

Robert **GRYGO** • Kevin **BUJNAROWSKI** • Jolanta Anna **PRUSIEL**

ANALYSIS OF THE POSSIBILITY OF USING PLASTIC POST-PRODUCTION WASTE IN CONSTRUCTION

Robert **Grygo** (ORCID: 0000-0002-2522-4313)

Kevin **Bujnarowski** (ORCID: 0000-0002-6471-8180)

Jolanta Anna **Prusiel** (ORCID: 0000-0001-6827-1059)

*Białystok University of Technology, Faculty of Civil Engineering
and Environmental Sciences*

Correspondence address:

Wiejska Street 45E, 15-351 Białystok, Poland

e-mail: j.prusiel@pb.edu.pl

ABSTRACT: This paper presents the possibility of managing plastic post-production waste, i.e. ordinary and heat-shrinkable film, in the construction sector. For this purpose, two types of lightweight 16 mm aggregate were produced from plastics using proprietary technology (i.e. polyethylene terephthalate (PET) and PET/PVC/OPS (MIX) mixtures). The raw material was sourced from post-production waste generated during the production of film labels. The results of the experimental testing of aggregate properties (bulk density, grain density, absorbability, compressive strength) are presented, the aggregate being sourced from recycled plastics. This paper presents the physical and mechanical properties of the plastic, as well as other popular lightweight aggregates (Certyd and Kermazyt) used in construction. In addition, the financial efficiency of lightweight aggregate production from the by-products of plastic label production was analysed. The economic analysis has shown that the use of plastic waste for the production of lightweight aggregate is rational, not only in terms of environmental protection but also the financial benefits to companies that generate significant amounts of plastic waste.

KEYWORDS: PET waste; aggregate; recycling; artificial lightweight aggregates; economic analysis

Introduction

Plastics were designed to replace natural resources. Since then, they have been shaping the world, ensuring safety, hygiene, comfort, and social well-being.

Modern plastics are currently manufactured in endless varieties of products and uses, making it possible to reduce energy consumption, CO₂ emissions, and water consumption. They also make an important contribution to the idea of a 'closed-loop' and prevention of climate change. However, in order to fully exploit the potential of these materials, it is necessary to minimise their landfilling by reusing them, e.g. in the industrial sector.

The 'Plastics 2030' voluntary commitment (Plastics Europe, 2022) elevated the plastics industry to the next level of engagement through the establishment of ambitious goals and initiatives aimed at preventing plastics from entering the environment, improving the degree of reusing and recycling of waste (in the form of plastic containers), and offering benefits for the efficient management of natural resources.

The technical data in Figure 1 (sourced from 2018) concerning the European and worldwide production of plastics shows that as much as 348 million tons of plastics were produced worldwide in 2017, of which 64.4 million tons came from Europe (Plastics Europe, 2022). The trend of plastics production is upward, with an increase of 11 million in 2018, compared to 2017. However, it should be noted that there was a reduction in plastic production in Europe by approximately 4%.

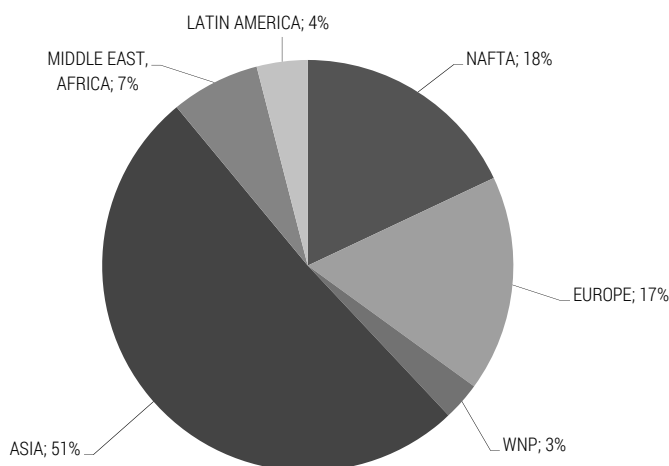


Figure 1. The proportional share of continents in the production of plastics

Source: Plastics Europe, 2022.

