Effect of Glass Fibres on the Mechanical Behaviour of Concrete with Recycled Concrete Aggregates (RCAs)

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Abstract. This paper presents an experimental study on the influence of glass fibres on the mechanical behaviour of concrete with recycled concrete aggregates (RCAs). In the test programme, four concrete mixtures with coarse RCAs and glass fibres are manufactured. The used fibres are the CEM-FIL Minibars with a fibre content of 5 kg/m³, 10 kg/m³ and 15 kg/m³, respectively. The investigated properties are the compressive strength, the splitting tensile strength, the modulus of elasticity as well as the flexural behaviour. The latter is determined by the three-point bending test on concrete beams according to the standard EN 14651: 2005+A1:2007 – Test method for metallic fibre concrete: Measuring the flexural tensile strength (limit of proportionality (LOP), residual). Based on the test observations, it seems that the used glass fibres are able to improve the mechanical behaviour of recycled aggregate concrete (RAC).

1. Introduction
The recycling and re-use of construction and demolition waste eg. recycled concrete aggregates (RCAs), saves land space, reduces the consumption of natural resources and CO₂ emissions. Numerous researches have been performed to investigate the mechanical properties of concrete with recycled concrete aggregates. The test results with the coarse recycled aggregates generally indicates a decrease in compressive strength as well as modulus of elasticity of the recycled aggregate concrete (RAC) [1]. This is mainly caused by the higher porosity of RCAs, due to the attached mortar. The attached mortar influences the interfacial transition zone (ITZ) and consequently the concrete performance [2].

Many researches have already been conducted to improve the quality of RAC. Many methods exist for this aim. One direct method is to improve the quality of RCAs. However, this usually leads to a significant increase of the energy consumption and cost. Adding fly ash, silica fume, increasing cement amount and using fibres [3] presents an alternative for improving the material performance of RAC. Various studies have already shown that fibres can significantly improve the tensile strength, flexural strength, fatigue and abrasion resistance, deformation capability, toughness and load bearing capacity after cracking. Due to this, the brittle concrete converts in a more ductile material [4].

The most common fibres are steel fibres, PP fibres as well as glass fibres. Jagannadha Rao et al. indicated that a glass fibre increment to 0.03% of the recycled concrete volume not only increases the
tensile and flexural strengths, but also the compressive strength [5]. Similar results were obtained by the research of Chandramouli et al. [6] and Tassew and Lubell [7]. Chandramouli reported an increase of 20–25% for the compressive strength and 15–20% increase in flexural and splitting tensile strength.

Based on those investigations, some additional tests are performed to further analyse the influence of glass fibres on the mechanical behaviour of concrete with RCAs.

2. Experimental program

In this study, four concrete mixtures with coarse RCAs and glass fibres (table 1) are manufactured according the two-staged mixing approach [8]. The target concrete strength is C40/50 and the workability of the different mixtures is slump class S4. To investigate the influence of glass fibres on the RAC properties, the CEM-FIL Minibars™ are used in three fibre contents: 5 kg/m³, 10 kg/m³ and 15 kg/m³. These glass fibres are produced by the international company OWENS CORNING. In table 2, the most important fibre properties are summarized. In all concrete mixtures, the used aggregates are sand 0–2 mm (fineness modulus: 2.25), limestone 2–6.3 mm and recycled aggregates 6.3–14 mm. The latter are produced from a recycling plant in Flanders, Belgium. In table 3, the physical and mechanical properties of the used natural aggregates and RCAs are given. The physical properties including the oven-dried particle density ($\rho_{rd}$), the saturated surface-dried (SSD) particle density ($\rho_{ssd}$), the apparent particle density ($\rho_a$) and the water absorption after 24h (WA24) are obtained according to the standard EN 1097-6:2013 – Tests for mechanical and physical properties of aggregates – Determination of particle density and water absorption. The mechanical properties which includes the resistance to fragmentation (LA) and wear (MDE) are performed according to the standard EN 1097-1&2:2010 – Tests for mechanical and physical properties of aggregates.

