Short Time Loads of T-Beams Made of Concrete Manufactured with the Use of High-Performance Recycled Aggregate

Barbara Sadowska-Buraczewska¹, Tomasz Chyz³
¹Białystok University of Technology, Faculty of Civil and Environmental Engineering, Wiejska 45A, Białystok, 15-351, Poland
barbara.sadowska@pb.edu.pl

Abstract. The paper summarises an experimental and a numerical analysis of the bearing capacity of concrete beams. The first examined beam was prepared from reinforced high-performance concrete (HPC) containing natural aggregate, another two were made of reinforced high-performance concrete (HPC) containing recycled aggregate. Beams used in the tests were prepared in modelling scale and had T-shaped cross sections of the upper width of 160 mm, the bottom width of 80 mm, the height of 120 mm, and the effective span of 1100 mm. The programme of the tests, a description of their implementation, as well as the obtained results of deflections and strain have also been presented. An analysis of the obtained results was carried out and its findings were compared to the results of a theoretical analysis based on standard regulations.

1. Introduction

The issue of ecological aspects of human activities has been gaining much popularity recently. One of the directions of pro-ecological actions is reusing construction materials. A common waste material in construction is concrete debris left after life-expired buildings have been demolished. This type of debris is often transported to dumping grounds where it becomes a huge problem for local ecosystems. And what would happen if it was used again? Among the literature available on the subject, there are not many publications on using recycled high-performance concrete aggregate for construction elements [1]. One can, on the other hand, find many publications describing the characteristics of recycled concrete, recycled aggregate, etc. [2-22].

In the present article, the authors suggest that concrete debris produced after demolishing structures made of high-performance concrete should be used. It is assumed that using HPC construction debris as the frame of a new concrete mixture will make it possible to produce HPC of high utilitarian properties. HPC is suitable for a wide range of applications, for example when higher loads need to be transferred or when ensuring increased impermeability of structures is required.

2. Experimental research concept

At present, Poland produced approximately 3.5 million tons of construction debris per year. Contemporary trends in the European Union policy require that in the year 2020 70% of construction and demolition debris should be reused. Because of that, the idea of recycling has been more and more popular. Another positive factor resulting from recycling is economic benefits. However, the use of waste materials raises a number of questions [7-13], and some of these are:
Will the application of recycled HPC aggregate as a component of concrete bring about a deterioration of the quality of such concrete? [15-19]

How does recycled HPC aggregate influence the strength and durability of a beam element made of such concrete?

The experimental tests and computer simulations performed by the authors of the present article aim to answer the above questions. To achieve this, a few control specimens as well as test specimens of reinforced concrete beams were made. First, the material properties of the HPC samples were tested. After that, the samples made of high-performance concrete were crushed in a jaw crusher with a regulated degree of crushing. The aggregate obtained in this way was then classified as RCAC Type II according to RILEM [23].

The next phase consisted in preparing reinforced concrete beams, using the obtained debris. Control samples and two types of T-shaped beams were made (See Figure. 1): the beams of the first type were produced with the use of recycled coarse HPC aggregate, and labelled T-RC, while the beams of the second type, labelled T-HPC, were made from natural aggregate concrete for the purpose of comparison. The geometry and structure of the beams are presented in Figure 1. The reinforcement system in the beams were 2 bars made of B550S steel both at the top and at the bottom, whereas the stirrups were made of bars of steel with a smooth finish and their diameter was 2 Ø 8 mm. The composition of the concrete mixture used in all the tests is shown in Table 1.

Figure 1. Reinforcement system in concrete beams

Table 1. Composition of designed concrete mixture made using recycled aggregate

| Component                        | Amount [kg/m³] |
|----------------------------------|----------------|
| CEM I 52.5R- NA cement           | 450            |
| Fine aggregate–sand              | 630            |
| Coarse aggregate: recycled aggregate | 1070         |
| Microsilica 10%                  | 45             |
| Superplasticiser 1.8 %           | 8.1            |
| Water                            | 119            |

The tests on both the samples and the reinforced concrete beams were conducted on the universal testing machine presented in Figure 2, while the static diagram for the test beam sand the beam loading diagram can be seen in Figure 3.
3. PREDICTIVE NUMERICAL ANALYSIS

Before the laboratory tests were made, a predictive numerical analysis had been performed, for which the finite element method (FEM) implemented in the DIANA – TNO DIANA BV, Delft computer system, was applied.

The computational model was developed on the basis of Q8MEMstandard4-node finite elements gaining the flat state of strain (in DIANA nomenclature); the elements were used to model the concrete. The reinforcement steel was modelled in the form of bars as the REBAR type. Figure 4 shows the discretisation of the system.