The market analysis presented in Figure 2 shows that, in the years 2006-2018, the recycling of plastics increased each year, with an increase of 100% since 2006 (9.4 million tons). On the other hand, Landfilling decreased by as much as 44%, yet it is still relatively high at 7.2 million tons (Plastics Europe, 2022).

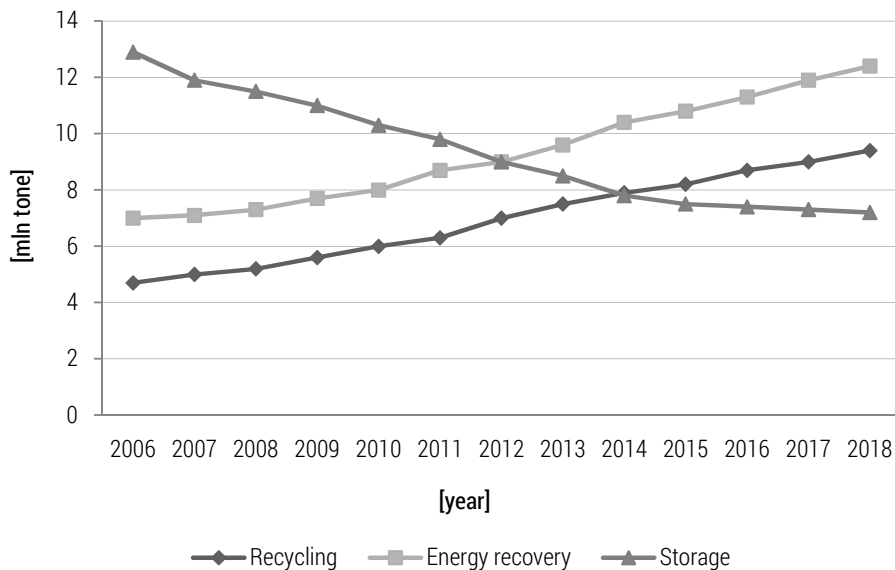


Figure 2. Management of post-consumer plastic waste in the years 2006-2018 (million tons)
Source: Plastics Europe, 2022.

In Poland, the recycling rate of plastic waste is as low as 26.8%, while 44.1% (759 thousand tons) of waste is landfilled; the rest is used in energy recovery (Sokołowski, 2020).

Marine litter is a global problem, and the fact that waste, including plastic waste, enters the natural environment is unacceptable. Plastics are a valuable resource, providing society with many benefits and offering solutions consistent with the principles of sustainable development in various sectors. One of the examples presented in this paper is the possibility of using plastic waste in the construction sector.

The technology of production of artificial aggregate

Two series of plastic aggregates, with a 16 mm fraction, i.e. PET (polyethylene terephthalate) and a PET/PVC/OPS mixture, were produced (Szlezyn-gier & Brzozowski, 2015; PLASTEM, 2022). The raw material was sourced from post-production waste generated during the production of film labels.

A single-screw extruder with a screw diameter of 25 mm, four heating zones, and a gravity feed was used for the production of aggregate. In the first stage of production, strips of film were shrunk under the influence of increased temperature in order to obtain a pre-densified raw material. A plastic mill was then used, which made it possible to obtain a fine fraction (approximately 5 mm diameter). The drying of plastic was performed for 4 hours at a temperature of 120°C (Figure 3) (Wilczyński, 2011). The final stage consisted of re-melting the plastic waste until a light aggregate (with a fraction of 16 mm) was obtained (Figure 4 and Figure 5).



Figure 3. Drying stage of milled plastic to reduce its moisture content

Source: author's work.

The goal was to obtain an optimised process of production (i.e. reduced energy consumption without the need to flush contamination from the original material), which is required for the reduction of landfilled plastic waste

and its successful use in construction concrete. This makes it possible to produce an innovative light aggregate, which constitutes an alternative to traditional raw materials, e.g. Keramzyt and Certyd.



Figure 4. Aggregate produced from PET film
Source: author's work.



Figure 5. Aggregate produced from a mixture of PET, PVC, and OPS films
Source: author's work.