Table 1. Concrete composition.

| Cement (kg/m³) | W/C-ratio (-) | Aggregates (kg/m³) | Fibre content (kg/m³) | Fibre content (V%) |
|----------------|---------------|---------------------|----------------------|-------------------|
| C0-RAC 400     | 0.48          | Sand 0-2 759        | Limestone 2-6.3 199  | RCA 6.3-14 703    | 0 0                  |
| C5-RAC 400     | 0.48          | 759 199             | 703                  | 5 0.25            |
| C10-RAC 400    | 0.48          | 759 199             | 703                  | 10 0.50           |
| C15-RAC 400    | 0.48          | 759 199             | 703                  | 15 0.75           |

Table 2. Fibre characteristics CEM-FIL Minibars™.

| Raw material | Specific gravity (-) | Fibre length (mm) | Fibre diameter (mm) | Young’s modulus (GPa) | Tensile strength (MPa) |
|--------------|----------------------|-------------------|---------------------|-----------------------|------------------------|
| CEM-FIL Minibars™ | 2.0 ± 0.1 | 43 ± 2 | 0.70 | 42 | > 1000 |

Table 3. Physical and mechanical properties of the aggregates.

|          | $\rho_{rd}$ (kg/m³) | $\rho_a$ (kg/m³) | $\rho_{ssd}$ (kg/m³) | WA24 (%) | LA (-) | MDE (-) |
|----------|---------------------|------------------|----------------------|----------|--------|---------|
| Sand 0-2 | 2580                | 2600             | 2590                 | 0.40     | -      | -       |
| Limestone 2-6.3 | 2680 | 2710 | 2690 | 0.45 | -      | -       |
| RCA 6.3-14 | 2380 | 2660 | 2500 | 4.42 | 24     | 17      |
2.1. Strength behaviour
The strength behaviour of each RAC mixture is examined on 12 cubes (150 x 150 x 150 mm³) and 6 cylinders (height: 300 mm – diameter: 150 mm). These specimens are cured in water for 28 days. After the curing period, the mechanical properties are determined according to the European Standard. The compressive strength is performed according the NBN EN 12390-3:200 – Testing hardened concrete. Compressive strength of test specimens. The splitting tensile strength and E-modulus are determined according to the NBN EN 12390-6 Testing hardened concrete – Part 6: Tensile splitting strength of test specimens and the NBN B 15-203 Concrete testing – Statical module of elasticity with compression, respectively. In figure 1, the different test set-ups are given.

![Figure 1](image1.png)

Figure 1. Test set-ups: compressive strength (a), tensile splitting strength (b) and E-modulus (c).

2.2. Flexural behaviour
In addition, also the flexural behaviour of each RAC mixture is examined on 6 beams (150 × 150 × 600 mm³) after a curing period of 28 days in water. This is done by the three-point bending test according to the standard EN 14651: 2005+A1:2007 – Test method for metallic fibre concrete: Measuring the flexural tensile strength (limit of proportionality (LOP), residual). The test set-up is shown in Figure 2. The concrete beam is subjected to a load F at midspan. According to the standard, a notch in the beam is required to locate the crack plane under the bending load. In the present test, the notch in the concrete beams is made through a wet saw. During the bending test, the applied force F is measured as a function of the crack mouth opening distance (CMOD). Each test is stopped as the CMOD reaches a value of 4.5 mm. During the test, not only the CMOD is measured (LVDT#1), but also the deflection (LVDT#2) of the beams is measured, as can be seen from figure 2.

![Figure 2](image2.png)

Figure 2. Test set-up of the three-point bending test according EN 14651.
From the load-CMOD curve, the limit of proportionality (LOP) and residual flexural tensile strength can be determined. The LOP represents the maximal stress at the top of the notch which is assumed to act as in an uncracked mid-span section, with linear stress distribution and can be calculated according to equation (1).

$$f_{ct L} = \frac{3F_L}{2bh_sp}$$

where:
- $f_{ct L}$ = the limit of proportionality (LOP) (MPa);
- $F_L$ = the load corresponding to the LOP (N);
- $l$ = span length (mm);
- $b$ = width of the specimen (mm);
- $h_sp$ = distance between the tip of the notch and the top of the specimen (mm).

