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Original scientific paper

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Abstract

Polystyrene concrete, as a type of lightweight aggregate concrete, has been used in civil construction for years. The use of waste expanded polystyrene (EPS) as a fill material in lightweight concrete production is highly recommended from the point of view of the circular economy. Published data shows that an increase in the proportion of lightweight aggregates, i.e. EPS, results in a decrease in strength, bulk density and thermal conductivity of the concrete. Utilizing large quantities of waste EPS in non-structural polystyrene concrete production is particularly important. Unlike structural polystyrene concrete, according to the published papers, non-structural polystyrene concrete has not been investigated sufficiently. The purpose of this paper is to determine the influence of the ratios of the basic components in a concrete mixture on the bulk density and compressive strength of non-structural polystyrene concrete produced by utilizing waste EPS as a fill material. The test specimens, i.e. cubes with an edge length of 100 mm each, were prepared in laboratory conditions by varying the proportions of EPS, sand up to 600 g and cement ranging from 300 g to 450 g per specimen. Bulk density and compressive strength were determined for the test specimens. Laboratory research results show a dependence of the component ratio on the bulk density ranging from 360 kg/m³ to 915 kg/m³ and compressive strength ranging from 0.385 MPa to 2.538 MPa.

Keywords:
waste expanded polystyrene, lightweight concrete, circular economy

1. Introduction

The aim of this research is to establish options for non-structural lightweight aggregate concrete production with the purpose of waste EPS disposal and to establish the principles of the dependence of cement, mineral fill material and waste granulated EPS proportions on the most important properties of concrete such as bulk density and compressive strength. This paper is focussed on polystyrene concrete investigations, prepared without additives, with a bulk density from 300 to 1000 kg/m³.

Concrete is an artificial building material consisting of aggregates (70-80 %), binder (10-20 %), water and various additives. Stone, gravel and sand are used as an aggregate, while cement is generally used as a binder. By selecting a particular type of aggregate, determining its exact mass, as well as the cement-water ratio, and, if necessary, by adding additives, it is possible to produce concrete for each specific purpose. Taking into account that aggregate is one of the main components of concrete, the quality of the concrete depends on the quality of the aggregate. Therefore, aggregate has to fulfill adequate requirements as a specific granulometric composition, approximately cubic shape of grains and must possess specific purity, regardless of the fact whether aggregate stone or gravel and sand are used (**Salopek et al., 2002; Sobota et al., 2011; Kujundžić, et al. 2008; Yari and Bagherpour, 2018.**). Taking into account its origin, an aggregate can be natural, unclassified, industrially produced and recycled, and according to its density, it is lightweight (ρ< 2000 kg/m³), normal weight (2000<ρ<3000 kg/m³) or heavyweight (ρ> 3000 kg/m³).

The limited reserves of mineral resources, economic circumstances (**Vorob'ev et al., 2017; Dychkovskyi et al., 2018**) and environmental standards impose the rational use of primary (mineral) resources through urban mining, i.e. the transition from the linear to circular economy. The application of circular economy principles imposes the use of waste as a secondary resource, unlike waste disposal common in the past century.

Polystyrene is one of the most widely used plastics, mainly in its expanded form, under the brand name of Styropor or Styrofoam. Expanded polystyrene (EPS) contains approximately 2 % of styrene, while the remaining 98 % consists of pores filled with air. EPS is mostly used for thermal insulation systems or as a pack-

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aging material. Its thermal conductivity ranges from 0.03 to 0.04 W/mK and depends on the bulk density ranging from 9 to 36 kg/m^3. Due to its wide use, large quantities of waste EPS are generated, while its low bulk density presents a huge problem, both during the use and disposal of EPS. Despite its low mass fraction in landfills, its volume is significant, in some countries even up to 7 % (**Kekanović et al., 2014**). The UK produces 300 000 tonnes per year, occupying $38 \cdot 10^6$ m^3 of landfill volume. Additionally, its large volume with low mass significantly increases the cost of recovery and transport. Every year, between 120 and 150 tonnes of waste EPS is collected in the Republic of Croatia, and millions of tonnes in the world (**Herki et al., 2013**). The company Tschanhenz & Križaj d.o.o. from Markuševac carries out the recovery of EPS through the production of beads intended for polystyrene concrete production or compacting.