Methods and Materials – Research procedures and properties of the produced light aggregate

Tests for bulk density were performed according to PN-EN 1097-3:2000. Absorbability and grain density were tested according to PN-EN 1097-6:2013-11. The compressive strength of the plastic aggregate was tested according to PN-EN 13055:2016-07.

Bulk density

The apparatus used for testing the bulk density of the aggregate was compliant with the general requirements of PN-EN 932-5:2012.

Before commencing the tests, aggregate samples were dried at a temperature of $110 \pm 5^\circ\text{C}$ to constant weight. An empty cylindrical container was weighed and then filled with aggregate to overflow. The excessive amount of aggregate was removed from the upper surface of the container. The last stage consisted of weighing the filled container and recording its mass, with an accuracy of 0.1%. This was determined for three aggregate samples (PN-EN 1097-3:2000, PN-EN 932-5:2012).

According to PN-EN 1097-3:2000, the bulk density of aggregate in its loose state is calculated using Eq. (1):

$$\rho_b = \frac{m_2 - m_1}{V}, \quad (1)$$

where:

ρ_b – bulk density in a loose state,

m_2 – the mass of the container and tested sample,

m_1 – the mass of the empty container,

V – the volume of the container.

Table 1. Bulk density test results for plastic aggregate

Technical data			
Type of plastic	Grain diameter (mm)	Bulk density (kg/m ³)	Average (kg/m ³)
PET	8	648.89	648.40
		651.85	
		644.44	
PET	16	617.78	613.33
		613.33	
		608.89	
MIX (PET,OPS,PVC)	16	635.56	635.75
		638.52	
		633.19	

Source: author's work.

Grain density and absorbability

The testing of grain density and absorbability was performed according to PN-EN 1097-6:2013-11.

Grain density and absorbability tests were performed on aggregate with a 16 mm diameter grain size. Before commencing the tests, the samples were dried in a laboratory drier at a temperature of $110 \pm 5^\circ\text{C}$, to constant weight. Then a pycnometer with a funnel (Figure 6) and the first sample were weighed. The next step consisted of filling the pycnometer with water and weighing it after removing air bubbles, and refilling the water to the appropriate level. These actions were repeated after 24 h. The final stage consisted

of transferring the aggregate to an absorbent cloth, removing water from its surface and then weighing the tested sample (PN-EN 1097-6:2013-11).



Figure 6. Pycnometer for determining grain density and absorbability

Source: author's work.

According to PN-EN 1097-6:2013-11, grain density ρ_a and absorbability W_F are calculated using Eq. (2, 3):

$$\rho_{rd} = \rho_w \cdot \frac{M_4}{M_1 - (M_2 - M_3)}, \quad (2)$$

where:

- ρ_{rd} – specific density of aggregate,
- ρ_w – density of water in a temperature of 22°C,
- M_1 – the mass of saturated and air surface-dried aggregate,
- M_2 – the mass of pycnometer with a sample of saturated aggregate,
- M_3 – the mass of pycnometer filled with water only,
- M_4 – masa of analytical sample dried in a dryer.

$$W_F = \frac{M_W - (m_2 - m_1)}{(m_2 - m_1)} \cdot 100, \quad (3)$$

where:

- W_F – absorbability of light aggregate,
- m_1 – a mass of pycnometer, funnel, and net,
- m_2 – a mass of pycnometer, funnel, dry test sample, and net,
- M_w – a mass of dry surface aggregate in the final stage of measurement.

Table 2. Absorbability test results for plastic aggregate

Technical data		
Type of plastic	Absorbability (%)	Average (%)
PET	5.04	5.31
	5.67	
	5.23	
MIX (PET, OPS, PVC)	1.28	1.66
	1.94	
	1.76	

Source: author's work.

Table 3. Determination of grain density for plastic aggregate

Technical data		
Type of plastic	Grain density (kg/m ³)	Average (kg/m ³)
PET	1094	1114
	1146	
	1103	
MIX (PET, OPS, PVC)	1114	1101
	1092	
	1098	

Source: author's work.

