Failure mechanism of recycled aggregate concrete

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Abstract

The use of recycled aggregate concrete (RAC) acquires particular interest in civil construction regarding sustainable development. Recycled aggregates usually present greater porosity and absorption, and lower density and strength than natural aggregates. Microstructural studies on RAC indicate differences in the characteristics of the interfacial transition zones between the cement paste and the aggregates. At the same time most experiences verify that reduction in concrete stiffness is higher than in strength. The failure mechanisms in RAC can be affected by the above stated factors. In this paper, three Series of concretes with different compressive strength levels are presented. Each Series includes a reference concrete prepared with natural crushed stone and two RAC prepared with two coarse aggregates obtained by crushing a normal strength and a high strength concrete. Flexural tests on notched beams and uniaxial compression tests on standard cylinders were performed. In addition, the characteristics of the fracture surfaces were analysed in order to determine the amount of broken aggregates. RAC present lightly lower strengths (1–15%), lower modulus of elasticity (13–18%) and significant reductions in the energy of fracture (27–45%) and, consequently on the fracture zone size, when it is compared with a concrete prepared with natural coarse aggregates.

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1. Introduction

The use of recycled aggregate concrete (RAC) acquires particular interest in civil construction regarding sustainable development. Diverse studies demonstrate the feasibility of the use of crushed concrete as coarse aggregates [1,2], its use being already incorporated in the regulations of many countries.

Recycled aggregates (RA) usually show particular characteristics as greater porosity and absorption, and lower density and strength than natural aggregates. In addition some studies on RAC indicate differences in the characteristics of the interfacial transition zones between the cement paste and the aggregates (ITZ). According to Rasheeduzzafar and Khan the matrix–aggregate bond strength in RAC is higher or at least equal to the one developed with natural aggregates [3]; this was verified by the author’s previous experiences [4]. On the contrary, Tam et al. [5] indicated that RAC had poor quality due to the higher water absorption, higher porosity and weaker ITZ; with the aim of improving the ITZ, the strength and the mechanical behaviour of concrete they modified the mixing process. Poon et al. [6] found that a concrete prepared with recycled aggregate derived from high-performance concrete developed higher compressive strength than a concrete prepared with recycled normal strength concrete aggregates; the first achieved the same strength level as a concrete prepared with natural crushed granite aggregates after 90 days of

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curing. This fact was attributed to the differences in both the strength of the coarse aggregates and the microstructural properties of the ITZ. Recently, microstructural techniques have been applied to study the properties of recycled coarse aggregates. It was found that in some cases the recycling process can enhance their properties compared to natural sandstone coarse aggregates [7].

Regarding the effect of RA on the mechanical properties of concrete, most of the previous researches confirm that the reduction in stiffness (i.e. elastic modulus) is higher than the reduction in strength [1–3]; more recent studies show the same tendency [8]. Ajdukiewicz and Kliszczewicz studied the mechanical properties of a high strength concrete made with recycled aggregate and found that the properties of original concrete have significant influence on mechanical properties of RAC [9].

The parameters of fracture in RAC may be different due, mainly, to changes in the ITZ and the strength of the RA particles. As the bond strength increases and the aggregates are weaker the possibilities of crack propagation through the aggregates increases. The influence of matrix–coarse aggregate adherence on the fracture energy of normal and high strength concretes prepared with natural aggregates has been demonstrated [10,11]. More recently, the effect of aggregate properties (modulus of elasticity, surface texture and size) on the weakness of ITZ and the failure process of concrete in compression were also discussed [12]. Based on the cited/these studies, differences in the failure mechanism of concretes prepared with recycled and natural aggregates can be expected, especially when concrete strength increases [13].

This paper studies the failure mechanism of RAC. Three Series of concretes with compressive strength levels near to 18, 37 and 48 MPa were analysed. Each Series includes a natural granitic crushed stone and two types of recycled aggregates, one obtained by crushing a normal strength concrete and the other a high strength concrete. Load–displacement and load–CMOD curves under flexural loading and the stress–strain behaviour under uniaxial compression are analysed.

