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USING PLASTIC WASTE TO PRODUCE LIGHTWEIGHT AGGREGATE FOR RC STRUCTURES

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ABSTRACT: This article compares the deflections of reinforced concrete beams with reinforcement degrees of ρ=1.02% and ρ=1.78%, made of lightweight aggregates, i.e. Certyd, LECA, and an innovative aggregate made of plastic waste. Two methods were used for the comparison experimental and computational. The computational part was performed using the finite element method (FEM) in ANSYS software. The adopted properties of lightweight concrete were sourced from the authors' experimental research. A comparison of deflections based on the data obtained using both methods showed that, for reinforced concrete elements with a degree of reinforcement of ρ=1.02%, the smallest difference was obtained in the case of beams made of plastic waste concrete, while the highest difference was obtained for beams made of concrete with lightweight expanded clay aggregate. In the case of reinforced concrete elements with a degree of reinforcement ρ=1.78%, the lowest differences were obtained for beams made of lightweight aggregates, i.e. Certyd and LECA. For those beams that used plastic waste aggregate, the difference was 20%, compared to experimental tests.

KEYWORDS: artificial aggregates, plastic aggregate, recycling; experimental tests, numerical analysis, ANSYS software

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Introduction

Concrete, primarily composed of cement, large particles, sand, water, and various inert elements, stands as the most widely used building material worldwide. The global per capita consumption of concrete has tripled compared to four decades ago, with an annual production of around 30 billion tons, a figure expected to increase (Monteiro et al., 2017). Aggregates, making up 65-80% of concrete's total volume, significantly influence its properties both before and after hardening (Saikia & de Brito, 2014). The enormous production of concrete is rapidly depleting natural resources, causing significant environmental impacts (Haas, 2012). Projections indicate a 59% rise in global aggregate demand by 2025 (Silva et al., 2019). Sand and gravel mining poses a major sustainability challenge in the 21st century (Curry-Lindahl, 2019), as these materials are among the least regulated in many regions compared to other mined resources. Preserving natural raw materials is vital to mitigate climate change effects and prevent future resource depletion. Consequently, researchers are exploring alternative natural aggregates in concrete, including construction and demolition waste for recycling (Abdollahnejad et al., 2019; Allujami et al., 2022a; Allujami et al., 2022b; Arabiyat et al., 2021; Ullah et al., 2021), and solid wastes like glass (Batayneh et al., 2007), cardboard, paper (Solahuddin & Yahaya, 2022), bricks (Joyklad et al., 2022), and crumb waste tyres (Batayneh et al., 2008).

Plastic, a widely used material known for its versatility, resilience, and durability, saw a global production of 359 million tons in 2018 (Marsh McLennan, 2019), with only a small fraction being recycled in the United States and Europe. Plastic pollution poses significant environmental and ecological challenges, impacting agricultural productivity and groundwater recharge potential and causing substantial water pollution, all of which harm marine life (Saikia & de Brito, 2012). A 2006 United Nations Environmental Program study found 46,000 pieces of plastic per square mile in the ocean (Kershaw et al., 2011; Sesini, 2011), with these fragments constituting 90% of floating ocean debris (Monteiro et al., 2017). Efforts to recycle plastics include incorporating them into various industrial products, such as the concrete industry using plastic waste aggregates to replace natural aggregates (Ferrotto et al., 2022; Mohammed & Hama, 2022; Saikia & de Brito, 2012). This not only addresses plastic pollution but also reduces reliance on natural concrete materials.

Recent studies focus on the environmental impact of the construction industry and strategies to enhance sustainability, including safeguarding natural resources and minimising waste. These strategies involve analysing the life cycle of buildings, especially considering the environmental impact of construction materials like concrete. Current standards (PN-EN 13055-1:2016-07) classify lightweight aggregates used in concrete into four categories: natural, those produced from natural or industrial waste, solely industrial waste, and recycled aggregates, excluding plastic waste aggregates due to a lack of standards, which complicates their practical use (Bujnarowski & Grygo, 2022; PN-EN 13055-1:2016-07).

Predicting the load-bearing capacity of construction elements under various loads is crucial for efficient and economical structures. While experimental methods provide valuable insights, they are time-consuming and costly, making them impractical for larger or more complex structures. Thus, alternative methods like the finite element method (FEM) are employed. FEM, a numerical approach, uses material nonlinearities for precise predictions of complex destructive behaviours (Demir et al., 2016; Enem et al., 2012; Kisała, 2014; Samir & Chris, 2005). The advancement in computational sciences has popularised FEM software like ANSYS or ABAQUS (Bacinskas et al., 2022; Yu et al., 2020).

The growth in computational power and numerical analysis allows for a more accurate representation of structural static work. Advanced software effectively simulates structural responses, closely mirroring laboratory test results (Enem et al., 2012; Kisała, 2014; Kisała, 2016; Samir & Chris, 2005). However, experimental data remains valuable for understanding FEM software effects.

In recent years, both numerical and experimental testing on reinforced concrete beams' response has expanded. Studies like Wolanski's (Wolanski, 2004) utilised ANSYS to test the bending response of reinforced and compressed concrete beams, comparing FEM results with Buckhouse's experimental findings (Buckhouse, 1997). However, digital models for reinforced concrete elements with waste plastic aggregate are scarce.

The paper presents the use of an all-plastic alternative aggregate. It is not PET, PP, HDPE LDPE or ABS plastic, which have usually been used in studies. Our aggregate was made from a mixture of polymers, i.e. PET/OPS/PVC. In addition, in the first publications, we used an oval-shaped aggregate, while after analysing the research, we found that tests should be performed on samples with broken aggregate. As a result of the mechanical treatment of the aggregate, a more porous surface was obtained, so the contact between the aggregate and the cement slurry was improved. As a result, the study showed better mechanical properties of the concrete.

In addition, it should be noted that a number of available publications present studies with partial replacement of natural aggregate, e.g. up to 25%, because as the waste used in concrete increases, the mechanical properties of concrete decrease. Only note that the waste used was in the form of, for example, PET flakes, which do not approach the shape of natural aggregate.

The current publication replaces 100% coarse aggregate, while it should be noted that work is also underway to replace 100% of all aggregates in the concrete mix, including the 0-2 mm fraction, in order to use all fractions of the obtained raw material from plastic waste, without creating new waste in the form of, for example, the 0-2 mm fraction.