The residual flexural tensile strength corresponding with different CMOD$_j$ values can be computed according to equation (2).

$$f_{R,j} = \frac{3F_j}{2bh_sp}$$

where:
- $f_{R,j}$ = the residual flexural tensile strength corresponding with CMOD$_j$ (MPa);
- $F_j$ = the load corresponding with CMOD$_j$ (N).

The purpose of adding fibres is to increase the residual flexural tensile strength. These fibres enhance the concrete toughness by their energy absorption capacity. Banthia and Trottier [9] created the PCS methodology in which the load-deflection curves are divided in two parts: a pre-crack part and a post-crack part. The pre-crack part occurs before the LOP, while the post-crack part occurs after. Hereby, the area under the pre-crack curve and the post-crack curve represents the pre-crack energy ($E_{pre}$) and the postcrack energy ($E_{post}$). Generally, it is known that fibres mainly influence the post-crack energy.

### 3. Test results and discussion

#### 3.1. Workability

In table 4, an overview is given of the workability tests on the RAC mixtures. The test observations indicate that the CEM-FIL Minibars™ have an important influence on the concrete workability. In the reference mixture (C0-RAC) only 0.7 g/l superplasticizer (SP) is added to obtain a slump class S4. For the fibre reinforced mixtures, a decrease of the workability is observed. The lowest fibre content (5 kg/m³) results in a slump class S3. This is also the case for a higher fibre content. To obtain a slump class S4 for all the RAC mixtures, the amount of SP must be increased. For a fibre content of 15 kg/m³, the amount of superplasticizer (SP) needs to be increased from 0.7 g/l to 1.4 g/l. Nevertheless by increasing the superplasticizer amount, a slump class S4 can still be achieved for all the concrete mixtures.

| Slump class (SP = 0.7 g/l) | C0-RAC | C5-RAC | C10-RAC | C15-RAC |
|---------------------------|--------|--------|---------|---------|
| 0.7                       | S4     | S3     | S3      | S3      |

#### 3.2. Strength behaviour

The mechanical concrete properties of the RAC mixtures are summarized in table 5 and figure 3. It seems that glass fibres have a small, but beneficial influence on the RAC concrete mixtures. By adding 15 kg/m³ glass fibres to the RAC mixtures, the compressive strength increases from 54.6 MPa (C0-RAC) to 59.8 MPa (C15-RAC). This corresponds with an increase of 9.5%. Also for a lower fibre content,
there is an increase visible. Similar conclusions can also be made for the modulus of elasticity. The modulus of elasticity increases from 33.9 GPa (C0-RAC) to 36.0 GPa (C15-RAC). During the splitting tensile tests of the reinforced RAC mixtures, it was observed that the cubes did not separate after the first cracking. This improvement indicates the enhanced ductile behaviour which is provided by the glass fibres, although only a small increase in splitting tensile strength is observed by adding a high fibre content (10 kg/m³ and 15 kg/m³). It seems that the highest splitting tensile strength is obtained when 10 kg/m³ glass fibres is used. The corresponding improvement is 5.5%.

|               | Cubical compressive strength (MPa) [st. dev] | Splitting tensile strength (MPa) [st. dev] | Modulus of elasticity (GPa) [st. dev] |
|---------------|---------------------------------------------|-------------------------------------------|-------------------------------------|
| C0-RAC        | 54.6 [1.0]                                  | 3.6 [0.2]                                 | 33.9 [2.5]                          |
| C5-RAC        | 56.1 [1.1]                                  | 3.6 [0.1]                                 | 34.1 [3.8]                          |
| C10-RAC       | 59.3 [3.6]                                  | 3.9 [0.2]                                 | 36.3 [4.0]                          |
| C15-RAC       | 59.8 [2.2]                                  | 3.8 [0.4]                                 | 36.0 [1.5]                          |

Figure 3. Cubical compressive strength (a) and Modulus of elasticity (b) of the RAC-mixtures.