### 2. Experimental

#### 2.1. Materials and mixtures

This study considers the mesolevel assuming concrete as a composite material where the inclusions (coarse aggregates) are embedded in a continuous matrix (mortar), both phases interact through the interface transition zone (ITZ). In this case recycled aggregates were used only as coarse aggregates, as the use of the fine fraction is much more restricted and in general, is not recommended [1,2].

Three Series of concretes with compressive strength levels of 18, 37 and 48 MPa were analysed. Each Series includes three concretes varying the type of coarse aggregate: two recycled aggregates (RA) and a natural granitic crushed stone (G). The RA, identified as A and B, were obtained by crushing old concretes (more than two years) and they correspond to a high strength (\( f'c = 55 \pm 5 \text{ MPa} \) at 28 days) and a normal strength concrete (\( f'c = 30 \pm 5 \text{ MPa} \) at 28 days) respectively. Table 1 shows the main properties of the coarse aggregates including density, water absorption (24 h), Los Angeles abrasion, and a point load strength index and the corresponding compressive strength estimated from this test [14]. As it can be seen, only small differences in water absorption between recycled aggregates A and B were found. This can be explained assuming that a greater loss of mortar takes place in the normal concrete during the crushing process, and that high paste content is usually present in high strength concrete. Compared with natural granitic coarse aggregate (G), recycled aggregates show lower density, greater weight loss in the abrasion test and a significant reduction in strength. It can be noted that there are only small differences in the physical properties and also in the estimated strength of recycled aggregates A and B; this can be justified considering the strength evolution with time and the elimination of weaker particles during crushing process.

Regarding matrix–aggregate bond, preliminary tests performed on small composed specimens showed that RA develop bond strength equal or greater than natural rocks. In these experiences, bond strength was measured using prisms of granitic rock, high strength and normal strength concrete [4].

Fig. 1 shows the particle size distribution on coarse aggregates G, A and B. The natural aggregate (G) was obtained by combining three different fractions of granitic crushed stone (15% of 6–12 mm, 70% of 6–20 mm and 15% 10–30 mm nominal sizes) with the purpose of minimising the differences in the particle size distribution, as the aggregate size has a significant effect on the concrete failure mechanism.

The great porosity of RA enhances water interchange with the surrounding paste. According to their moisture

<table>
<thead>
<tr>
<th>Coarse aggregate</th>
<th>Obtained from</th>
<th>Water absorption (%)</th>
<th>Density (g/cm³)</th>
<th>Los Angeles abrasion (%)</th>
<th>Point load strength index Is50 (MPa)</th>
<th>Estimated compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>Natural granitic crushed stone</td>
<td>0.5</td>
<td>2.70</td>
<td>28</td>
<td>9.5</td>
<td>208.5</td>
</tr>
<tr>
<td>A</td>
<td>High strength concrete</td>
<td>3.9</td>
<td>2.52</td>
<td>34</td>
<td>2.4</td>
<td>52.8</td>
</tr>
<tr>
<td>B</td>
<td>Normal strength concrete</td>
<td>3.8</td>
<td>2.51</td>
<td>39</td>
<td>2.5</td>
<td>54.0</td>
</tr>
</tbody>
</table>
content or grade of saturation RA particles can absorb or provide water to the matrix. This fact imposes some limitations in the comparison with natural aggregate concrete. If coarse aggregate is used in dry condition the water content can be reduced in the mortar phase and if RA are saturated the w/c ratio of the matrix can be lightly increased. For this reason as it will see later mortar samples were extracted in some concretes with the purpose of estimating and comparing the matrix strength.

Natural and recycled coarse aggregates were immersed in water for 24 h and left for 1 h in air before preparing the concrete. According to Poon et al., initial slumps and slump losses are not affected by using either saturated or air-dried recycled aggregate, but the later condition is better as saturated aggregate seemed to impose the largest negative effect on the concrete strength, which might be attributed to “bleeding” of the excess water in the pre-wetted aggregates in the fresh concrete [15].

With the aim of comparing the effect of coarse aggregate in the failure mechanism the volume of coarse aggregates remained constant in each Series of different strength level. All concretes were prepared using natural siliceous river sand and blended Portland cements (Series 1 and 2: lot 1; Series 3: lot 2). In Series 2 and 3 a naphthalene based superplasticizer was used. In Series 1 the water content was adjusted to obtain comparable workability. Table 2 shows the mixture proportions, the unit weight, the slump and the air content of concretes.