Compressive strength

Testing of the compressive strength of the aggregate from plastic waste was performed according to PN-EN 13055:2016.

The pre-prepared sample of light aggregate was placed in a steel cylinder and densified by vibration. Then, a piston was placed on the upper surface of the aggregate. The depth to which the piston was pressed was set to 20 mm. Afterwards, the test set was placed in a hydraulic press, and the force exerted on the piston was increased so that it was pushed down 20 mm for approximately 100 s. Compressive strength was calculated using Eq. (4):

$$C_a = \frac{L + F}{A}, \quad (4)$$

where:

C_a – compressive strength of aggregate, determined according to the method I,

L – force exerted by the piston,

F – force necessary to press down the piston,

A – piston area.

Table 4. Results of compressive strength testing on plastic aggregate

Technical data		
Type of plastic	Grain diameter (mm)	Average compressive strength (MPa)
PET	8	5.30
PET	16	4.34
MIX (PET, OPS, PVC)	16	6.26

Source: author's work.

Results and Discussion

Comparison of properties of light aggregates

From the aggregates available on the market, CERTYD (Figure 7) was selected for comparison. CERTYD is a sintered fly ash aggregate produced by lightweight sintered aggregate technology through the autothermal sintering of waste sourced from CHP plants. The raw material is characterised by low bulk density, good thermo-insulating properties, frost resistance, and resistance to fungi, mould, and pests (Aggregate Certyd. 2022).



Figure 7. Certyd light aggregate

Source: author's work.

Moreover, Leca Keramzyt (Figure 8), a light ceramic aggregate, was also used for comparison. It is characterised by high thermal and acoustic insulation and owes its characteristics to its porous internal structure, enclosed in a rugged ceramic coating. Due to its properties, Leca Keramzyt aggregate is used in construction, e.g. for the insulation of ground floors, the structure of walls and ceilings, the insulation of ceilings and flat roofs, underground installations, drains, and floating tank covers (Leca LWA aggregate, 2022).



Figure 8. Keramzyt light aggregate

Source: author's work.

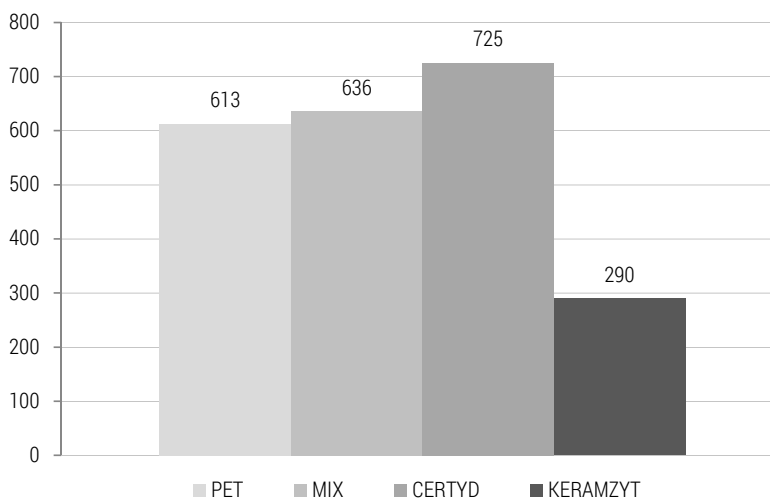


Figure 9. Comparison of bulk densities of selected light aggregates [kg/m³]

Source: author's work according to PN-EN 1097-3:2000.

When comparing the properties of CERTYD sintered fly ash aggregate, whose bulk density is 725 kg/m^3 , with the aggregate produced from plastic, it is clear that the innovative raw material is characterised by a bulk density which is lower, by as much as 15% (Figure 9). Moreover, bulk density can be reduced to 460 kg/m^3 by using a blowing agent (Grygo et al., 2021).

Table 5. Summary of grain densities for selected light aggregates (according to PN-EN 1097-6:2013-11)

Technical data		
Type of plastic	Grain density (kg/m^3)	Average (kg/m^3)
PET	1094	1114
	1146	
	1103	
MIX (PET, OPS, PVC)	1114	1101
	1092	
	1098	
CERTYD	1360	1360
KERAMZYT	1250	1250

Source: author's work.