3.3. Flexural behaviour
Figure 6 presents the obtained load-CMOD curves of different concrete specimens. In these graphs, it is clear that fibre addition results in a higher peak load $F_L$ (see also table 6). Even for a small fibre content, there is a significant influence on the flexural tensile strength (figure 4). For a fibre content of 5 kg/m³, the flexural tensile strength is 4.2 MPa, while for the plain RAC mixture it is only 3.1 MPa. Therefore, it is evident that fibre addition in RAC mixtures has a beneficial influence on the flexural tensile strength. The fibre reinforced mixtures effectively limit the crack propagation, providing higher flexural tensile strength. Although, not only the flexural tensile strength increases with increasing fibre content, the CMOD (and the deflection) which corresponds with the LOP increases as well. A higher fibre content allows a higher deformation before failure. For the RAC-mixture with 15 kg/m³ glass-fibre, the $\delta_{LOP}$-value was 1.33 times that of the plain concrete.
Table 6. (Residual) Flexural tensile force according EN 14651:2005.

|             | FL (kN) [st. dev] | CMODLOP (mm) | δLOP (mm) | FR,j at prescribed CMODj values (kN) [st. dev] |
|-------------|-------------------|--------------|-----------|-----------------------------------------------|
|             |                   |              |           | 0.5 mm | 1.5 mm | 2.5 mm | 3.5 mm |
| C0-RAC      | 10.0 [0.8]        | 0.051        | 0.069     | 1.3 [0.7] | -     | -     | -     |
| C5-RAC      | 13.0 [0.5]        | 0.041        | 0.060     | 4.4 [0.8] | 3.6 [0.7] | 2.8 [0.6] | 2.1 [0.5] |
| C10-RAC     | 12.4 [1.1]        | 0.062        | 0.074     | 7.1 [0.7] | 6.2 [1.3] | 5.0 [1.3] | 4.0 [1.2] |
| C15-RAC     | 12.6 [1.0]        | 0.080        | 0.092     | 10.0 [1.2] | 10.3 [1.2] | 8.6 [0.9] | 6.9 [0.7] |

Table 7. (Residual) Flexural tensile strength according EN 14651:2005.

|             | fR,j (MPa) [st. dev] | FR,j at prescribed CMODj values (MPa) [st. dev] |
|-------------|----------------------|-----------------------------------------------|
|             | 0.5 mm | 1.5 mm | 2.5 mm | 3.5 mm |
| C0-RAC      | 3.1 [0.2] | 0.4 [0.2] | - | - |
| C5-RAC      | 4.2 [0.2] | 1.4 [0.2] | 1.1 [0.2] | 0.9 [0.2] | 0.7 [0.1] |
| C10-RAC     | 4.0 [0.3] | 2.3 [0.2] | 2.0 [0.4] | 1.6 [0.4] | 1.3 [0.4] |
| C15-RAC     | 4.1 [0.3] | 3.2 [0.4] | 3.3 [0.4] | 2.8 [0.3] | 2.2 [0.2] |

In table 7, the measured residual flexural tensile strength at 0.5mm, 1.5mm, 2.5mm, 3.5mm CMOD is given. For higher fibre contents, the residual flexural tensile strength increases at the different CMOD values. According to the NBN EN 14889-2, the unit volume of fibres in kg/m³ must be determined to achieve a residual flexural strength of 1.5 MPa at 0.5 mm CMOD and a residual flexural strength of 1 MPa at 3.5 mm CMOD. Based on the measurements, the concrete mixture with 5 kg/m³ glass fibres does not meet these requirements.