Studies of shrinkage and creep are planned for the next stage of work, which is related to the use of plastic waste mix.

A comparative analysis of the numerical model with experimental studies showed that the work on the model should be continued, and the reviewer's comments should be followed regarding the modelling of the effect of concrete drawing as well as shear.

This study involved testing lightweight aggregate reinforced concrete beams in two phases: experimental and computational. The experimental phase was conducted at Bialystok University of Technology's Laboratory of the Department of Building Structures, focusing on concrete properties and reinforced concrete beam testing. The computational phase involved modelling and simulating the same beams using ANSYS software (ANSYS Inc., 2013), based on FEM with nonlinear analysis. The study concludes with a discussion comparing results to formulate conclusions.

Methods and Materials

Properties of lightweight concrete

Studies concerning the density of concrete, its compressive strength, and the modulus of longitudinal elasticity were performed. Three series of tests were performed, which were marked as Certyd (CER), LECA (LEC), and aggregate from plastic waste (PWA).

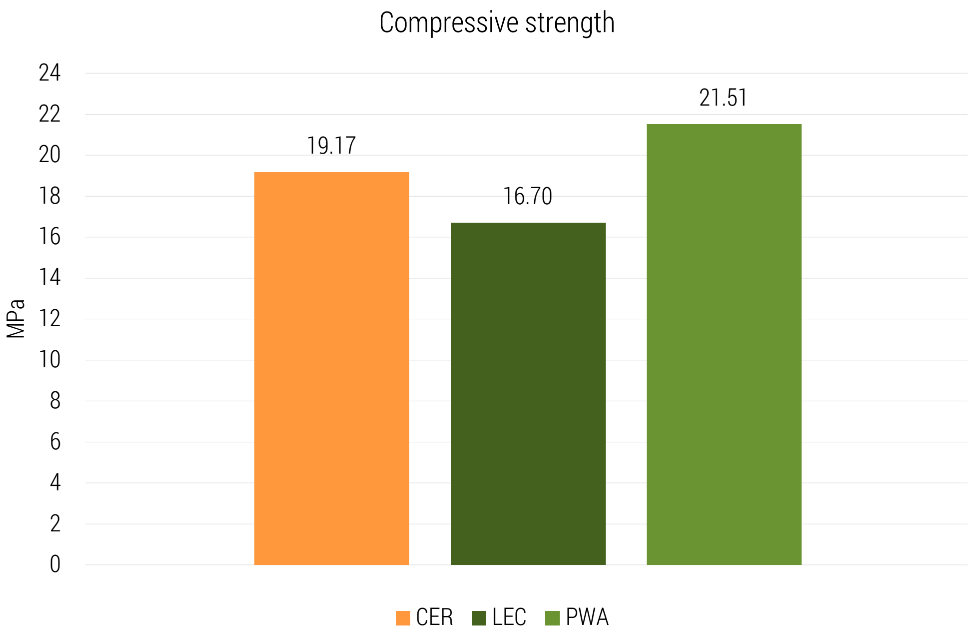

Figure 1. Results of the compressive strength tests of lightweight concrete after 28 days

Samples were prepared in accordance with the standard (PN-EN 12350-1:2019-07) and the formulations presented above were matured for 28 days and then their properties were tested, including the compressive strength of the concrete, pursuant to the standards (PN-EN 206+A2:2021-08; PN-EN 12390-3:2019-07), whose results are presented in Figure 1.

Figure 1 shows that the compressive strength of lightweight plastic waste aggregate concrete is 12% higher than Certyd aggregate concrete and 29% higher than LECA aggregate concrete, at a cement content of less than 44% compared to plastic aggregate concrete.

Figure 2. Results of the density tests of lightweight aggregates

Testing of the density of lightweight concretes (Figure 2) was performed in accordance with the standards (Bujnarowski & Grygo, 2022) and showed that LECA aggregate concrete has the highest density, i.e. 1750 kg/m^3. This value is 16% higher than plastic waste aggregate concrete.

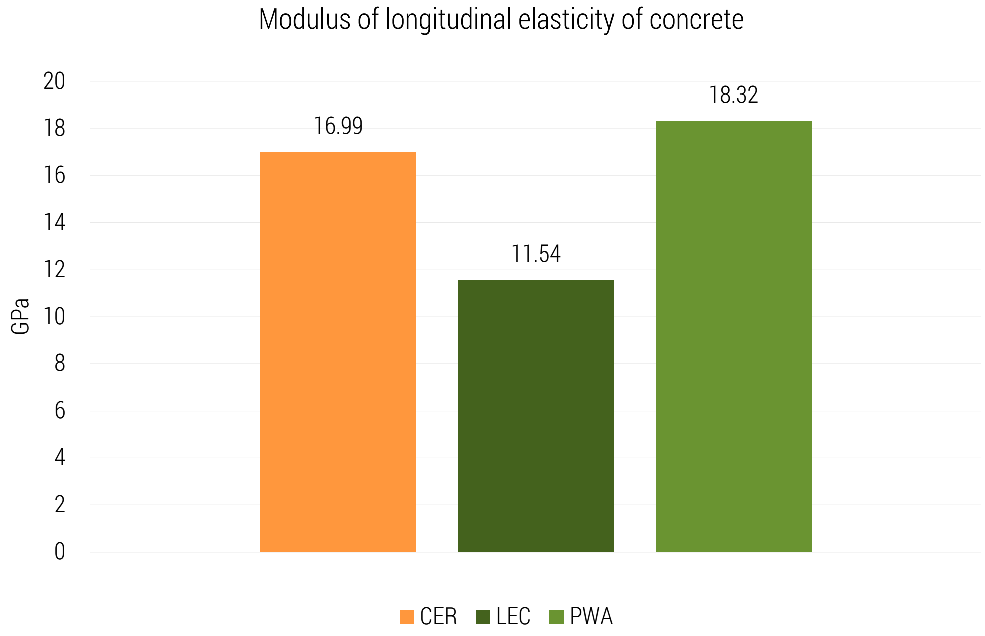

Figure 3. Modulus of longitudinal elasticity of concretes

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Testing of the modulus of longitudinal elasticity (Figure 3), performed pursuant to the standards (PN-EN 12390-13:2021-12), showed that the lowest value was obtained for LECA lightweight aggregate concrete (11.54 GPa). The greatest stiffness, on the other hand, was obtained for lightweight plastic waste aggregate concrete, i.e. 18.32 MPa.