Concrete is a suitable product for the economically and environmentally acceptable disposal of various types of waste (**Premur et al., 2018**). Lightweight concrete is a multi-purpose material for construction, which offers a range of technical, economical and environment-enhancing and preserving advantages and is destined to become a dominant material for construction in the new millennium (**Sadrmomtazi et al., 2013**). Its main advantage is its low volumetric weight starting from 90 kg/m^3 (**Schackow et al., 2014**), and according to **HR EN 206-1:2006** between 800 kg/m^3 and 2000 kg/m^3. It is classified as a structural lightweight concrete with a compressive strength higher than 17 MPa or a non-structural lightweight aggregate concrete with a compressive strength lower than 17 MPa (**Saradhi Babu et al., 2005**). Non-structural concrete is widely used in building construction (**Sadrmomtazi et al., 2012**), mostly as an insulation material, i.e. for filling voids. In lightweight concrete production, an aggregate with uniform grain size is used to obtain air-filled cavities, resulting in lower bulk density and thermal conductivity. Cellular concrete is a type of lightweight concrete with a "spongy" structure with gas bubbles obtained by an injection or as a result of a chemical reaction. The lightweight concrete manufactured in this manner is called gas concrete or foamed concrete. Lightweight concrete can be produced by replacing the mineral aggregate with solid density mainly between 2500 kg/m^3 and 2800 kg/m^3 with a natural or artificial expanded aggregate with lower solid density. Concrete produced in this manner is called lightweight aggregate concrete (LAC).

EPS is also used in the production of polystyrene concrete, either as virgin beads or waste granulated EPS. Literature contains research results on various properties of green and hardened LAC, mostly on compressive strength in 86 % of papers, and bulk density in 71 % of papers (**Vakhshouri and Nejadi, 2018**). The research is mostly focussed on structural polystyrene concrete with a bulk density higher than 1000 kg/m^3. Lightweight aggregate concrete with a bulk density lower than 1000 kg/m^3 with the addition of EPS as a fill material was investigated by Bagon, and Frondistou-Yannas. They investigated the samples of bulk density ranging from 650 to 800 kg/m^3 by inserting 425 kg to 505 kg of cement in 1 m^3 of concrete (**Bagon and Frondistou-Yannas, 1976**). They measured the compressive strength fc ranging from 3.3 to 5.0 MPa on 14 day old test specimens in the shape of cylinders. **Chen and Fang** (**2009**) produced concrete with a bulk density from 975 kg/m^3 to 983 kg/m^3 with an EPS volume fraction of 55%. The compressive strength of the samples reinforced by fibres was between 8.5 and 10.5 MPa. **Saradhi Babu et al.** (**2005**) carried out the experimental programme with concrete specimens by varying the proportion of a mineral fill material, fly ash and EPS beads, with the EPS volume fraction in the concrete varying from 0 to 66.5 %. They obtained concrete with a bulk density ranging from 582 to 984 kg/m^3 with 49 to 66.5 % of volume filled with EPS beads, while the compressive strength of test specimens ranged from 1.1 to 3.83 MPa. **Chen and Liu** (**2013**) tested the samples of foamed concrete by varying the pore-EPS beads ratio. In their paper, polystyrene concrete with a bulk density of 400 and 800 kg/m^3 had the compressive strength of 1.58 and 7.79 MPa, respectively. Their research confirmed a significant influence of EPS content on compacting. It also confirmed that by combining the polystyrene concrete and aerated concrete, with an increase in the proportion of pores while maintaining density, insulation properties and strength were improved. They determined that the aforementioned specimens had a thermal conductivity of 0.15 and 0.3 W/mK, respectively. **Herki et al.** (**2013**) and **Herki and Khatib** (**2016**) replaced natural aggregate, in different ratios, with waste EPS beads stabilised with clay, with a bulk density of 457 kg/m^3. When they completely replaced natural aggregate with EPS, they obtained a strength of 4.56 MPa with a bulk density of 1007 kg/m^3.

