Reinforced Concrete Beams Made of High-Performance Recycled Aggregate with Use Steel Fibre

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Abstract. The paper presents experimental studies of model reinforced concrete beams with a rectangular section using high-performance recycled aggregates with and without steel fibre. The experimental analyses conducted as immediate studies concerned the following: deflection, load capacity, and strain of concrete, and the width and range of cracks. The comparative analysis entails the behaviour of beams made of concretes using high-performance recycled aggregates with model control elements made of regular concrete based on natural aggregates.

1. Introduction

The construction industry such as designers or manufacturers of concrete operating in Poland treat the application of recycled aggregates with reserve due to the scarce information on the classification of recycled aggregates, particularly those applied in structural elements [1,2]. The classification of artificial and recycled aggregates according to the kind of raw material applied for their production has been developed as a Final Report on aggregates obtained from secondary resources as document CEN/TC154/TG10/N736. The classification for secondary aggregates according to [3] is presented in Table 1.

Table 1. Secondary materials: recycled aggregates [3]

| Type       | Source                        | Subtype | Material characteristics |
|------------|-------------------------------|---------|--------------------------|
| A          | Construction                  | A1      | Retrieved asphalt        |
| A          | and recycling                 | A2      | Crushed concrete         |
| A          |                               | A3      | Crushed brick masonry    |
| A          |                               | A4      | Mix of A1, A2, and A3    |

Sustainable development [4] in the construction industry and appropriate waste management, reuse of waste not only result in benefits for the environment but also solve the problems of the disposal, storage, and utilisation of waste. The annexe to the Act [5] provides forecasts of construction waste amounts to as far as 2022. The forecast of the resource base for the production of recycled aggregates is presented in the National Waste Management Plan. The forecast is presented in Table 2.
Table 2. The forecast of the amount of construction waste along with an estimate of recycled aggregate production [5]

| Details                   | Year |       |       |       |       |     |
|---------------------------|------|-------|-------|-------|-------|-----|
|                           | 2014 | 2015  | 2016  | 2018  | 2019  | 2022|
| Mass of waste produced    | 4.260| 4.400 | 4.520 | 4.890 | 5.060 | 5.600|
| Construction materials²   | 1.278| 1.320 | 1.356 | 1.467 | 1.518 | 1.680|
| Recycled aggregates³      | 1.150| 1.188 | 1.220 | 1.320 | 1.366 | 1.512|

¹ Mg (the megagram) is a derivative unit of mass defined as one million grams using the SI prefix system and commonly referred to as ton. The megagram is a standard unit applied in practice and legal regulations relating to recycling with which amounts of waste are expressed.

² with the assumption of a 30 per cent share,
³ with a 90 per cent rate of reclamation.

When analysing the data presented in Table 2, it is worth considering the application of recycled aggregates in structural elements. The authors of this paper use experimental studies to propose the application of high-performance recycled aggregates in beam-type elements.

2. Experimental studies

The studies conducted aimed to determine the results of replacing natural coarse aggregate with high-performance recycled aggregate modified with steel fibre in comparison to regular concrete as well as applying high-performance recycled aggregate in structural elements.

2.1. Tests of samples

HPC elements (average compression strength after 28 days of maturing 104.3 MPa, tensile strength 9.46 MPa) were crushed and fractioned, obtaining a secondary aggregate necessary for the production of concrete mixes. Apart from the secondary aggregates, CEM I 45.5 cement, fine fractions of sand, superplasticizer, and water were used to produce concrete mixes [9]. Samples of concrete were produced for 3 series with varied content of secondary aggregate. The series tested are presented in Table 3.

Table 3. Experimental series using natural and recycled aggregates.

| Series no. | Amount of natural aggregate | Amount of high-performance recycled aggregate |
|------------|-----------------------------|-----------------------------------------------|
| I          | 50%                         | 50%                                           |
| II         | 50%                         | 50%+steel fibre                               |
| III        | 100%                        | 0%                                            |

After 28 days of maturing, the concrete samples produced were tested; the average values of strength obtained are presented in Table 4.
Table 4. Average values of compression strength of 10x10x10 cm cubic samples in the series.

| Item no. | Average values of compression strength [MPa] |
|----------|---------------------------------------------|
| I - 50%REC | Ⅱ - 50%REC+F | III - NAT |
| $\bar{x}$ = | 106.4 | 102.6 | 45.6 |

The analysis of concrete samples with natural aggregate compared to concrete samples with high-performance recycled aggregate (with the same amount of natural aggregate being replaced with secondary aggregate) with respect to compression strength allows us to state that the difference in the values obtained is considerable. It transpires from the above results that we have the first beneficial effect of secondary aggregate, which can be used in structural elements thus saving natural resources. The strength values obtained for cubic samples with secondary aggregate are similar to the values for their original elements, from which they were taken.

2.2. Immediate studies of reinforced concrete beams on a pilot scale.

2.2.1. Preparation of test elements. The subject of the key studies is the analysis of deflection and strain of concrete in reinforced concrete beam-type elements (with the dimensions of 1,100x102x80) produced using high-performance recycled aggregate. The control beams were produced using regular concrete based on natural aggregate. The scheme of the beams is presented in Figure 1.