Description of the analysed elements/reinforced concrete beams

Reinforced concrete beams with dimensions of 80×120×1100 mm were used for the tests. They were made of lightweight concrete based on the following three aggregates: LECA, Certyd, and plastic waste. The beams were differentiated according to their degree of reinforcement, which was ρ=1.02% and ρ=1.78%.

The reinforcement consisted of 2×6 mm top-ribbed bars and the following bottom-ribbed bars: 3×6 mm for the degree of reinforcement ρ=1.02%, and 3×8 mm for the degree of reinforcement ρ=1.78%. The stirrups were made from 3 mm diameter bars. Figure 4 shows the reinforcement scheme of the reinforced concrete bars.

The properties of the concrete used for the numerical calculations were adopted from the authors' own experimental studies performed in the Laboratory of the Department of Building Structures of the Bialystok University of Technology. The properties of the reinforcing steel were adopted as being the same as those for B500SP grade steel (EPSTAL, 2022).

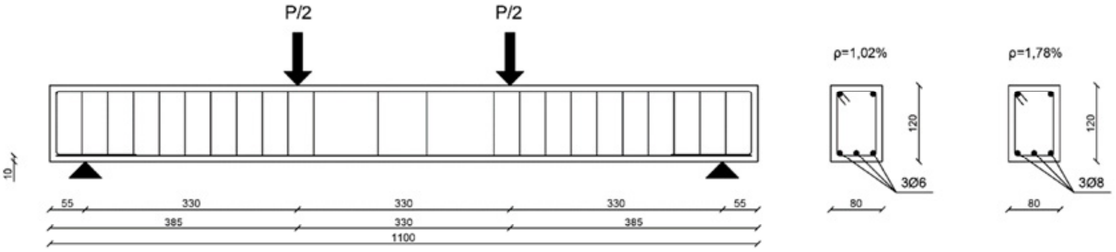

Figure 4. Static scheme and the arrangement of reinforcement in reinforced concrete beams

Experimental testing procedure

The loading procedure for a beam element is specified in the standards (PN-EN 12390-5:2009) i.e. the strength of the force was increased, and recordings of the deflections and deformations were performed for every 2 kN added.

The loading force was transmitted and measured by the CONTROLS destructive testing device. Deflections were measured using electronic sensors with an accuracy of 0.001 mm. Concrete deformations were measured for the beams using DEMEC-type sensors with a base of 300 mm.

With increased loading force, the bending moment caused by the load transferred by the upper rollers of the crosshead acted on the beam (Figure 5). The four-point bending system consisted of two upper rollers supported by a transverse articulate element dividing a given load equally between these rollers and two supporting rollers. The loading rollers could rotate freely.

Before commencing the experimental tests, the laboratory equipment and the tested elements were cleaned of contamination. Excess surface moisture was removed from the samples stored in water before they were placed in the machine. Each sample was placed in such a way as to be centred properly, ensuring that the direction of loading was perpendicular to the direction of sample forming (Enem et al., 2012).

The tests did not begin until all the supporting and loading rollers stuck to the sample in the same manner. A constant rate of load increase was determined at 0.06-0.04 MPa/s. After using the initial force, which did not exceed 20% of the destructive load, the sample was loaded without vibrations, and the force was increased at the selected rate ± 10%, until the sample was unable to transfer a higher load. The appropriate loading rate for the two-point test was determined using the following equation (PN-EN 12390-5:2009):

$$R = \frac{s \cdot d_1 \cdot d_2^2}{l}. \tag{1}$$

where:
s – load increase rate, in MPa/s,
d_1 and d_2 – transverse dimensions of the sample, in mm,
l – span between the bottom rollers, in mm.

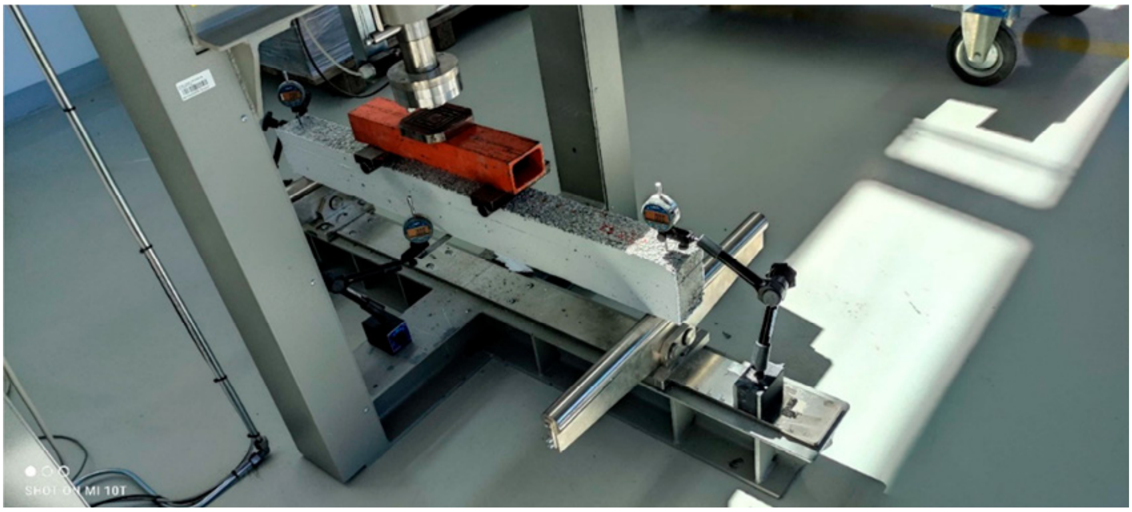

Figure 5. Reinforced concrete beam during compressive strength tests

Table 1. Load bearing capacity of the tested reinforced concrete beams

Series	Destructive force [kN]	Ultimate moment [kNm]
CER ρ=1.02%	36.04	6.01
LEC ρ=1.02%	29.57	4.93
PWA ρ=1.02%	32.75	5.46
CER ρ=1.78%	47.49	7.91
LEC ρ=1.78%	42.39	7.06
PWA ρ=1.78%	42.32	7.05

Characteristics of the model of the reinforced concrete beam in ANSYS computing software

The calculation model was designed with the same dimensions as the reinforced concrete elements used for the experimental tests. The analysed beam was modelled as being freely supported. A FEM mesh with a size of 20 mm was designed in the computing element. Figure 6 shows the mesh generated on the tested numerical model, and Figure 8 shows the place where the load was applied. A model of the beam reinforcement is presented in Figure 9.

