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Analysis of the Possibility of Using Extruded Polystyrene (XPS) Wastes to Make Lightweight Cement Composites

Bartosz Zegardło[1], Krzysztof Kobyliński[1*]

[1] Siedlce University of Natural Sciences and Humanities, Research Team of Quantitative Methods and Spatial Management, ul. B. Prusa 14, 08-110 Siedlce, Poland

* Corresponding author's e-mail: krzysiek.kobylinski.uph@gmail.com

ABSTRACT

The paper presents the problem of utilization of extruded polystyrene wastes by its secondary use as filler for cement composites. Wastes were obtained from a company carrying out thermomodernisation works in the form of shapeless, undersized construction waste. The remains of the boards were crushed and separated using the sieve method. The basic technical parameters of thus prepared waste were assessed in terms of its use as a lightweight aggregate for concrete. The technical properties of wastes were compared with those of traditional aggregates used in concrete composites. During the research work, the samples of a cement composite were produced in which the waste served as a filler. In successive test series, the waste constituted 30, 50 and 100% of the aggregate substitution in the mix. Comparative samples without waste were also made. The results showed that the waste could potentially be used to produce lightweight cement composites with high strength parameters.

Keywords: extruded polystyrene, XPS, waste aggregates, recycled concrete

INTRODUCTION

The issue of waste recycling is a priority in current scientific and industrial activities. It is becoming increasingly common for manufacturers of new products to develop the systems for re-using their products after use. The problem, however, is still the waste generated during the repair or assembly processes. As a result of the fact that unwanted matter appears here both outside the manufacturer of the product and outside the final user, the ways of neutralizing it are often neglected. Moreover, the form of waste and the quantities generated at this stage of the product's life cycle are often so individual that the system of its disposal should be different than for post-production and post-operation waste. An example of this type of products includes the boards made of extruded polystyrene, also referred to as XPS or hard foamed polystyrene. The quantities of such products collected during installation works are not large, and they are disposed of in landfills together with foamed polystyrene. Significant differences between technical properties of polystyrene and XPS allowed the authors of the paper to propose a thesis that their use as a filler in cement composites can be much more beneficial than that of styrofoam and it will allow obtaining a light composite with more favourable strength parameters. The local availability of this waste to concrete producers could potentially allow it to be recycled only after collection and crushing in standard crushers. This type of recycling would be in line with the principles of operation of municipal mines and could potentially meet the rules of the so-called low-energy recycling, i.e. disposal of unwanted matter almost at the place of its creation.

Extruded polystyrene XPS [Frankiewicz, Łysiuk 2006] is a petroleum-derived product. Polystyrene, as a semi-finished product – a synthetic raw material for the production of polystyrene – also has the form of hard, glassy granules with the diameter of the balls from 0.2 to 2.5 mm. The first stage of manufacturing the product from semi-finished product is pre-foaming. During this stage, the granules of the raw material soften and their volume increases due to the action (expansion) of the blowing agent. This stage lasts from 2 to 5 minutes and is performed with steam at a temperature higher than 90°C. The polystyrene granules expand from 25 to 65 times their volume. In this way, particles with a closed structure are formed, which affects the later final characteristics of the product, such as low water absorption. The expansion process is enhanced by diffusion of hot steam into the particles. The next stage of production is cooling and seasoning of polystyrene foam balls. Up to this stage, the production of XPS is identical to the production of expanded polystyrene (EPS).In the next process, block forming takes place, which is done by filling the moulds with the described expanded polystyrene together with granulate and subjecting the granulate to the foaming process again. The expanding granulate causes the filling of free spaces between the spheres of previously foamed polystyrene. At the same time, the contacting molten surfaces of the spheres fuse together forming a durable product. The sintering and extrusion of polystyrene, i.e. thermoplastic processing under high temperature and pressure (pressing), produces extruded polystyrene (XPS), a closed-cell material with very good insulating properties, high compressive strength, high resistance to moisture, soil acids and biological corrosion. Basic properties of extruded polystyrene (XPS) in comparison with properties of expanded polystyrene (EPS) are presented in Table 1 [Radziszewska-Zielina 2009].

As it can be seen from the table presented, extruded polystyrene (XPS) in comparison to polystyrene (EPS) has 2% lower water absorption, three times higher compressive strength and five times higher tensile strength than polystyrene. The values described above were the basis for the research work described in this paper.