The obtained results of displacement and strain are presented in diagrams further in the present article and marked as FEM results. The analysis of the stress in steel and concrete indicates that the beams of the RCA type should be destroyed by breaking of the reinforcement steel, which is illustrated in Figure 5. Following Figure 6 presents the stress for the HPC-type beam.
Figure 5. Stress in reinforcement steel and in concrete for the load of 37.5 kN in RCA beam

Figure 6. Stress in reinforcement steel and in concrete for the load of 50 kN in HPC beam

4. Results of strain measurements in test beams

First, measurements of horizontal strain in the test beams were conducted. Measurement points were located along the height of the beams in the middle of the beam span. The strain was measured with a DEMEC extensometer with the measurement accuracy of +/- 0.01mm. The use of the extensometer required contact benchmarks to be permanently fixed; their location is shown in Figure 7.
Figure 7. Location diagram of benchmarks for DEMEC extensometer (Figure. 8) with measuring range of 150mm

Figure 8. DEMEC extensometer with measurement accuracy of +/- 0.01mm

The strain measurement results for the different measurement points are presented in Figure 9, Figure 10, and Figure 1. The results were obtained in a number of stages, adopting the increase of the loading force of 5 kN. Figure 12 and 13 show the elastic and plastic strain results obtained from the predictive numerical analysis. In the line charts, the line marked as element 415 corresponds to point no. 1, the line ‘element 330’ corresponds to point no. 2, and the line ‘element 2518’ corresponds to point no. 3.

Figure 9. Relative strain measured at measurement point no. 1
In the line charts, the following symbols are used:

- T1-HPC – reinforced concrete bar made of high-performance concrete with natural aggregate (100% of natural aggregate)
- T2-RCA – reinforced concrete bar made using recycled high-performance concrete aggregate (fine aggregate – natural sand, coarse aggregate – recycled high-performance concrete)
- T3-RCA – reinforced concrete bar made using recycled high-performance concrete aggregate (fine aggregate – natural sand, coarse aggregate – recycled high-performance concrete).

![Figure 10. Relative strain measured at measurement point no.2](image)

| Force F [kN] | Relative strain |
|--------------|-----------------|
| Symbol of beam | T1-HPC | T2-RCA | T3-RCA |
| 0            | 0   | 0   | 0   |
| 5            | 0.01| 0.03| 0.07|
| 10           | 0.04| 0.07| 0.10|
| 15           | 0.05| 0.09| 0.14|
| 20           | 0.07| 0.15| 0.22|
| 25           | 0.12| 0.20| 0.26|
| 30           | 0.19| 0.27| 0.35|
| 35           | 0.24| 0.33| 0.41|
| 40           | 0.36| 0.47| 0.52|
| 45*          | 0.55| 1.91| 2.01|
| 50*          | 1.97| -   | -   |

![Figure 11. Relative strain measured at measurement point no.3](image)

| Force F [kN] | Relative strain |
|--------------|-----------------|
| Symbol of beam | T1-HPC | T2-RCA | T3-RCA |
| 0            | 0   | 0   | 0   |
| 5            | 0.11| 0.15| 0.17|
| 10           | 0.17| 0.28| 0.41|
| 15           | 1.12| 1.41| 1.64|
| 20           | 1.87| 2.29| 2.49|
| 25           | 2.51| 2.89| 3.20|
| 30           | 3.04| 3.96| 4.53|
| 35           | 3.68| 4.21| 4.72|
| 40           | 4.51| 5.87| 8.96|
| 45*          | 7.47| 13.49| 16.19|
| 50*          | 17.95| -   | -   |
Figure 12. Elastic strain in RCA beam

Figure 13. Plastic strain in RCA beam
The interpolated diagrams of strain along the beam height for two example levels of the loading force are represented in Figure 4.

![Diagram of concrete strain along beam height, depending on force value](image)

**Figure 14.** Diagrams of concrete strain along beam height, depending on force value

An analysis of the presented strain results shows that the strain values for the HPC beam with natural aggregate are the lowest throughout the whole test. The mean strain values in the compressed zone of the beam made using recycled high-performance concrete aggregate are by 42% higher than these for the natural aggregate beam, whereas the mean strain values in the tension zone differ by 33%.

5. Results of deflection measurements in test beams

The deflection measurements were taken with the use of clock displacement gauges located in the beams’ midspan, and on the beams’ supports Figure 15).

The measurements were performed each time after the force level had been increased by 5 kN, until the beams were destroyed. The obtained results are presented in Figure 16.
Figure 15. Diagram of test stand for testing beams

Figure 16. Deflection measured in beams’ midspan

An analysis of the test results concerning the deflection of the model reinforced concrete beams with recycled aggregate in comparison to the results for the control beams made from natural aggregate, reveals that the deflection values for the natural aggregate HPC beams under study were by approximately 20% lower than the deflection values for the beams made from recycled high-performance aggregate.