To evaluate the mechanical properties in compression and in tension, cylinders and prisms were cast. All the specimens were cured in moist room until testing. Tests were performed at 28 days.

3. Test methods

Uniaxial compression tests were performed on cylinders of 150 × 300 in Series 18 and 37. Axial and lateral deformations were monitored through LVDTs. Three loading-unloading cycles, up to 40% of the maximum stress, were applied to determine the modulus of elasticity and Poisson’s ratio (ASTM C 469), after which the load was increased monotonically up to failure. Complementarily, and with the purpose of evaluating the matrix strength in concrete (fcM), 50 × 100 mm cylinders were cast with the mortar obtained by sieving the concretes through 4.8 mm mesh. In Series 48 cylinders of 100 × 200 mm were cast to measure compressive strength (fc) and modulus of elasticity (E). A minimum of four cylinders were tested in each case.

Three-point bending tests were performed in middle notched specimens to study the stress–strain behaviour in tension, using beams of 105-mm height and 75-mm width. The notch was cut, 1 day before testing, up to a depth equal to half the beam’s height using a diamond saw. A controlled closed loop system was used. The beams were loaded over a span of 400 mm and the tests were controlled by the average of the central deflection with a rate of 0.02 mm/min. In addition, the crack mouth opening displacement at the notch (CMOD) was measured with a clip gage. A minimum of four prisms were tested in each case.

The net bending stress at maximum load (fnet) and the fracture energy (Gf) were obtained from the load–deflection curves, following the general guidelines of the RILEM 50-FMC Committee [16]. The load–CMOD curves were also recorded. The energy of fracture was calculated as W0+mgd0/Ailig, where W0 is the work of fracture (equal to the area below the load–deflection curve), mg the contribution of the weight of the beam, d0 the displacement at the final fracture of the beam, and Ailig the cross-sectional area.
of the ligament before the test. The net bending stress at maximum load was calculated as  
\[ f_{\text{net}} = 6 \left( F_{\text{max}} + \left( \frac{mg}{2} \right) \right) \frac{1}{bh^2} \]  
where \( b \) is the beam width, \( h \) the net depth of the beam, \( l \) the span and \( F_{\text{max}} \) the maximum load.

The density (Dss), the absorption in water (24 h, Abs) and the splitting tensile strength (\( f_{\text{cd}} \)) were obtained using the beams halves after the bending tests. The characteristic length was calculated as  
\[ l_{\text{ch}} = \frac{E \alpha f_s}{f_{\text{cd}}} \]  
where \( f_s \) was estimated as 0.8 \( f_{\text{CD}} \) [11]. The modulus of elasticity was obtained from compression tests, in Series 48 the values were divided by 1.05 as they were obtained using 100 × 200-mm cylinders.

Finally, a survey of fracture surfaces was performed to analyse the characteristics and type of fracture, particularly the distribution of coarse aggregates and their interfaces.

4. Test results and discussion

Test results are presented in Table 3 including the mean values and the COV. As expected the water absorption increased and density decreased in RAC (A and B) compared with natural aggregate concrete (G).

Previous studies indicate that partial replacement of natural coarse aggregate by RA does not affect the compressive strength significantly. However, when 100% of RA was used as coarse aggregate strength loss of about 20% takes place [17,18]. In these experiences, in Series 1 and 2, concretes prepared with aggregate A have similar strengths than concretes prepared with aggregate G. In RAC incorporating aggregate B there were found small reductions in strength (lower than 15%); in this case it must be observed that a reduction in matrix strength (\( f'c_M \)) was also verified. In Series 3 the compressive strength of both RAC was near 10% lower than in concrete prepared with natural aggregate.