All of the presented research works proved the benefits of using lightweight aggregates for composites in terms of improving their insulating properties. At the same time, the research indicated that the strength parameters of the composites decreased with increasing polystyrene content and decreasing volume density of the composite. For the EPS composites with density of 1340–1360 kg/m^3, the compressive strength was about 12MPa, while at density of 100–120 kg/m^3, the compressive strength was only 0.8MPa. This fact prompted the authors of this paper to use a material with similar insulation properties to polystyrene foam (EPS), but with higher strength parameters.

Taking the above into consideration, this paper presents the problem of utilization of extruded polystyrene (XPS) waste by its secondary use as filler for cement composites. The results obtained showed the potential possibility of using this waste to produce lightweight cement composites.

MATERIALS

The main research material was waste from the thermal modernisation of a residential building.The extruded polystyrene collected from the construction site was in the form of board remains with dimensions of 100x50cm. This material is customarily used to cover the foundations of buildings that are below the ground level. The contractors who carry out this type of work are always left with panel elements that are too small to be used for cladding the rest of the building. For this reason, they must already be recycled at this stage of the product life cycle. The examples of XPS elements remaining after thermomodernisation of a building are shown in Photo 1. The waste collected from the landfill was mechanically cleaned and transported to the laboratory. The styrodur fragments of different sizes were shredded mechanically on a grater. The waste after shredding is presented in Photo 2.

Portland cement CEM I 42.5N – SR 3/NA was used as the cement for the concrete.This cement is characterised by stable physical and chemical parameters, appropriate setting time, high early and final strength parameters, low alkali content and high resistance to aggressive chemical agents. Owing to these advantages, it is popularly used in the production of commodity concrete mixtures. Table 2 shows the physicochemical parameters of the cement used. Ś

CHRYSO Omega 132 is a new generation water-reducing plasticising admixture. The admixture is produced using the latest hybrid polymer technology. This technology, based on the synthesis of molecules, allows for strong reduction of batch water quantity, long-lasting maintenance of the concrete mix consistency, homogeneity and cohesion of the concrete mix. The basic technical parameters of the admixture based on its technical card are presented in Table 3.

Silica dust was used as a concrete additive. According to the manufacturer's description,

Photo 1. XPS waste after thermomodernisation

Photo 2. Waste after shredding (0–2mm and 2–4mm)

microsilica originated as a by-product obtained during the production of silicon metal and ferro-silicon alloys in arc furnaces. It consists of fine dust particles, the diameter of which is estimated to be on average 100 times smaller than the average grain size of cement. For technical reasons, the silica dust was supplied in a compacted form, as microgranules which are agglomerates of single particles. As described, microsilicais a very important additive for watertight concretes. Replacing 15% of cement with microsilica increases the tightness of concrete by several dozen times, which is difficult to achieve with other methods. The basic characteristics of microsilica from the technical data sheet are given in Table 4.

For the design of the concrete mix, the method of T. Bukowski was used. The concrete design was based on sand and gravel aggregate. The research programme assumed that this mix would be the base – control mix. The remaining test mixes were to be the mixes in which recycled aggregate was to replace traditional aggregate in the following amounts: 30% (for the XPS30 test series), 50% (XPS50) and 100% (XPS100). As a control mixture, the samples in which all the aggregate was sand and gravel aggregate were made (CONTR)

In the first design phase, the designed concrete consistency class was assumed [Szmigiera, Łukowski, Jemioło 2015]. It was determined as

Table 1. Basic properties of extruded polystyrene in comparison with those of polystyrene foam [Radziszewska-Zielina 2009].

Parameter	Extruded Polystyrene (XPS)	Expanded Polystyrene (EPS)
Thermal conductivity	manufacturer’s declared value: 0.030–0.04 W/mK	manufacturers’ declared value: 0.031–0.042 W/mK
Volume density (apparent)	declared value: 28–32 kg/m^3	declared value: 14–19 kg/m^3
Total porosity	voids (entrails filled with air) occupy approximately 95% of the total volume	voids (air-filled pores) occupy about 98% of the total volume of the material
Soakability (waterabsorption)	normal water absorption by volume after long-term immersion – not more than 3.0	normal water absorption by volume after long-term immersion – not more than 5.0
Compressive strength	0.250 MPa	0.070 MPa
Tensile strength perpendicular to the superficial surface	not less than 0.100 MPa	not less than 0.020 MPa
Deformation of the material under external loading	the declared linear deformation (shortening) at 0.3 MPa is not more than 10	the declared linear deformation (shortening) at 0.3 MPa is not more than 10
Resistance to biological agents	resistant	resistant
Resistance to chemical compounds	resistant to organic solvents (toluene, xylene, benzene, acetone, ethyl and amyl acetate), swells under the influence of petrol and crude oil	resistant to organic solvents (toluene, xylene, benzene, acetone, ethyl and amyl acetate), swells under the influence of petrol and crude oil