Kekanović et al. (**2014**) confirmed the possibility of obtaining polystyrene concrete with crushed waste EPS with a grain size smaller than 5 mm. They established that it was easier to produce polystyrene concrete from waste EPS than from EPS virgin beads, and that the hardened concrete had better mechanical and insulation properties. They determined thermal conductivity of 0.0763 W/mK for the concrete sample with a bulk density of 560 kg/m^3. Thermal conductivity of the samples obtained by combining the gas concrete and polystyrene concrete with the bulk density ranging from 300 to 330 kg/m^3 was determined by **Wang and Fu** (**2013**) with values ranging from 0.068 to 0.085 W/mK.

A large number of papers are related to lightweight aggregate concrete with a bulk density between 1000 and 2000 kg/m3 with the possibility of adding fly ash (**Park and Chisholm, 1999; Herki et al. 2013**), silica fume (**Ganesh Babu and Saradhi Babu 2003; Abd-**

ElAziz et al. 2017) rice husk ash and silica fume (**Sadrmomtazi et al., 2012**), or blast-furnace slag (**Wang and Tsai, 2006**). The mechanical properties of lightweight aggregate concrete are successfully improved by adding steel (**Chen and Liu, 2004**), glass (**Herki and Khatib, 2016**), or polymer fibres (**Muravljov et al., 2000; Chen and Fang, 2009**), and using stabilised polystyrene (SPS) (**Herki and Khatib, 2016**). The workability and the proportion of pores were frequently tested for green concrete, while compressive and tensile strength, bulk density, elastic modulus and other properties were tested for hardened concrete, on the test specimens of different sizes, shapes and age. The tests confirmed that, in addition to its basic components ratio, granulometric composition, waste EPS and placement operations (**Chen and Liu, 2013**), curing conditions (**Ling and Teo, 2011**) also influence the properties of lightweight aggregate concrete.

The influence of the size of EPS virgin beads was also investigated (**Ganesh Babu and Saradhi Babu 2003; Liu and Chen, 2014; Miled et al., 2007, Ning and Chen 2014**) and it was established that the size of beads was inversely proportional to the strength with equal bulk density. Based on published papers, all authors concluded that strength, bulk density and thermal conductivity of lightweight aggregate concrete decrease with an increase in lightweight aggregate fill proportion.

2. Materials and methods

Compressive strength and bulk density investigations were carried out on test cubes made of the following components: mineral fill material, cement as a binder, waste EPS and EPS wetting agent. The aforementioned components were used for the laboratory production of test specimens – the cubes with an edge length of 100 mm. NexeSpecijal CEM II/A-M (S-V) 42.5 N, i.e. mixed Portland cement, strength class 42.5 N was used as a binder. The chemical composition of cement is presented in **Table 1**, and granulometric composition in **Figure 1**. The sand of a local supplier, grain size class 4 mm, was used for the preparation of test specimens. The