![Figure 1](image1.png)

**Figure 1.** The arrangement of reinforcement bars in reinforced concrete beams.

2-bar reinforcement (top and bottom) $\varnothing 8$ was made of BSt500S steel with a plasticity limit, $R_e = 500 MPa$ while the stirrups were made of plain steel of $\varnothing 3$.

2.2.2. Experimental studies of structural elements. The tests were conducted in a DR MB-60 strength tester. The static scheme was a freely supported beam. The load consisted of two concentrated forces applied at 1/3 of the beam span. The manner in which the load was applied is presented in Figure 2.

![Figure 2](image2.png)

**Figure 2.** Loading scheme
For each beam, after placing them in the testing stand, initial distances between top and bottom benchmarks were read. Next, the load was increased to 5 kN and reduced back to 0. After the procedure was performed three times, the initial distances between benchmarks were read providing initial data for the observation of further strains during the tests. The values of deflection and strain of concrete at the top (compression) and bottom (tension) level were recorded every 5 kN.

2.2.3. Measurements of strain. Strain was read at two levels: top and bottom. Both couples of benchmarks were placed approximately 1 cm from the top and bottom surfaces of the beam. A Demec strain gauge was used for the measurement of strain levels. The measurement results are presented in Tables 5 and 6, while a graphical breakdown is shown in Figures 3 and 4.

### Table 5. Average values of concrete strain in the area submitted to tension ε [%]

| Force F [kN] | Average values of concrete strain ε [%] |
|--------------|--------------------------------------|
|              | 50%REC I | 50%REC+fibre II | NAT III |
| 5            | 0.071    | 0.089           | 0.120   |
| 10           | 0.191    | 0.218           | 0.276   |
| 15           | 0.320    | 0.378           | 0.373   |
| 20           | 0.436    | 0.480           | 0.511   |
| 25           | 0.538    | 0.627           | 0.618   |
| 30           | 0.658    | 0.747           | 0.742   |
| 35           | 0.773    | 0.907           | 1.009   |
| 40           | 1.013    | 1.047           |         |

### Table 6. Average values of concrete strain in the area submitted to compression ε [%]

| Force F [kN] | Average values of concrete strain ε [%] |
|--------------|--------------------------------------|
|              | 50%REC I | 50%REC+fibre II | NAT III |
| 5            | 0.076    | 0.138           | 0.142   |
| 10           | 0.289    | 0.556           | 0.916   |
| 15           | 1.209    | 1.338           | 1.680   |
| 20           | 2.000    | 1.991           | 2.240   |
| 25           | 2.702    | 2.689           | 2.707   |
| 30           | 3.356    | 3.218           | 3.231   |
| 35           | 4.440    | 4.533           | 4.640   |
| 40           | 11.107   | 8.227           |         |
The values of concrete strain are similar in control beams produced with a regular concrete based on natural aggregates than beams made with recycled aggregate. A difference can be observed in the values for beams made using high-performance recycled aggregate without fibres and those obtained using control beams.

2.2.4. Measurements of deflection. The measurements of deflection were performed with a displacement sensor. The measurements were performed after each load increment of 5 kN. The relation between the force applied and deflection levels is shown in Figure 5.
The analysis of results of tests of strains of concrete in beams produced with recycled aggregate with and without steel fibre, in comparison with control beams made of regular concrete based on natural aggregates, confirm that deflection is lower in series I and II beams than those of series III beams. It is yet another testimony to the viability of replacing natural aggregates used in structural elements with secondary aggregates.

3. Breaking force
The tests of all of the beams used continued until the beams broke. Table 7 presents the results of the strength analysis of the beams subjected to the tests.

| Beam series | Breaking force [kN] | Average breaking force value [kN] |
|-------------|---------------------|-----------------------------------|
| 50%REC - I  | 46.4 ; 41.6; 38.1    | 43.33                              |
| 50%REC+F - II | 45.1, 47.4, 41.8     | 44.76                              |
| NAT - III   | 39.1, 39.5, 38.1     | 38.9                               |

When analysing Table 7, we once again find that recycled aggregates in concretes has a beneficial effect on properties of concrete, this time in terms of their load capacity.

4. Cracks
Cracks and their apertures were analysed in parallel during the tests, with the values being recorded every 5 kN. Figures 6, 7 and 8 below show the manner in which cracks changed their shape and developed while the loads for series I, II and III beams increased. The measurements of crack apertures were performed using a Brinell microscope.
When analysing the photographs, one can see a smaller aperture and number of cracks in the area of simple bending in series II beams with added fibre, compared to the other ones.

5. Summary
The construction industry generates considerable amounts of waste not only during the demolition of structures but also over the course of their use (modernisation, renovation). A possibility of using recycled aggregates in structural elements is a concept worth considering.

6. Conclusions
The analysis of the results of the experimental studies presented in this paper confirms that the application of high-performance recycled aggregates in concretes enables the obtainment of better concrete properties in comparison to regular concretes.

Concretes based on recycled aggregates, when used in structural elements, can replace natural aggregates, which was proven correct with the tests of beams performed with respect to concrete strain, beam deflection, and load capacity.

By reusing construction rubble, we protect the environment and natural resources.
The use of aggregates obtained from high-performance concretes in structural elements is undoubtedly more beneficial and better than those based on regular concretes.

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