Table 2. Physical and chemical parameters of the cement used taken from the manufacturer’s product sheet

Feature	Unit.	Average score	Requirements
Start of bond	min	233	> 60
End of bond	min	291	
Water efficiency	%	27.5	
Constant volume	mm	1.1	< 10
Specific surface area	cm^2/g	3688	
Compressive strength: after 2 days	MPa	23,9	<10
Compressive strength: after 28 days	MPa	55.9	42.5 – 62.5
Chemical analysis: SO_3	%	2.77	< 3.0
Chemical analysis: Cl	%	0.070	< 0.10
Chemical analysis: Na_2Oeq	%	0.53	<0.6

densely plastic. For a given consistence class, using sieve analysis and the known percentages of individual aggregate grain sizes, the aggregate water capacity was calculated on the basis of tables, as the product of the percentage of aggregate of the respective grain size and the water capacity of the partial aggregates. Following these calculations, the composition of the concrete was corrected in Excel. This was dictated by the fact that there was a significant difference in the density of the recycled and gravel aggregate. In order for the slurry designed for the gravel aggregate to envelop the grains of the polystyrene aggregate, the volume of the cement slurry was increased in relation to the aggregate. The final determined composition of the starting concrete for 1m^3 of the mix contained 436 dm^3 of aggregate, 140dm^3 of water and 400dm^3 of cement, respectively. In accordance with the guidelines provided by the manufacturers of additives and admixtures, which are commonly used in concrete batching plants, it was decided to use a plasticising admixture in the amount of 4dm^3 per 1m^3 of the mixture and 20 dm^3 of an additive in the form of microsilica. The final composition of the mixtures is presented in Table 5.

Table 3. Basic properties of the admixture: CHRYSO Omega 132 on the basis of the manufacturer’s technical card

Property	Description
Form	Homogeneous liquid
Colour	Brown
Density (20°C)	1.075 +/- 0.02 kg/dm^3
pH	5 +/- 1
Cl- ion content	up to 0.1%.
Alkali content calculated as Na_2O	up to 2.0%

Table 4. Basic properties of microsilica based on the product data sheet

Parameter	Unit	Value	Assessment method
Form	–	fine powder	Visual
Colour	–	grey	Visual
Fragrance	–	odourless	–
Density	g/cm^3	2.05	EN 1097–6
Bulk density	g/cm^3	1.1	EN 1097–3
Alkalinity	pH	less than 11.5	PN-EN-ISO 10523

RESEARCH METHODOLOGY

The standard method was used to determine the bulk density of aggregates according to [PN-EN1097–7:2011]. The vessel was filled with aggregate and its weight was measured. On the basis of the ratio of the weight of the aggregate to its volume, the bulk density was assessed. Nine density measurements were carried out for both the recycled aggregate and the reference aggregate.

The absorbability of the aggregate was tested using the method based on [PN-EN 1097–6: 2011]. Successive measurements were performed of the weight of dry and wet grains. On this basis, the amount of water that the aggregate can absorb in relation to the weight of the dry aggregate was assessed.

The bulk density of the composites [EN 12390–7:2009] was tested on rectangular specimens with the dimensions of 40x40x160 mm. Ten specimens of each concrete were prepared. The test was conducted according to the guidelines of the standard and was calculated as the ratio of the mass of the sample to its volume.

In order to assess the shape of the grains [PN EN 933- 4] of both types of aggregates, a comparative method was used to measure the length, width and thickness of representative grains whose occurrence was most numerous, and then the ratios of the measured values were compared.

The surface structure of the grains was assessed using microscopic observations [PN-EN 933–1:2012]. Water absorption was tested on the same 40x40x160 mm rectangular samples [PN-EN 1097–6]. Ten specimens of each concrete were also tested. The specimens were immersed in water and remained there until their weight was established. The water absorption rate was calculated as the ratio of the amount of water that the concrete was able to absorb to the mass of dry concrete expressed as a percentage.

The bending strength in the three-point scheme was tested according to the guidelines of the standard [PN-EN 196–1]. The specimens measuring 4x4x16 cm were prepared for the test. The strength test was carried out on a testing machine with a 0–200 kN strain gauge from UTILCELL, model: M740. Photo 3 shows a specimen during testing.