A loading step of 2 kN was adopted for the calculations. The duration of the loading application was unmodified in order to optimise the computing power required by ANSYS computing software. The loading steps for the numerical model of the beam (Figure 7) are presented in Table 2.

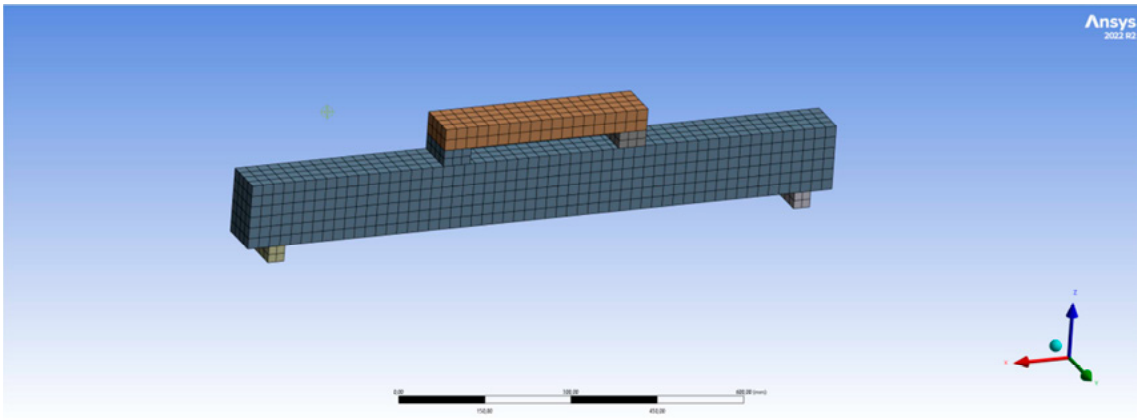

Figure 6. The FEM mesh generated in the beam's calculation model

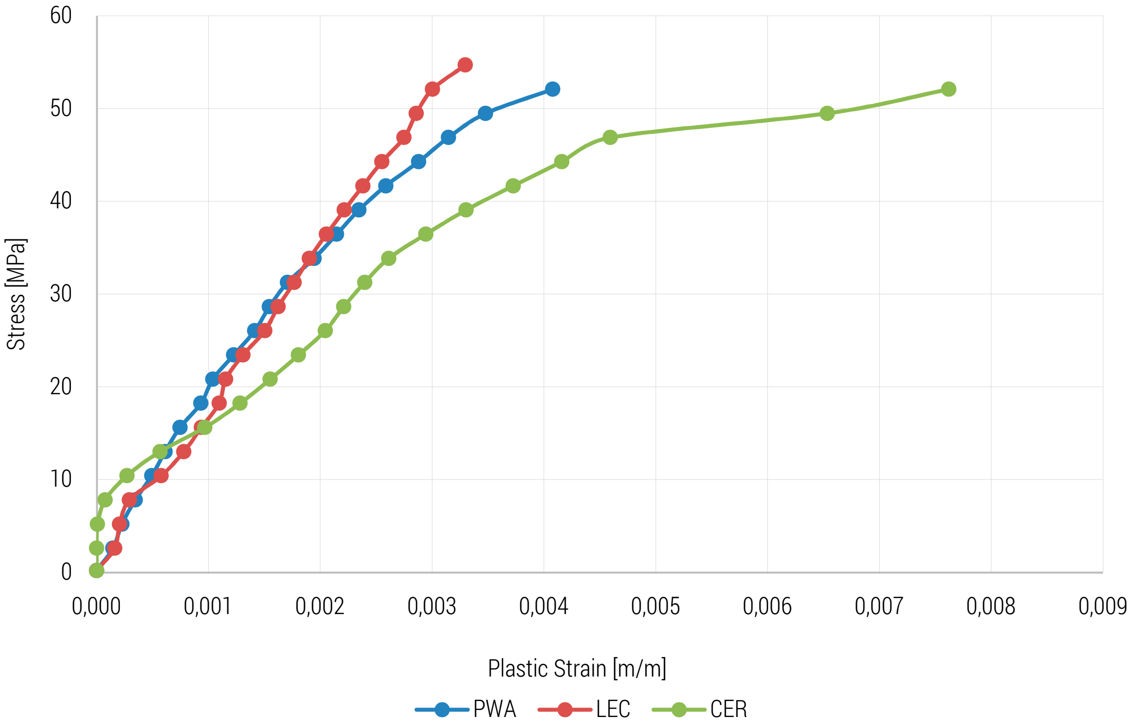

Figure 7. Stress-strain values adopted for numerical calculations for concrete

Table 2. Beam loading steps in ANSYS software

Time [s]	Force [N]
0	0
1	2000
2	4000
3	6000
4	8000
5	10000
6	12000
7	14000

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Time [s]	Force [N]
8	16000
9	18000
10	20000
11	22000
12	24000
13	26000
14	28000
15	30000
16	32000
17	34000
18	36000
19	38000
20	40000