Table 3

<table>
<thead>
<tr>
<th>Test results</th>
<th>Abs (%)</th>
<th>Dss</th>
<th>( f'c_M ) (MPa)</th>
<th>( f'c ) (MPa)</th>
<th>E (GPa)</th>
<th>Poisson ratio</th>
<th>( f_{\text{net}} ) (MPa)</th>
<th>( f_{\text{cd}} ) (MPa)</th>
<th>( G_F ) (N/m)</th>
<th>( l_{\text{ch}} ) (mm)</th>
<th>( \delta_l ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-18</td>
<td>5.6</td>
<td>2.42</td>
<td>20.1</td>
<td>18.1</td>
<td>27.1</td>
<td>0.186</td>
<td>3.9</td>
<td>3.4</td>
<td>143</td>
<td>514</td>
<td>1.67</td>
</tr>
<tr>
<td>A-18</td>
<td>7.4</td>
<td>&lt;1</td>
<td>25</td>
<td>5</td>
<td>3</td>
<td>6</td>
<td>8</td>
<td>4</td>
<td>13</td>
<td>30</td>
<td>0.11</td>
</tr>
<tr>
<td>B-18</td>
<td>7.6</td>
<td>2.33</td>
<td>20.8</td>
<td>18.0</td>
<td>23.4</td>
<td>0.186</td>
<td>3.7</td>
<td>2.7</td>
<td>90</td>
<td>436</td>
<td>1.01</td>
</tr>
<tr>
<td>G-37</td>
<td>4.5</td>
<td>2.44</td>
<td>46.4</td>
<td>37.5</td>
<td>33.1</td>
<td>0.164</td>
<td>5.2</td>
<td>4.1</td>
<td>147</td>
<td>447</td>
<td>1.25</td>
</tr>
<tr>
<td>A-37</td>
<td>6.0</td>
<td>&lt;1</td>
<td>43.4</td>
<td>36.4</td>
<td>28.8</td>
<td>0.168</td>
<td>5.3</td>
<td>4.0</td>
<td>107</td>
<td>305</td>
<td>0.92</td>
</tr>
<tr>
<td>B-37</td>
<td>6.3</td>
<td>2.35</td>
<td>39.5</td>
<td>35.7</td>
<td>28.3</td>
<td>0.166</td>
<td>4.7</td>
<td>3.5</td>
<td>81</td>
<td>285</td>
<td>0.93</td>
</tr>
<tr>
<td>G-48</td>
<td>3.5</td>
<td>2.48</td>
<td>nm</td>
<td>48.4</td>
<td>39.9</td>
<td>nm</td>
<td>7.3</td>
<td>5.3</td>
<td>155</td>
<td>328</td>
<td>1.21</td>
</tr>
<tr>
<td>A-48</td>
<td>5.4</td>
<td>&lt;1</td>
<td>34.4</td>
<td>34.2</td>
<td>nm</td>
<td>6.0</td>
<td>4.9</td>
<td>4.0</td>
<td>113</td>
<td>312</td>
<td>1.20</td>
</tr>
<tr>
<td>B-48</td>
<td>5.5</td>
<td>2.41</td>
<td>nm</td>
<td>43.8</td>
<td>32.7</td>
<td>nm</td>
<td>5.8</td>
<td>3.9</td>
<td>106</td>
<td>339</td>
<td>1.02</td>
</tr>
</tbody>
</table>

nm: not measured.

\(^a\) COV.
than the decrease in compressive strength [1–3,17,18]. There was not a great difference observed in the Poisson’s ratio in concretes prepared with RA. This is in accordance with previous studies on RAC with compressive strengths between 20 and 30 MPa where no significant effect on the failure mechanism in compression was found.

Comparing concretes prepared with natural and recycled coarse aggregates it was found that the tensile/compressive strength ratio is not significantly modified both measured by bending or by splitting tests; as expected this relationship decreases as strength level increases. Fig. 3a shows the variation of net bending strength vs. compressive strength. Fig. 3b compares the results of tensile strength obtained in flexure and splitting tests. The results given in Table 3 show that the reductions in strength in RAC tend
to be higher in tension than in compression, specially the splitting strength. In this sense it is possible that the changes in bond, stiffness and strength of the particles of coarse aggregate have a different influence in each test.

Typical load–deflection and load–CMOD curves obtained from notched beam tests are presented in Fig. 4. A steeper softening branch was observed in RAC. This behaviour can be attributed to a great amount of broken coarse aggregates and less branching of cracks; this fact was more evident in Series 2 and Series 3. In the case of RAC the fractured surfaces were smoother than in concretes prepared with aggregate G.