The compressive strength tests on the specimens after moisture treatment were carried out according to the guidelines of [EN 12390–3:2006]. The sests were performed on the specimens that had been broken during the bending strength test. The compression strength test was carried out

Table 5. Composition of concrete mixes in dm^3 per 1 m^3 of mix

No.	Substrate	Samples with individual XPS content (dm^3/1m^3 concrete)			
		(CONTR) 0%	(XPS30) 30%	(XPS50) 50%	(XPS100) 100%
1	Cement CEM I 42.5N-SR3/NA	400	400	400	400
2	Microsilica	20	20	20	20
3	Aggregate 0–2mm	291	203	145	-
4	Aggregate 2–4mm	145	102	73	-
5	Styrodur 0–2mm	-	87	145	291
6	Styrodur 2–4mm	-	44	73	145
7	Superplasticizer	4	4	4	4
8	Water	140	140	140	140
Total		1000	1000	1000	1000

Photo 3. View of composite sample during flexural strength testing

using a MATEST 2000 testing machine, with a 0–300 kN strain gauge attachment, also produced by MATEST, model: C089PN468, serial number: C089PN468/AA/0001. Photo 4 presents the composite sample which was tested.

RESULTS AND THEIR ANALYSIS

A summary of the results obtained for both recycled aggregates and the sand-gravel mixture is given in Table 6. Other parameters of the described aggregates, which were taken from the technical sheets of the materials, are also given in Table 6.

The tested density of the recycled aggregate was lower than that of the gravel aggregate and was 30 kg/m^3. This value was almost 86 times lower than the gravel aggregate. The average values of bulk density were also significantly different for both types of aggregate. For the recyclate, this value was 200 kg/m^3 and for the traditional aggregate 2200 kg/m^3. The water absorption of the polystyrene aggregate was negligible at 0.03%. For the sand and gravel aggregate, the value was 2.1%. The comparison of these values proved that the tested recycled material itself is dense, has no pores and there are no free spaces inside.

The size ratios of individual polystyrene aggregate grains calculated as mean values were closer

Photo 4. View of a sample subjected to compressive strength testing

Table 6. Properties of aggregate-fillers in the designed composites

Type of aggregate / Feature	Unit.	Traditional aggregate: sand, gravel	Extruded polystyrene aggregate
Specific gravity	kg/dm^3	2.65	0.03
Bulk density	kg/dm^3	2.20	0.02
Compressive strength	MPa	33	0.250
Modulus of elasticity	MPa	330	700
Water absorption	%	2.1	0.1
Crushing indicator	%	14,3	-

to 0.5 than to 1, so the shape of the grains was assessed as longitudinal. As a result of observing the grains under magnification, it was assessed that the grains had a rough but closed surface structure.

The size ratios of individual grains of sand and gravel aggregate calculated as mean values were closer to 1 than to 0.5, so the shape of grains was assessed as spherical. As a result of observing these grains under magnification, it was assessed that the grains have a rough, partly open surface structure (with pores).

The volumetric density of the composite samples averaged measured with a coefficient of variation of less than 2% were: CONTR–2269.53 kg/m^3, XPS30 – 2134.77 kg/m^3, XPS50 – 2005.86 kg/m^3, XPS100 – 1453.30 kg/m^3 The results of this study showed that the influence of recyclate on this characteristic is significant. A trend of a clear decrease in density with the amount of recyclate was observed, which was the reason for the lower density of the aggregate itself. The results of this study are presented in Figure 1. The results of the absorbability test are presented in Figure 2.

The presented average values tested showed a significant decrease in absorbability with an increase in the amount of styrodur aggregate. The absorbability of the samples was determined after a long period of time during which water had a chance to penetrate the aggregate structure. The quality of the gravel aggregate used was relatively low, which was proven by the rather high absorbency of the gravel grains. This was probably the reason for the higher absorbability of the composite. The low absorbency of the styrodur was evident in the test results for this feature of the composite. The results of the flexural strength test on the Portland cement composites are presented in in the Figure 3.

The analysis of the results of the bending strength of the composites proved that the value of the bending strength decreased significantly with an increase in the content of the recycling additive. The value tested for the composite with gravel aggregate was 10.29 MPa, while for the composite to which only polystyrene aggregate (XPS100) was used it was 4.38 MPa, which was 57.43% lower. The flexural strength of the composites is significantly affected by the aggregate strength itself. The tensile strength of the grains of which styrodur is made is low. It is several times lower than that of gravel grains. Therefore, there was an observed decrease in the value of this technical parameter. The results of the compressive strength test are presented in Figure 4.