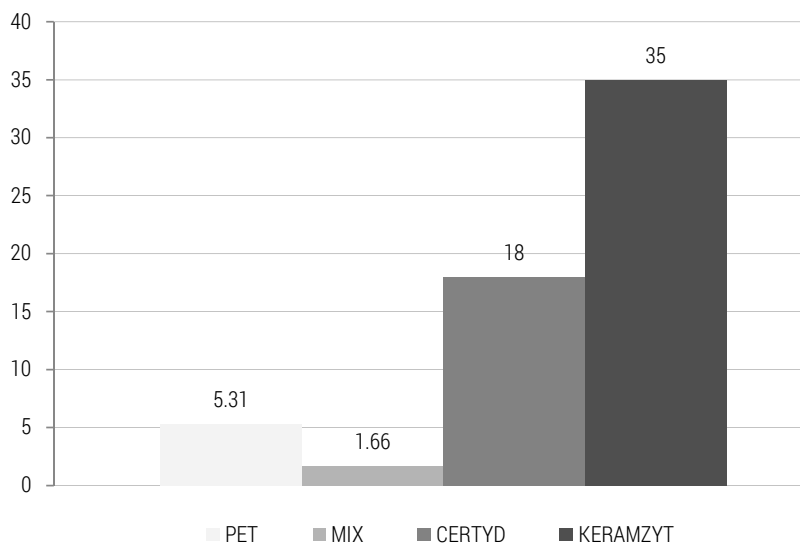


Figure 10. Comparison of absorbability for selected light aggregates [%]

Source: author's work according to PN-EN 1097-6:2013-11.

When comparing the values of grain density of sintered fly ash aggregate, whose density is 1360 kg/m^3 , and the aggregate produced from plastics, it is clear that the obtained material is characterised by a lower grain density, by as much as 20% (Table 5).

When comparing the absorbability of CERTYD sintered fly ash aggregate, whose absorbability is 18%, with the absorbability of the aggregate produced from MIX (PET/PVC/OPS) plastics, it is clear that the innovative raw material is characterised by an absorbability which is lower, by as much as 90% (Figure 10).

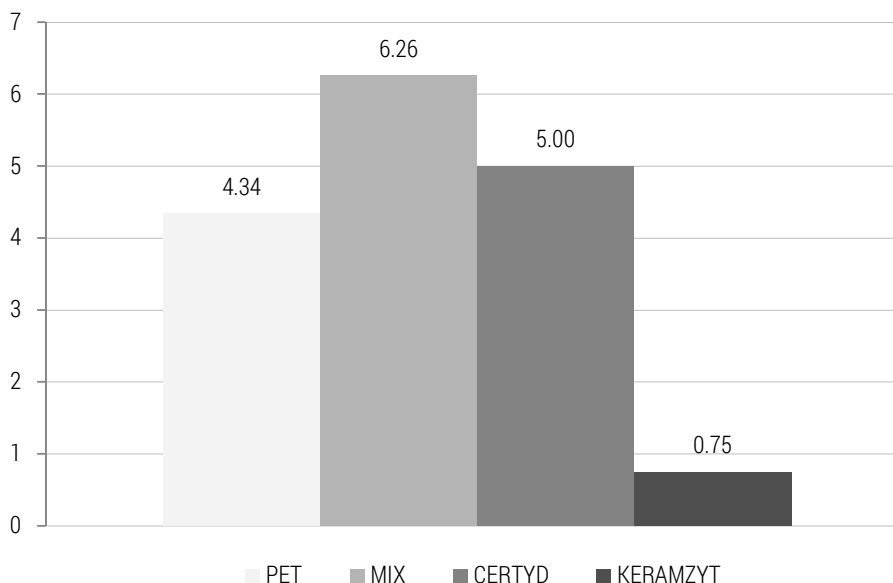


Figure 11. Comparison of compressive strength of light aggregates [MPa]

Source: author's work.