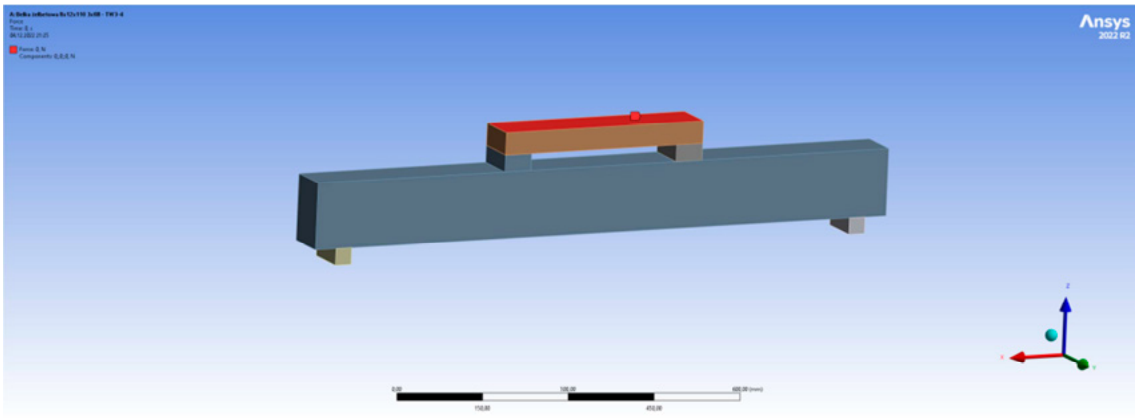

Figure 8. The place where the load was applied is marked in red

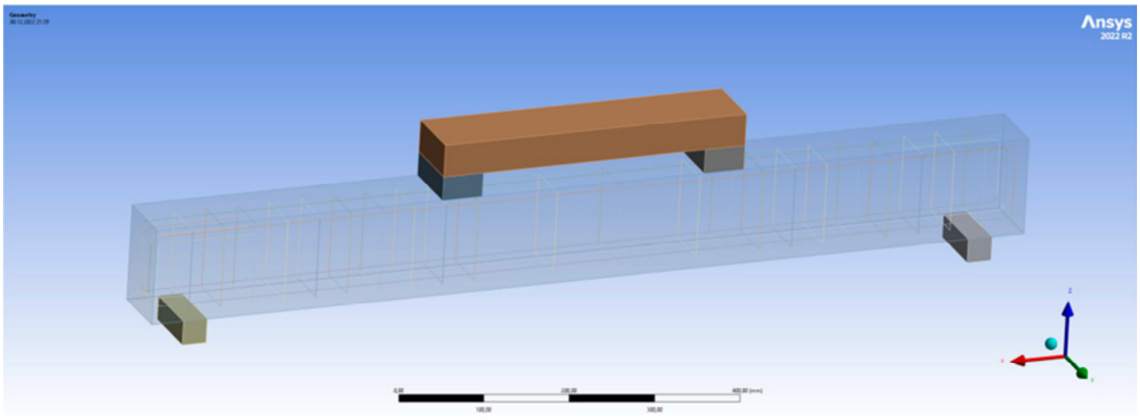

Figure 9. Model of the reinforcement of a beam with a degree of reinforcement of ρ=1.78%

The properties of the concrete obtained in the experimental tests were adopted for the numerical calculations, considering the tension-deflection value, which is presented in Table 3-5. The properties of the reinforcing steel were adopted as for B500SP grade steel.

Table 3. Defined properties of concrete with aggregate from plastic waste in the digital model

Models made of concrete made on aggregate from plastic waste (PWA)		
Density	1510	kg/m^3
Young's Modulus	18.32	GPa
Poisson's Ratio	0.2	-
Tensile Ultimate Strength	3.2	MPa
Compressive Ultimate Strength	21.51	MPa

Table 4. Defined properties of concrete using LECA aggregate in digital model

Models made of concrete made on LECA aggregate (LEC)		
Density	1750	kg/m^3
Young's Modulus	11.54	GPa
Poisson's Ratio	0.2	-
Tensile Ultimate Strength	2.03	MPa
Compressive Ultimate Strength	16.70	MPa

Table 5. Defined properties of concrete using CERTYD aggregate in digital model

Models made of concrete made on CERTYD aggregate (CER)		
Density	1565	kg/m^3
Young's Modulus	16.99	GPa
Poisson's Ratio	0.2	-
Tensile Ultimate Strength	2.59	MPa
Compressive Ultimate Strength	19.17	MPa

Results and Discussion

Deflections of the tested reinforced concrete beams at mid-span were compared. The beams were modelled with the following degrees of reinforcement: ρ=1.02% and ρ=1.78%. Deflections of the models of the beams are shown in Figures 10-11.

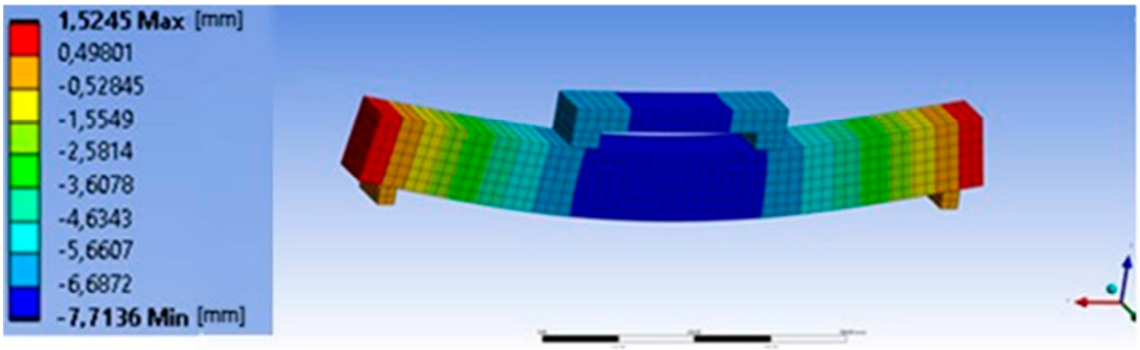

Figure 10. Map of deflection of the computational model for PWA beam with a degree of reinforcement of ρ=1.02%

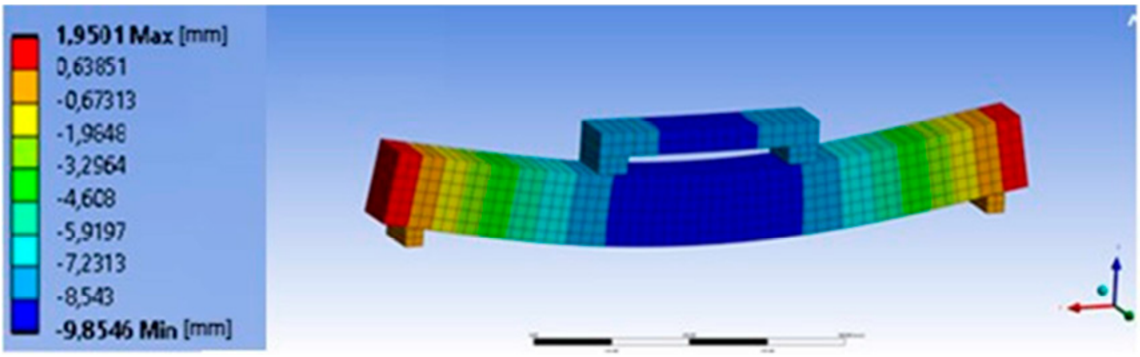

Figure 11. Map of deflection of the computational model for PWA beam with a degree of reinforcement of ρ=1.78%

The graphs in Figures 12-17 show comparisons of the deflections of lightweight aggregate reinforced concrete beams obtained in the experimental tests and the numerical analysis. The graphs also illustrate standard deviations for the deflections obtained in the experimental testing of reinforced concrete beams.