Deflection is inevitably connected to the mechanism of cracking in bent beams. As it was the case with the strain and deflection measurements, cracking was tested every time after the loading force had been discretely increased by 5kN. To facilitate the observation of crack formation, one surface of each beam had been painted white. Information on newly formed cracks as well as on changes in the previously existing cracks was marked on the beams’ surfaces under study.

The cracking observed in all the beams looked similar. The first cracks were perpendicular and they appeared when the value of the applied loading force amounted to 15 kN. These cracks were formed in the middle area, in the constant bending moment region. Because of the very small width of the cracks formed at this loading force level, it seems that cracks appeared only in the lime surface layer. A significant increase in the influence of diagonal cracks on the entire cracking pattern took place at the loading force level of 35 kN. These cracks started to form in the sections between the points at which the forces were applied and the supports, and later the cracks progressed in the direction at which concentrated forces were applied. Figure 17, 18, and 19 illustrate the way in which the cracks formed and progressed as the loading increased.
The beams were tested until they were destroyed, their destruction being understood as:
- plasticization of concrete in the compressed zone,
- plasticization of the beam reinforcement.

The destruction of the beams was sudden, and it was accompanied by a characteristic cracking sound. Testing of all the beams continued until they were destroyed, and the values of the rupture force were recorded. No differences in the failure models were observed – all the beams, both those made from
natural aggregate and those with recycled high-performance aggregate, were destroyed by plasticization of their reinforcement in the tension zone. The results of the flexural strength tests performed on the beams under study are listed in table 2.

| Symbol of beam | Rupture force $F$ [kN] | Breaking moment $M_{sd}$[kNm] |
|----------------|------------------------|-------------------------------|
| T1- HPC        | 53                     | 9.01                          |
| T2- RCA        | 50                     | 8.50                          |
| T3- RCA        | 47                     | 7.99                          |

Short-time load tests on T-shaped reinforced concrete beams indicate that the beam containing natural aggregate shows higher strength in comparison to the strength of the tested beams made from recycled high-performance aggregate. The T1- HPC beam was destroyed when the value of the loading force was 53kN, while the beams containing recycled aggregate were destroyed when the loading forces of 50kN and 43kN were applied, respectively. It results from the above that the beam with natural aggregate was capable of withstanding loads which were by approximately 8% higher than the loads applied to the other beams.

6. Conclusions

Construction waste presents a serious problem not only in terms of ecology but also economy. Reusing aggregate produced from crushed demolition and building debris in the construction industry is a good solution here. This reduces the amount of generated waste, thus limiting mining of natural resources and lowering transport costs. The authors of the article suggested using recycled aggregate in construction elements as substitute of natural aggregate in concrete mixtures. After having conducted the experimental tests, the following conclusions were formulated:

1. The performed analysis of the beam deflections shows that HPC beams containing natural aggregate are characterised by a higher rigidity than beams made using recycled high-performance aggregate. The experimental deflection values for the reinforced concrete beams under concern make it possible to conclude that the deflection values for HPC beams containing natural aggregate are by approximately 20% lower than the deflection values for beams made using recycled high-performance aggregate.
2. Beams made with the use of recycled high-performance concrete aggregate showed higher strain values than these for natural aggregate beams for a given loading force. The mean strain in the compressed zones of beams containing recycled high-performance concrete aggregate is by 42% greater than this in natural aggregate beams, whereas the mean strain in the tension zones differs by 33%.
3. The cracking patterns of the tested natural aggregate beam sand of the recycled aggregate beams were similar. The first, perpendicular cracks were observed when the loading force of 15 kN was applied. A considerable increase in the influence of diagonal cracks on the whole cracking pattern occurred at the loading force level of 35 kN.
4. It results from the experimental tests that the rupture force value in the case of the high-performance concrete aggregate beams under study was on average by o 4.5kN lower than the rupture force value for the beam made of natural aggregate HPC. Thus, the bearing capacity of reinforced concrete beams made using natural aggregate HPC is by approximately 8% higher than in the case of beams made using recycled high-performance aggregate.
5. The deflection values for the HPC and RCA beams, obtained from the FEM numerical analysis, implemented in the DIANA – TNO DIANA BV, DELFT computer system, are comparable to the values obtained in the experimental tests, which confirms the test results.
6. In order to obtain higher loading capacity of T-shaped beams, it is planned to apply reinforcement at the top, throughout the entire width of the cross-section (in the flanges of T-shaped beams) during further short-time load tests. Also, to ensure that the bearing capacity of the beam cross-section is used to the maximum extent, it is planned to use supporting pressure plates whose areas would be equal to the area of the examined sample (the effect of uniform load application). Research on reinforced beams produced using recycled high-performance aggregate will be completed in the future by tests on full-size element sand also by long-term tests.

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