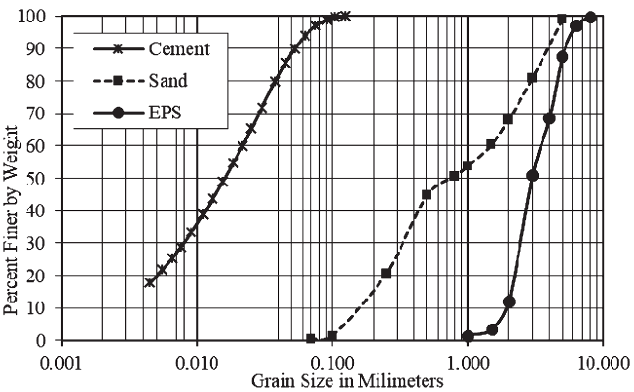

Figure 1: Granulometric composition of cement, sand and EPS

Figure 2: Granulated waste EPS

Table 1: Chemical composition of cement according to HRN EN 196-2:2013

Component	Mass fraction, %
Loss of ignition, L.o.i.	2.38
Corrected L.o.i.	2.47
Sulphate, SO_3	3.42
Insoluble residue, HCl and Na_2CO_3	3.92
Insoluble residue, HCl and KOH	1.39
Sulfide, S^{2-}	0.07
Manganese oxide, MnO	0.32
Total silicium dioxide, SiO_2	23.87
Iron (III) oxide, Fe_2O_3	2.61
Aluminium oxide, Al_2O_3	6.54
Calcium oxide, CaO	56.40
Magnesium oxide, MgO	2.96
Chlorine, Cl^-	0.022
Sodium oxide, Na_2O (according to 4.5.19.4.2.)	0.32
Potassium oxide, K_2O	0.85
Na_2O (according to 4.5.19.6.2.)	0.88
Carbon dioxide, CO_2	1.69

Table 2: Mineral composition of sand, grain size class -4 mm

Component	Mass fraction, %
Quartzite	37.67
Quartzite	36.03
Feldspar	6.70
Igneous rock	6.56
Siltstone	2.13
Sandstone	2.03
Quartz with Feldspar	2.03
Garnets	2.01
Chalcedony	1.56
Mica	0.76
Dolomite	0.73
Limestone	0.55
Amphibolite	0.45
Opaque minerals	0.39
Pyroxene	0.20
Amphibole	0.20

Table 3: Test cube preparation list

Series	Sample no.	Sand<4 mm	Cement	EPS	Water	w/c
		g	g	g	ml	
I. Series	1	0	300	22.0	165.0	0.55
	2	0	350	22.0	192.5	0.55
	3	0	400	22.0	220.0	0.55
	4	0	450	22.0	247.5	0.55
II. Series	5	200	300	22.0	165.0	0.55
	6	200	350	22.0	192.5	0.55
	7	200	400	22.0	220.0	0.55
	8	200	450	22.0	247.5	0.55
III. Series	9	400	300	22.0	165.0	0.55
	10	400	350	22.0	192.5	0.55
	11	400	400	22.0	220.0	0.55
	12	400	450	22.0	247.5	0.55
IV. Series	13	600	300	22.0	165.0	0.55
	14	600	350	22.0	192.5	0.55
	15	600	400	22.0	220.0	0.55
	16	600	450	22.0	247.5	0.55

Figure 3: Preparation of concrete mixture, preparation and curing of concrete cubes, and compressive strength testing

granulometric and mineral composition of the sand are presented in **Figure 1** and **Table 2**, respectively. Waste granulated EPS was obtained by crushing the mixture of waste insulation EPS and polystyrene packaging (see **Figure 2**). Since the EPS granulometric composition significantly influences concrete strength and bulk density, the granulometric composition was determined by sieving (see **Figure 1**). The density of beads was not determined since the material was a mixture of different types of waste EPS. The bulk density of waste EPS beads in a scattered condition was 14.5 kg/m^3. Stigodur D was used as an EPS wetting agent in the preparation of test cubes.

Concrete test cubes, with an edge length of 100 mm, were prepared under laboratory conditions. Due to unknown concrete placement conditions, it was not possible to determine the exact quantity of a necessary mixture, therefore, the mixture of a volume larger than 1 dm^3 was prepared. The mixture was put in moulds, and the excess mixture was removed after weighing. Four series of specimens were prepared: without sand, and with 200, 400 and 600 g of sand per specimen. In each series test specimens with 300, 350, 400 and 450 g of cement per specimen were prepared. In each mixture 22 g of EPS and 5 ml of EPS casting agent were added. The water-cement ratio was 0.55 during the preparation of all test cubes. A test cube preparation list is presented in **Table 3**.

The EPS substance was weighed and then put in a planetary mixer of 5.0 l volume and mixed with a corresponding quantity of water and 5 ml of EPS wetting agent. After three minutes of mixing, sand was added and the mass was mixed for three more minutes. Then cement was added and the mass was mixed for five more minutes. The fresh cement mixture was put into metal moulds manually, according to **EN 12390-2:2009**. The mixture was put in moulds manually due to the possibility of an EPS segregation during compacting by vibration (**Sayadi et al., 2016; Herki et al., 2013**). Since waste EPS is heterogenous, the shape of its beads is irregular, its density is not defined and the volume of pores in the concrete specimens are unknown, and so the exact volume of EPS in the specimens was not determined.