The European Standard EN 14651 describes the equivalence between the CMOD and deflection (δ) for conventional concrete beams according equation (3). However, a small difference is obtained for the RAC mixtures. The relation for the C5-RAC, C10-RAC and C15-RAC mixtures is given by equation (4), (5) and (6), respectively. These formulas (and figure 5) indicate that the European Standard overestimates the deflection values of the RAC mixtures.

\[ \delta = 0.85 \text{CMOD} + 0.04 \]  \hspace{1cm} (3)
\[ \delta = 0.80 \text{CMOD} + 0.03 \]  \hspace{1cm} (4)
\[ \delta = 0.79 \text{CMOD} + 0.03 \]  \hspace{1cm} (5)
\[ \delta = 0.77 \text{CMOD} + 0.03 \]  \hspace{1cm} (6)

Figure 4. Flexural tensile strength.

Figure 5. Equivalence CMOD and deflection.
In table 8, the energy absorption capacity of the different concrete mixtures is summarized. The energy-absorption capacity of fibre-reinforced concrete is determined by the concrete matrix and the fibres. If the elastic modulus of the fibres is quite close to those of the concrete, then the energy absorption of the concrete matrix depends mainly on their flexural tensile strength [10]. Due to this, the energy absorption $E_{post}$ shows the same variation trend with the flexural tensile strength. By increasing the fibre content, no big influence on the precracking energy absorption ($E_{pre}$) is visible, but a high influence on postcracking energy absorption ($E_{post}$) is observed. Adding 15 kg/m³ CEM-FIL Minibars™ increases the energy absorption capacity for the RAC mixtures from 1.7 J until 28.9 J.

Table 8. Energy absorption capacity.

|        | $E_{pre}$ (J) [st. dev] | $E_{post}$ (J) [st. dev] | Energy absorption capacity at prescribed deflections (L=500mm) (J) [st. dev] |
|--------|-------------------------|--------------------------|-----------------------------------------------------------------------------|
|        | L/600                   | L/150                    |                                                                            |
| C0-RAC | 0.5 [0.1]               | 1.7 [0.5]                | -                                                                          |
| C5-RAC | 0.5 [0.1]               | 10.8 [2.1]               | 4.7 [1.0]                                                                  | 11.3 [2.1] |
| C10-RAC| 0.6 [0.3]               | 18.1 [3.6]               | 6.4 [0.5]                                                                  | 18.7 [3.4] |
| C15-RAC| 0.8 [0.6]               | 28.9 [2.8]               | 8.6 [0.9]                                                                  | 29.7 [3.2] |
4. Conclusion

In this study, the mechanical behaviour of glass fibre reinforced concrete with coarse recycled concrete aggregates was studied. The mechanical properties which are taken into account are the compressive strength, the splitting tensile strength and the modulus of elasticity. Three-point bending tests on the beam specimens are carried out according to the EN 14651 to determine the flexural performance. Within the scope of this study, the following conclusions can be drawn:

(1) The CEM-FIL minibars™ have a small, but beneficial influence on the RAC concrete mixtures. By adding 10 kg/m³ glass fibres to the RAC mixtures, the compressive strength increases with 8.6%. For the modulus of elasticity, similar conclusions can be made. The modulus of elasticity increases from 33.9 GPa (C0-RAC) to 36.3 GPa (C10-RAC). A fibre content higher than 10 kg/m³ does not further improve the mechanical properties.

(2) Already a small fibre content has a significant influence on the flexural tensile strength of the RAC mixtures. For a fibre content of 5 kg/m³ the flexural tensile strength is 4.2 MPa while for the plain RAC, this is 3.1 MPa.

(3) By increasing the fibre content, also the CMOD (and the deflection) which corresponds with the LOP increases. A higher fibre content can allow a higher deformation before failure.

(4) The RAC mixtures with 10 kg/m³ and 15 kg/m³ glass fibres can meet the requirements of the standard NBN EN 14889-2.

(5) The formula in the EN 14651, which gives the relation between CMOD and deflection, overestimates the deflection values of the RAC mixtures.

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