When comparing the compressive strength of CERTYD sintered fly ash aggregate, whose load-bearing capacity is 5 MPa, with the total produced from MIX plastics, it is clear that the produced material is characterised by a 25% increase in strength (Figure 11).

Economic analysis

To analyse the economic aspects, data collected from several companies that produce waste of the studied kind was used and statistical data. The appropriate amounts of energy consumed per hour, the number of processed plastics, and depreciation of the equipment necessary for its production were also included.

Data sourced from the companies showed that the monthly generation of waste from a single company was approximately 100 tons. The cost of waste plastic, on the other hand, was calculated in three variants, i.e. A – cost of waste purchased from recycling companies (2.40 PLN), B – cost of waste (0 PLN) and C – cost of waste (-0.50 PLN); companies that produce waste often pay for the disposal of post-production waste. The annual depreciation was 14% in the case of machines for the production of plastics and the chemical industry (Depreciation rates, 2022). The rate of electricity was fixed at 0.87 PLN/kWh (Electricity rates, 2022). The machine's performance for the calculations was 500 kg/h; however, due to maintenance and possible downtime, the actual productivity was adopted at 300 kg/h.

Moreover, information obtained from the producers of extruders showed that the average power consumption was 0.4 kW/kg. A summary of the production costs of the aggregate from plastic waste is presented in Table 6, while a comparison of the prices of the aggregates is shown in Figure 12. The analysis does not include operating, employee, or real estate costs.

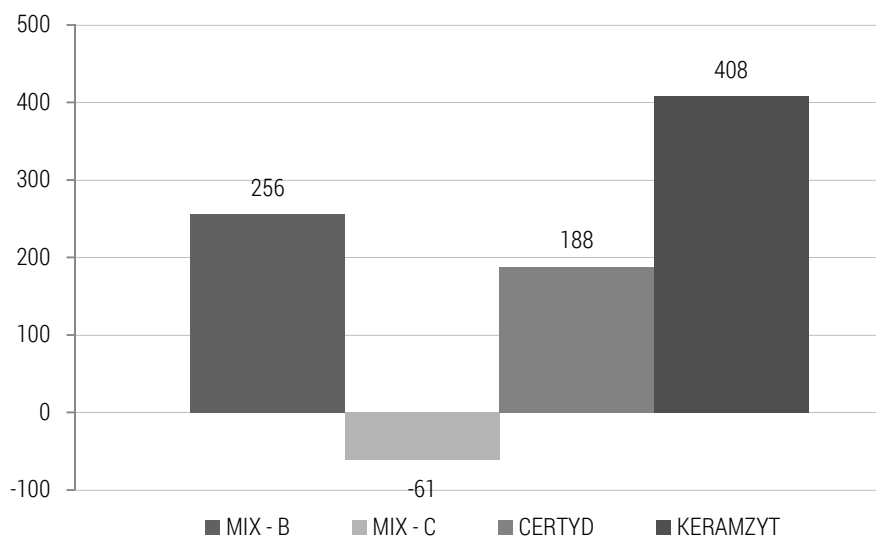


Figure 12. Comparison of costs of production of MIX aggregate with the market prices of CERTYD and KERAMZYT light aggregates [PLN/m³]

Source: author's work.

Table 6. Summary of production costs of 1 m³ of aggregate

Name	A		B		C	
	Consumption	Unit cost (PLN)	Consumption	Unit cost (PLN)	Consumption	Unit cost (PLN)
Energy	120 (kW)	0.87 (PLN/kWh)	120 (kW)	0.87 (PLN/kWh)	120 (kW)	0.87 (PLN/kWh)
Waste plastic	300 (kg/h)	2.40 (PLN/kg)	300 (kg/h)	0.00 (PLN/kg)	300 (kg/h)	-0.50 (PLN/kg)
Bulk density	635 (kg/m ³)					
Productivity	0.47 (m ³ /h)					
Depreciation	34.00 (PLN/m ³)					
Production costs	1780.13 (PLN/m ³)		256.13 (PLN/m ³)		-61.37 (PLN/m ³)	

Source: author's work.

When analysing the costs presented in Table 6 and Figure 12, it should be noted that the production of aggregate from plastic sourced from post-production waste is beneficial, not only because of the environmental aspects but because it can also compete on price with the light aggregates already on the construction market.

