alumina; therefore, it did not compensate for the negative effect resulting from the presence of permeable voids in the mixture.
4. Conclusions

This study presents the influence of total incorporation of recycled aggregates on the durability parameters in SCC (self-compacting concrete) mixtures exposed to aggressive chloride ion attacks. It also examines the effect of adding 10% metakaolin to these mixtures. Based on the results and discussions presented, the following conclusions about the use of recycled sand and gravel in SCC can be drawn:

1. SCC mixtures with incorporated recycled CDW aggregates demonstrated self-compacting properties, with no signs of segregation or bleeding. It was necessary to add the absorption water of the recycled aggregates and slightly increase the superplasticizer content.

2. The use of recycled aggregates in SCC led to a compressive strength reduction. However, the addition of 10% metakaolin (MK) compensated for the strength loss, and the SCC mixture with recycled sand and metakaolin (RS_NG (MK)) achieved a compressive strength similar to that of the reference mixture (55.10 MPa). There was no significant difference in the compressive strengths of the SCC mixtures after the aggressive chloride attack.

3. The ultrasonic pulse velocity of the SCC mixtures decreased with the incorporation of recycled aggregates due to their high porosity. However, the SCC mixture with recycled sand and metakaolin (RS_NG (MK)) obtained values similar to those of the reference mixture. There were no significant changes in the ultrasonic pulse velocities of the SCC mixtures after the aggressive chloride attack.

4. The chloride ion penetration depth in the SCC mixture with recycled aggregates (RS_RG) was quite similar to that of the reference mixture. However, the addition of MK limited the chloride’s ingress in mixtures with recycled aggregates, resulting in better results compared to the reference mixture.

5. The SCC mixture with recycled aggregates had a higher chloride ion diffusion coefficient when compared to the reference mixture. The addition of MK to SCC mixtures with recycled aggregates is essential for chloride diffusion reduction.

6. The electrical resistivity was slightly higher in the SCC mixture with recycled aggregates than in the SCC mixture with natural aggregates (reference) at 118 days of age. The addition of MK significantly increased the electrical resistivity of the SCC mixtures containing recycled aggregates. The electrical resistivity of the mixtures decreased after the aggressive chloride attack. SCC mixtures that incorporated recycled fine and coarse aggregates separately remained in the moderate corrosion risk range.
The results show that using recycled aggregates from construction and demolition waste (CDW) for the production of self-compacting concrete (SCC) is feasible. It is possible to produce SCC with recycled CDW sand and the addition of metakaolin without neglecting existing structural criteria, while also ensuring good performance under the environmentally aggressive conditions of a salt attack.

5. Future Research

As a result of this work, the following aspects should be evaluated in future research:

1. The behavior of SCC with recycled aggregates from construction and demolition waste exposed to accelerated and natural carbonation;
2. The behavior of SCC with recycled aggregates from construction and demolition waste exposed to combined cycles of aggressive exposure, i.e., carbonation and chloride ion attack;
3. Specific treatments on recycled aggregates from construction and demolition waste, such as treatment with acid solution to remove the old mortar layer, selective separation by density, and improvement of granulometry, for use in structural concrete.


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