The concrete cubes were removed from the moulds after 24 hours (see **Figure 3**), their mass was determined, and they were cured in air filled with water vapour at a temperature of 20°C until compressive strength testing took place. Although **Xu et al.** (**2015**) established that in the case of different EPS proportions the water-cement ratio influences the strength, a water-cement ratio of 0.55 was used in the preparation of all test cubes. For each test cube preparation list, three test cubes were made. Compressive strength testing was carried out on 28 days old test cubes, on a load frame manufactured by GDS Instruments, type: GDSLF50, according to **EN 12390-3:2009** (see **Figure 3**). Bulk density was determined by measuring the dimensions of the test cubes according to **EN 12390-7:2009**.

3. Results and discussion

Research results show that polystyrene concrete can be produced with no difficulties with defined preparation instructions. The sections of specimens 1 and 16 (see **Figure 4**) show that in a specimen of polystyrene concrete with a lower portion of cement and without sand, a larger space is filled by EPS than in specimen 16, which contains sand and a higher proportion of cement (see **Figure 4**). EPS beads of an irregular shape (a), cement binder (b), pores filled with air (c) and coarse grains of sand (d) are clearly visible in **Figure 4**.

The results of bulk density depending on the mass fraction of individual components are presented in **Figure 5**. The bulk density of the test cubes was between 360 kg/m^3 for specimen 1 and 915 kg/m^3 for specimen 16, i.e. within the aimed range of the research. The specimens from series 1, i.e. the specimens prepared without

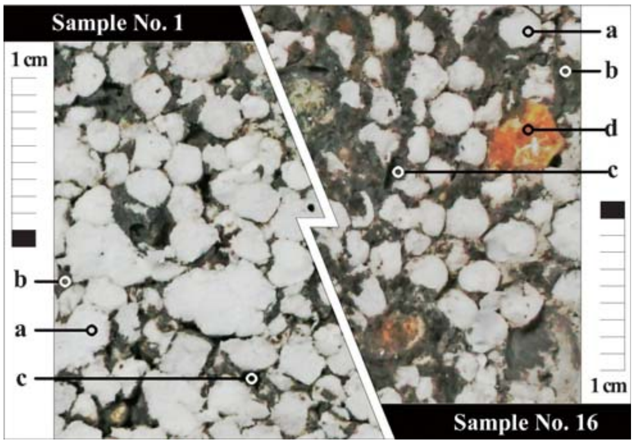

Figure 4: Sections of concrete cubes: a- EPS beads, b-cement, c-pores filled with air, d-grains of sand).

sand, have the lowest bulk density ranging from 360 to 480 kg/m^3. The specimens from series 4, i.e. the specimens with the highest mass fraction of sand have the highest bulk density ranging from 735 to 915 kg/m^3.

The compressive strength of the polystyrene concrete cubes fc increases, as expected, when the mass fraction