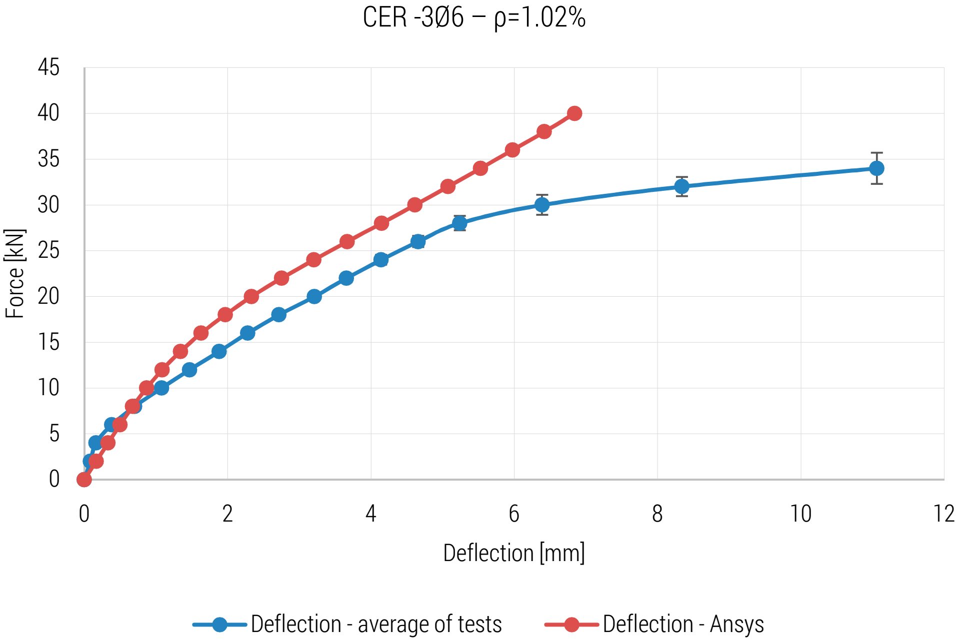

Figure 12. Comparison of the deflection values – CER reinforced concrete beams

Considering the above graph (Figure 12), it is worth noting that the deflections overlap, up to and including a force of 8 kN. With increasing load, however, the results increasingly diverge by as much as 38% just prior to the beam's destruction.

In the above case, the deflections overlap for a force of 10 kN (Figure 13). However, as was the case with the Certyd beam with a degree of reinforcement of ρ=1.02%, with increasing load, a significant divergence of results occurs (by as much as 61%) just before the destructive phenomenon takes place.