Conclusions

When comparing the summary of the values of bulk density for light aggregates presented in this paper, it should be noted that MIX aggregate is lighter than the aggregate produced from waste generated as a result of the combustion of hard coal by more than 10%. In addition, it is possible to obtain a lower bulk density by more than 35%. When analysing the density of light aggregate grains, a decrease of approximately 20% was also noted.

By far, the most significant advantage of MIX aggregate is its low absorbability, which is lower by over 90% in comparison with the competing light aggregates (Keramzyt, Certyd) used in construction. As a result, this enables the easier formation of architectural concretes and prefabricated elements by minimising the problem of adjusting the amount of water in the concrete mixture.

An additional benefit of aggregate from plastic waste is its compressive strength, which is greater by 25%. Owing to this, it is possible to build warm floors in residential and industrial buildings, contributing to reduced CO₂ emissions and heating costs.

Moreover, the economic analysis confirmed the possibility of using MIX aggregate in the construction sector. Variant C comprises the collection of waste from manufacturing companies and is the most beneficial, as it is pos-

sible to sell the aggregate, after production, for 0 PLN/m³, with a profit of 61.37 PLN/m³. Moreover, during the construction of buildings, attention should be paid not only to the product's price, but also to the benefits of its use, as a lower weight of construction elements translates to a reduction in cross-sections, which results in lower investment costs and shorter completion times.

Acknowledgements

The paper was prepared at the Bialystok University of Technology within a framework of the WZ/WB-IIL/4/2020 and WI/WB-IIL/1/2021 projects sponsored by the Ministry of Education and Science.

The contribution of the authors

Robert Grygo: conception – 50%, literature review – 40%, experimental research – 50%, analysis and interpretation of data – 40%.

Kevin Bujnarowski: conception – 30%, literature review – 40%, experimental research – 50%, analysis and interpretation of data – 40%.

Jolanta Anna Prusiel: conception – 20%, literature review – 20%, analysis and interpretation of data – 20%.

References

- Aggregate Certyd. (2022, January). <http://www.certyd.pl>
- Depreciation rates. (2022, January). <http://www.wskazniki.gofin.pl/8,210,1,roczne-stawki-amortyzacyjne.html>
- Electricity rates. (2022, January). <https://www.gkpge.pl/>
- Grygo, R., Prusiel, J. A., & Bujnarowski, K., 2021. Use of lightweight ecological aggregates in reinforced concrete structures. *Economics and Environment*, 79(4), p. 112–132, <https://doi.org/10.34659/2021/4/31>
- Leca LWA aggregate. (2022, January). <http://lecadom.pl/keramzyt>; Plastics – PET. <http://www.plastem.pl/oferta/tworzywa-sztuczne/pet/>
- PLASTEM. (2022, January). Plastics – PET. <http://www.plastem.pl/oferta/tworzywa-sztuczne/pet/>
- Plastics Europe. (2022, January). *Resources, market data*. <https://www.plastics-europe.org/pl/resources/market-data>
- PN-EN 1097-3:2000 Mechanical tests and properties of aggregate properties – Determination of bulk and voids properties.
- PN-EN 1097-6:2013-11 Tests for mechanical and physical properties of aggregates – Part 6: Determination of particle density and water absorption.
- PN-EN 13055:2016-07 Lightweight aggregates.
- PN-EN 932-5:2012 Tests for general properties of aggregates – Part 5: Common equipment and calibration.

- Sokołowski, J., Bucka, E., Kalinowska, R., Mieżaniec, A., & Wieczorkowski M. (2020). *Recycling of plastics*. Warsaw: Warsaw University of Technology.
- Szlezyngier, W. & Brzozowski, Z. K. (2015). *Plastics – special and engineering polymers*, Volume 2. Rzeszów: FOSZE Publishing House.
- Wilczyński, K. (Ed.). (2011). *Wybrane zagadnienia przetwórstwa tworzyw sztucznych*. Warsaw: Oficyna Wydawnicza Politechniki Warszawskiej.