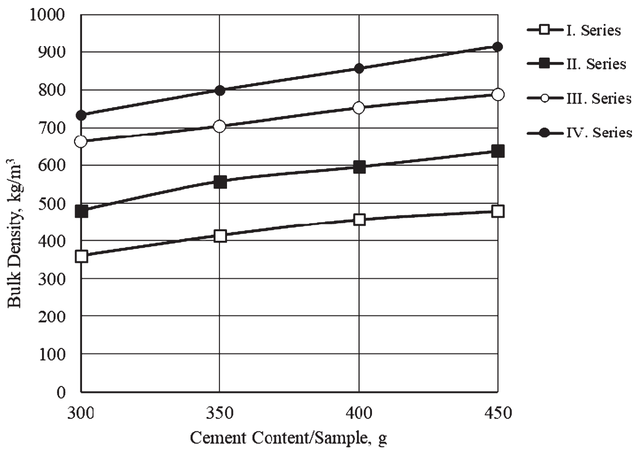

Figure 5: Dependence of bulk density on cement and sand proportion

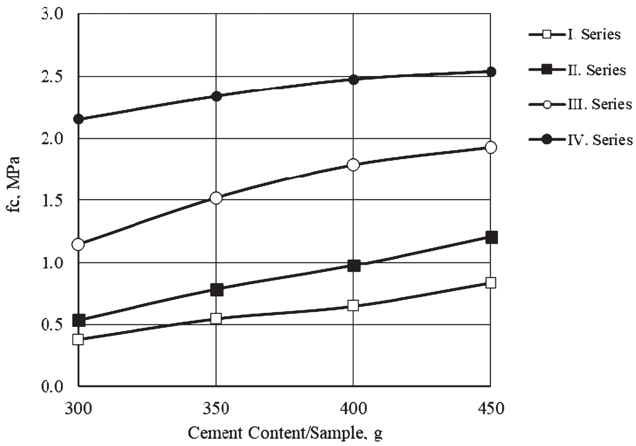

Figure 6: Dependence of compressive strength fc on cement and sand proportion

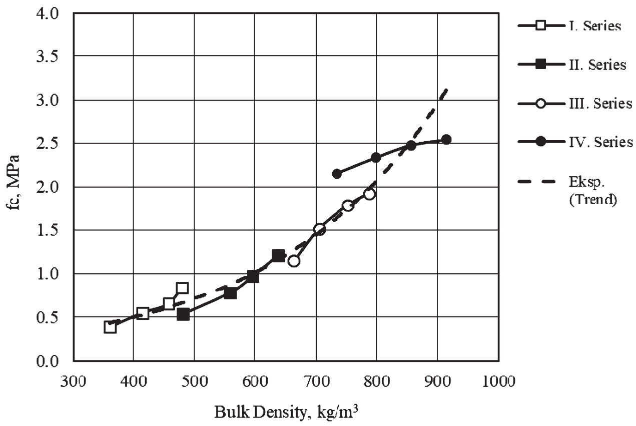

Figure 7: Dependence of strength and bulk density of specimens of different series

of sand and cement increases, which can be concluded from the diagram in **Figure 6**. As expected, the specimens from series 1, i.e. the specimens without sand, have the lowest strength ranging from 0.385 to 0.883 MPa. The specimens from series 4, i.e. the specimens with the highest mass fraction of sand, have the highest strength ranging from 2.150 to 2.538 MPa.

The results presented in **Figures 5** and **6** present the arithmetic mean of measurements on three specimens of identical preparation. If the dependence of strength on bulk density is observed, as presented in **Figure 6**, a more or less increasing linear trend for strength with bulk density can be observed. The curves of series 1 and 2 are of a concave shape, i.e. the strength increases faster with an increase in cement proportion than in the case of the specimens from series 4 and 5.

The results presented in diagrams in **Figures 5** and **6** show the expected increasing trends for bulk density and strength with an increase in sand and cement proportions (**Vakhshouri and Nejadi, 2018**). The slopes of the lines that present the dependence of bulk density on the cement proportion (see **Figure 5**), indicate an increase in bulk density with an increase in cement proportion, while the position of the curves indicates an increase in bulk density with an increase in sand proportion. It is expected that the dependence of bulk density on cement proportion will be linear in the diagram with linear measurements on axes, but the deviation from the linear dependence is observed. The deviation from the linear dependence of bulk density on cement and sand proportion can be attributed to the modification of properties of green concrete mixture, as well as to the possibility of compacting (**Xu et al., 2015**), therefore, to bulk density. With an increase in sand proportion, the curves are transformed into lines. With the approximation of individual curves with a straight line, the correlation coefficient increases from 0.9657 for series 1 to 0.9978 for series 4. **Figure 6** shows that the lines of series 1 and series 2 are closer than other curves which indicates the non-linear increase in strength with an increase in sand proportion.