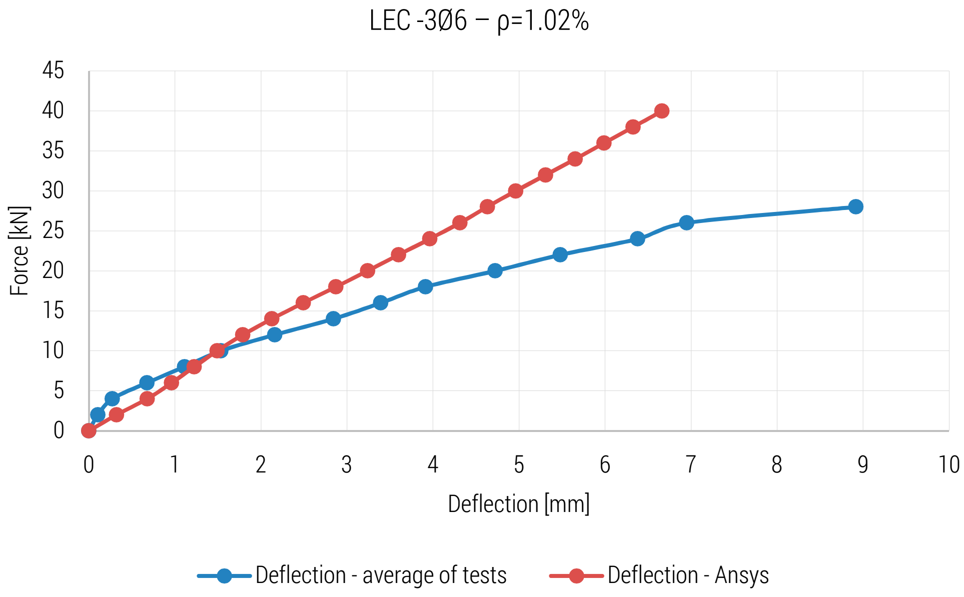

Figure 13. Comparison of the deflection values – LEC reinforced concrete beams

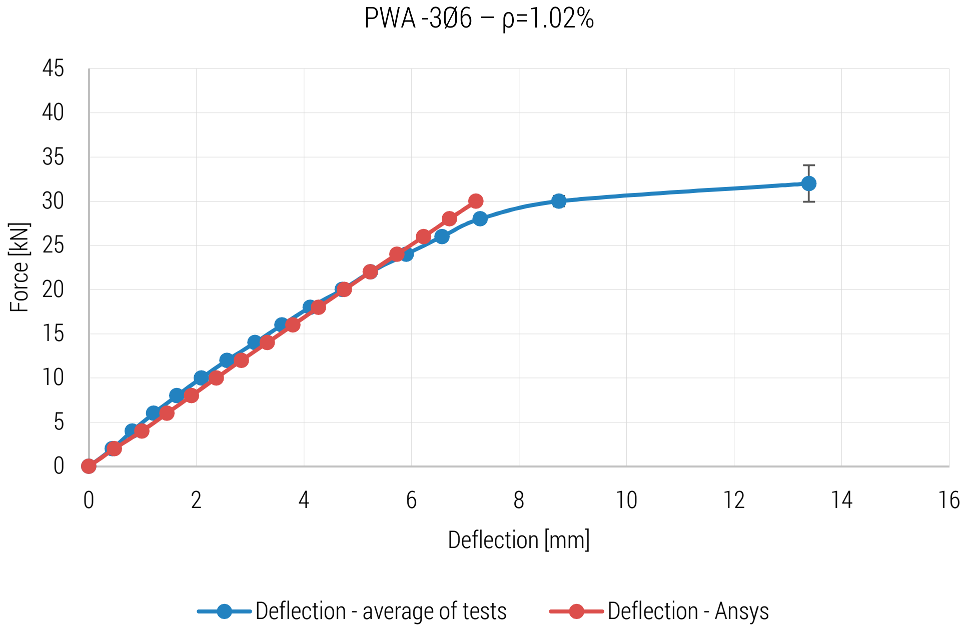

Figure 14. Comparison of the deflection values – PWA reinforced concrete beams

In the case of the reinforced concrete beam made of lightweight plastic waste aggregate, with a degree of reinforcement of ρ=1.02%, the results for deflection at mid-span, obtained from the experimental tests and the numerical analysis, largely overlapped (Figure 14). It should be noted that the discrepancy between the results obtained using both methods was as little as 8.5% just before the reinforced concrete element developed yield.

In the case of the reinforced concrete beam made of Certyd aggregate, with a degree of reinforcement of ρ=1.78%, the deflection results obtained using both methods largely overlapped (Figure 15). The value of deflection just before the reinforced concrete beam developed yield and was destroyed was 6.93 mm.

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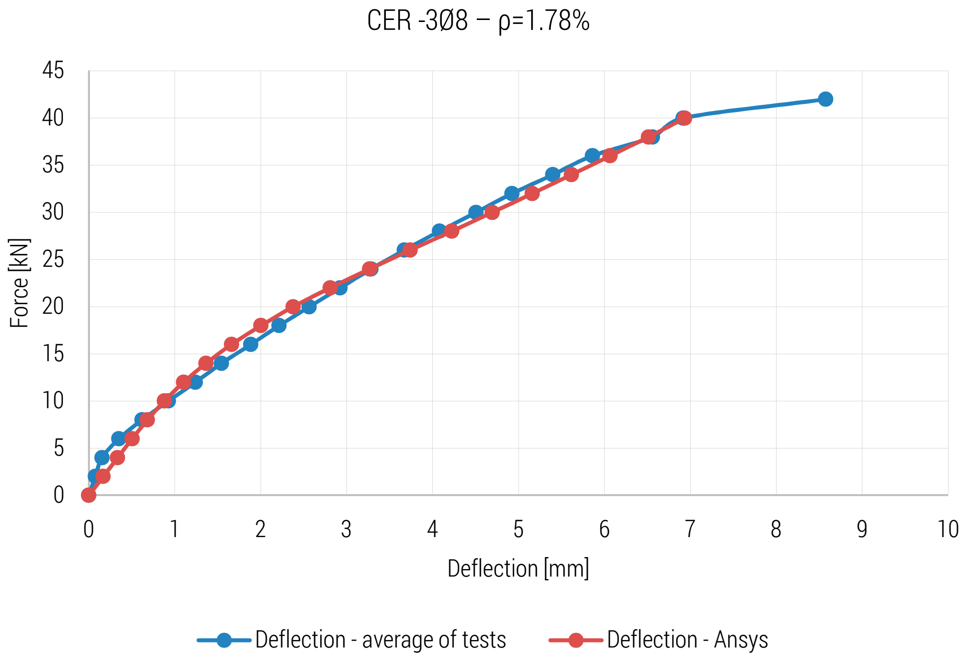

Figure 15. Comparison of the deflection values – CER reinforced concrete beams

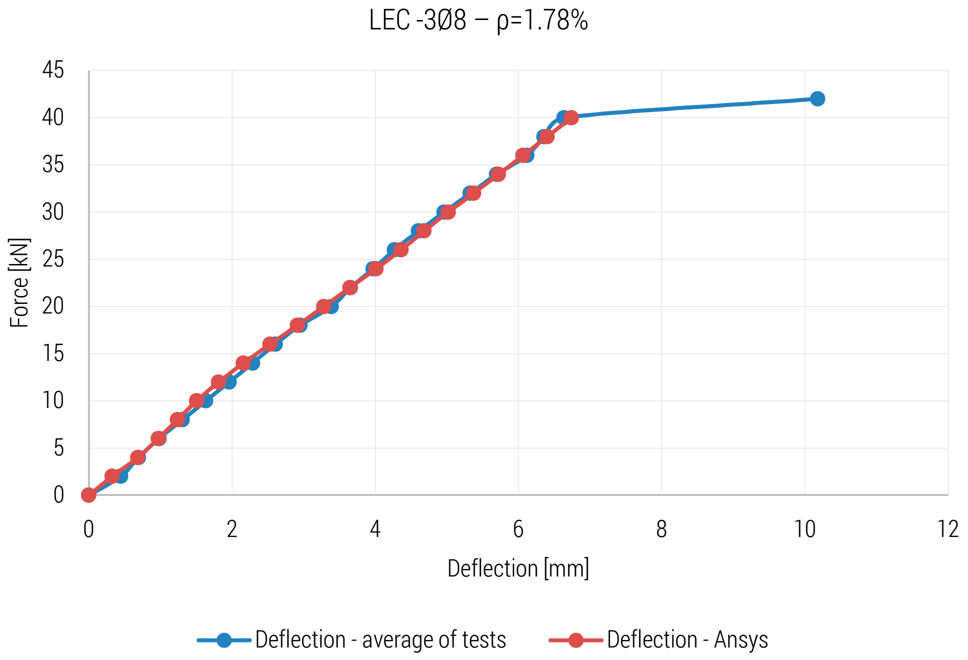

Figure 16. Comparison of the deflection values – LEC reinforced concrete beams

For reinforced beams made of lightweight concrete made of LECA aggregate, deflections also overlapped (by 6.74 mm) just before beam destruction (Figure 16).

In the case of reinforced concrete beams made of plastic waste aggregate, with a degree of reinforcement of ρ=1.78%, the results for deflections obtained in the experimental tests and the numerical analysis differed by as much as 20%. The value of deflection just before destruction was 9.85 mm (Figure 17).