As a contribution to the discussion of the failure mechanisms involved in these concretes, an analysis of the fracture surfaces was done after splitting tests. The number and area of coarse aggregates were determined in each section. Aggregates with interface failure (debonded) and fractured aggregates (cracks through the particles) were also distinguished (see Table 4). It can be observed that a greater percentage of fractured coarse aggregate was measured in RAC A and B, decreasing the amount of debonded coarse aggregates when comparing with concretes G. This is in accordance with the lower particle strength and higher bond strength of RA. The area of coarse aggregate tends to decrease as strength increases which is in accordance with the coarse aggregate content used in mix design.

Fig. 5 shows the variation of the energy of fracture ($G_F$) with the compressive strength. As expected, $G_F$ increases as strength increases both in concrete with natural aggregate or RA, however losses in $G_F$ greater than 20% were found in the later case. These reductions are higher than those measured in stiffness and compressive or tensile strength. The final displacement of the beam also decreased in RAC (see Table 3) making evident the reduction in branching and meandering of cracks during the failure of RAC.

Fig. 6 presents the variation of the characteristic length ($l_{ch}$) with the compressive strength. It can be seen that the size of the fracture zone decreased in RAC, especially in normal strength concrete. There is a toughness reduction in normal strength RAC compared to the concretes prepared with natural coarse aggregate. This is coherent with previous researches where an increase in the relative concrete brittleness was found when coarse aggregates with substantial improvements in interface bond strength and in elastic compatibility between mortar and coarse aggregates were used [10,11]. As strength increases the differences in the characteristic length between concrete with natural aggregate or RAC are substantially reduced, as it occurs in Series 3.

Finally, it is interesting to observe that although the RA were obtained by crushing a high strength (A) and a normal strength (B) concrete both RAC behave in a similar way. This is in accordance with the properties measured on the coarse aggregate particles (see Table 1) and, as it was mentioned, can be attributed to the age of concretes were crushed and also to the absence of weaker particles as the coarse fraction only is incorporated as aggregate, as it is usually recommended.

### 5. Conclusions

The failure mechanism in tension and in compression of RAC was discussed in this paper. The obtained results indicate that the increase in bond strength and the reduction in stiffness that take place when natural coarse aggregate is

<table>
<thead>
<tr>
<th>Concrete</th>
<th>Surface density of aggregates (%)</th>
<th>Fractured aggregates (%)</th>
<th>Debonded aggregates (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-18</td>
<td>40</td>
<td>41</td>
<td>59</td>
</tr>
<tr>
<td>A-18</td>
<td>27</td>
<td>57</td>
<td>43</td>
</tr>
<tr>
<td>B-18</td>
<td>30</td>
<td>58</td>
<td>42</td>
</tr>
<tr>
<td>G-37</td>
<td>36</td>
<td>51</td>
<td>49</td>
</tr>
<tr>
<td>A-37</td>
<td>26</td>
<td>55</td>
<td>45</td>
</tr>
<tr>
<td>B-37</td>
<td>28</td>
<td>63</td>
<td>37</td>
</tr>
<tr>
<td>G-48</td>
<td>29</td>
<td>59</td>
<td>41</td>
</tr>
<tr>
<td>A-48</td>
<td>20</td>
<td>86</td>
<td>14</td>
</tr>
<tr>
<td>B-48</td>
<td>16</td>
<td>73</td>
<td>27</td>
</tr>
</tbody>
</table>

* Area of aggregates greater than 5 mm/area of concrete.
replaced by recycled aggregate, increases the elastic compatibility between concrete phases (mortar and coarse aggregates) modifying the fracture process. This has a special interest in normal strength concrete. Compared with concrete including natural crushed stone as coarse aggregate, RAC has a lower stiffness, shows smaller reduction in tensile or compressive strengths and presents clear decrease in the energy of fracture and in the size of the fracture zone. A reduction in branching and meandering of cracks on the fracture surfaces was also observed. This fact is consistent with the increase in brittleness observed in concretes having aggregate with both improved interface strength and the elastic compatibility within mortar and coarse aggregate.

References