Data on the dependence of bulk density and individual components proportion have higher values if they are observed in the context of realized strength, as presented in **Figure 7**. The trend line of all measured values can be approximated by an exponential curve with a correlation coefficient of 0.9496. The curve of series 4 shows the highest deviation from the general trend line. Based on the presented data, it can be concluded that the equal range of strength values can be achieved with different sand-cement ratio. In the case of lower sand proportion, the curves of series 1 and series 2 overlap for identical strength. Series 3, even with 450 g per specimen (specimen 12) cannot obtain the strength of concrete of series 4 with only 300 g of cement (specimen 13). The bulk density of specimens 12 and 13 exceed the bulk density of specimen 14 of series 4. Varying the water-cement factor would probably influence the compaction of concrete; therefore, it would probably influence measurement results.

4. Conclusions

Based on the obtained data, it is established that a non-structural polystyrene concrete can be produced by using waste granulated EPS.

- The strength and bulk density of polystyrene concrete increases with an increase in the sand and cement proportion.
- Within the tested range of sand and cement proportions, dry bulk density of the concrete cubes ranging from 360 to 915 kg/m^3 with strength ranging from 0.385 to 2.538 MPa were determined.
- The dependence of the increase in the proportion of volumetric weight on sand and cement proportion could be approximated by straight lines, and the dependence of the increase in strength with an increase in volumetric weight by an exponential curve.
- Within individual ranges of testing, the polystyrene concrete of equal bulk density and compressive strength can be produced with different sand and cement proportions. It is recommended to continue the research of thermal and acoustic properties of the tested polystyrene concrete.

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SAŽETAK

Oporaba otpadnoga stiropora izradom lakoga betona

Stiroporbetoni, kao vrsta lakoagregatnih betona, u gradnji se koriste već niz godina. Sa stajališta kružne ekonomije, od interesa je korištenje otpadnoga ekspandiranog polistirena (EPS) kao punila u njihovoj proizvodnji. Iz dostupnih podataka lako je uočiti kako s povećanjem udjela lakih agregata, odnosno EPS-a, betonima opadaju čvrstoća, zapreminska masa i toplinska vodljivost. Posebno je važna izrada nekonstrukcijskih stiroporbetona zbrinjavanjem što veće količine otpadnoga EPS-a. Za razliku od konstrukcijskih stiroporbetona, a prema dostupnoj literaturi, nekonstrukcijski nisu dovoljno istraženi. Svrha je ovoga rada utvrđivanje zakonitosti udjela osnovnih sastojaka betona na zapreminsku masu i tlačnu čvrstoću nekonstrukcijskoga stiroporbetona načinjenoga korištenjem otpadnoga EPS-a kao punila. U laboratorijskim uvjetima izrađena su probna tijela, kocke stranica 100 mm, variranjem udjela EPS-a, zatim dodavanjem pijeska do 600 g i cementa od 300 do 450 g. Probnim tijelima određene su zapreminske mase i tlačne čvrstoće. Rezultati laboratorijskih istraživanja pokazali su ovisnost udjela sastojaka na zapreminske mase koje variraju u rasponu do 360 do 915 kg/m^3 i tlačne čvrstoće u rasponu od 0,385 do 2,538 MPa.

Ključne riječi:
otpadni ekspandirani polistiren, lakoagregatni beton, kružno gospodarstvo

Authors contribution

Gordan Bedeković, (PhD, Full Professor, mining engineer) carried out the analysis of production, use and properties of standard and lightweight concrete. Based on the published results on the properties of polystyrene concrete and on his own results presented in this paper, he made conclusions on the influence of binders, filling materials and waste EPS proportions on the properties of polystyrene concrete. **Ivana Grčić**, (PhD, Assistant Professor, chemical engineer), based on the published data, analysed production, properties and use of EPS, and its possible role in the production of polystyrene concrete. **Aleksandra Anić Vučinić**, (Ph.D., Associate Professor, food engineer), analysed the possibility of the disposal waste EPS by applying the principles of circular economy. **Vitomir Premur**, (Ph.D., Senior Lecturer, mining engineer), carried out laboratory tests and processed measurement results.