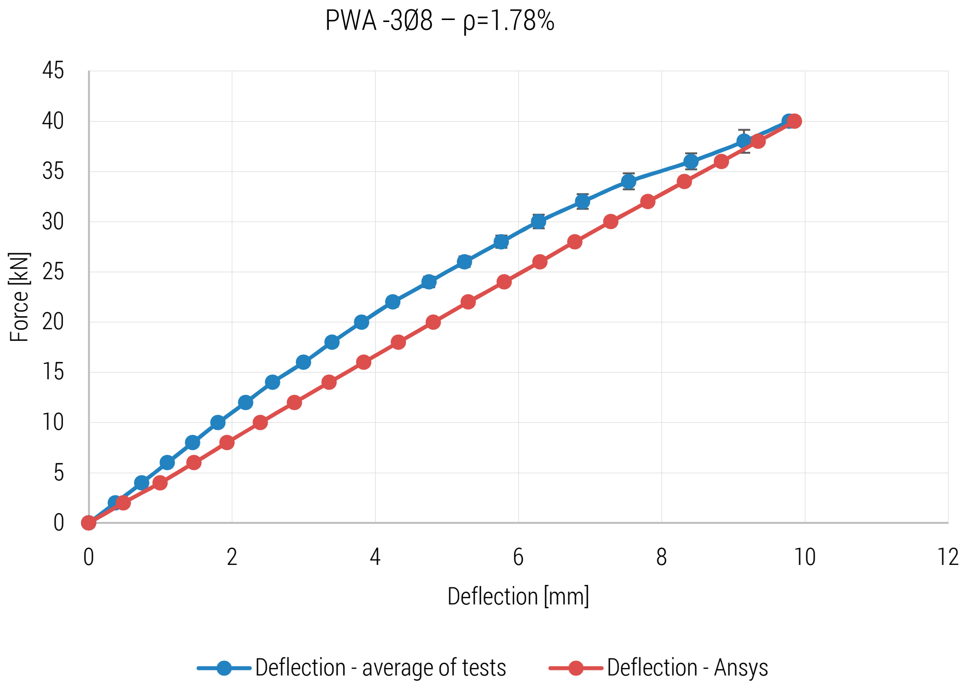

Figure 17. Comparison of the deflection values – PWA reinforced concrete beams

Conclusions

The aim of the article was to determine and compare deflections of reinforced concrete beams with degrees of reinforcement of ρ=1.02% and ρ=1.78% at the mid-span. Two methods were used for the determination of deformations of reinforced concrete beams: the experimental method, in which destructive tests were performed pursuant to standards (PN-EN 12390-5:2009) and the computational method in which ANSYS software was used. The finite element method (FEM) was used for the calculations.

On the basis of the results obtained in the experimental tests and the numerical analysis, the following conclusions were formulated:

- Testing of the concrete properties shows that the compressive strength of the concrete samples made of Certyd, LECA, and plastic waste aggregates was 19.17, 16.70, and 21.51 MPa, respectively. The greatest compressive strength was noted for the plastic waste aggregate concrete, which was 29% higher, compared to LECA-based samples, at a 44% lower cement content.
- The value of concrete density, determined pursuant to the standards (PN-EN 12390-7:2019-08), was the lowest for plastic waste concrete, i.e. 1510 kg/m^3. The lowest modulus of elasticity, however, was obtained for the LECA aggregate concrete and was 11.54 GPa.
- The difference between the experimental tests and the computational methods for reinforced concrete beams with a degree of reinforcement of ρ=1.02% was at its highest in the case of LECA aggregate beams. The obtained values of deflection at mid-span differed by as much as 61%. On the other hand, the lowest value and, thus, the most accurate model was obtained for plastic waste-reinforced concrete beams (8.5%) just before beam destruction.
- Overlapping deflection values were obtained in the case of Certyd and LECA reinforced concrete beams with a degree of reinforcement of ρ=1.78%. The difference between the values of deflection obtained with the use of both methods for elements made of plastic waste aggregate, on the other hand, was 20%.

Based on these conclusions, further work on the computational model designed for plastic waste aggregate needs to be continued in order to improve the accuracy of the obtained results and make the interested designers' task easier. An accurate computational model would contribute to a greater interest in innovative plastic waste aggregate compared to other lightweight aggregates.

The Plastics Europe – Plastics – the Facts 2022 (Plastics Europe, 2022) report shows that global plastic production is constantly growing, up 6% from 2018. The use of plastic waste aggregate in concrete will contribute to significant waste management, reducing the amount of waste lying in landfills and going to incinerators. In addition, the aggregate has a much smaller carbon footprint because it is processed at a much lower temperature compared to other light-weight aggregates, which are baked at around 1,000 degrees Celsius.

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The contribution of the authors

Conception, R.G., K.B. and J.A.P.; literature review, R.G., K.B. and J.A.P.; experimental research, R.G. and K.B.; analysis and interpretation of data, R.G., K.B. and J.A.P.

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WYKORZYSTANIE ODPADÓW Z TWORZYW SZTUCZNYCH DO PRODUKCJI LEKKIEGO KRUSZYWA DO KONSTRUKCJI ŻELBETOWYCH

STRESZCZENIE: W artykule porównano ugięcia belek żelbetowych o stopniu zbrojenia ρ=1,02% i ρ=1,78%, wykonanych z lekkich kruszyw, tj. Certyd, LECA i innowacyjnego kruszywa wykonanego z odpadów tworzyw sztucznych. Do porównania wykorzystano dwie metody: eksperymentalną i obliczeniową. Część obliczeniowa została wykonana przy użyciu metody elementów skończonych (MES) w oprogramowaniu ANSYS. Przyjęte właściwości betonów lekkich pochodziły z badań eksperymentalnych autorów. Porównanie ugięć na podstawie danych uzyskanych za pomocą obu metod wykazało, że dla elementów żelbetowych o stopniu zbrojenia ρ=1,02% najmniejszą różnicę uzyskano w przypadku belek wykonanych z betonu z odpadów tworzyw sztucznych, natomiast największą różnicę uzyskano dla belek wykonanych z betonu z lekkim kruszywem keramzytowym. W przypadku elementów żelbetowych o stopniu zbrojenia ρ=1.78% najmniejsze różnice uzyskano dla belek wykonanych z kruszyw lekkich, tj. Certyd i LECA. W przypadku belek, w których zastosowano kruszywo z odpadów tworzyw sztucznych, różnica wyniosła 20% w porównaniu z badaniami eksperymentalnymi.

SŁOWA KLUCZOWE: kruszywa sztuczne, kruszywa z tworzyw sztucznych, recykling, testy eksperymentalne, analiza numeryczna, oprogramowanie ANSYS

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