The analysis of the compressive strength test results clearly determined the effect of the

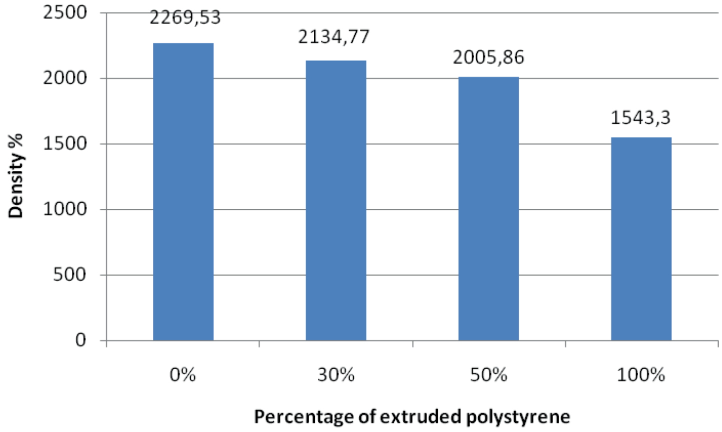

Figure 1. Results of volumetric density testing of composites

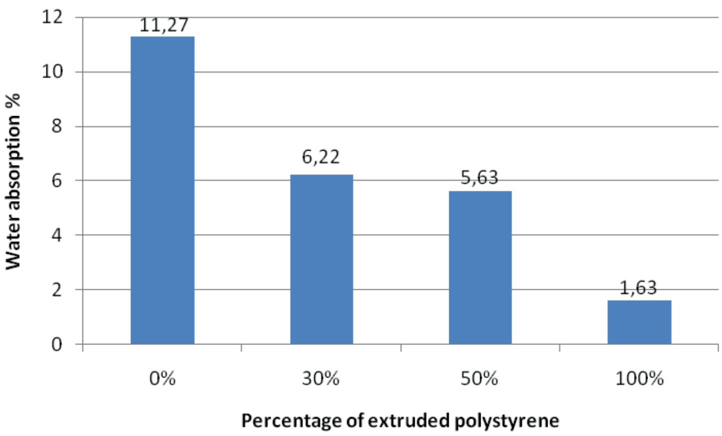

Figure 2. Results of the absorbability test on composites

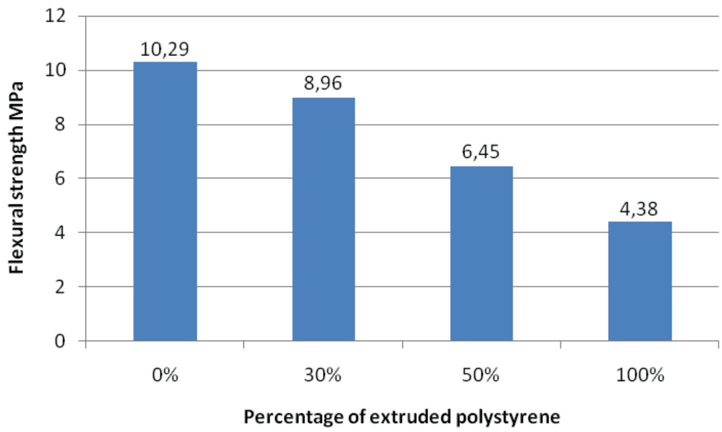

Figure 3. Results of flexural strength testing of the composites based on Portland cement

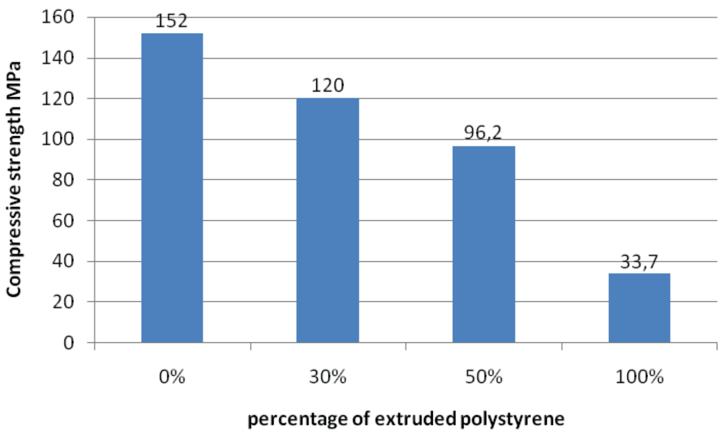

Figure 4. Compressive strength test results

recycled aggregate addition on this parameter. The average compressive strength values tested for the composite with 100% styrodur additive were 77.83% lower than for the control composite without the additive. The compressive strength values tested for the composite with 50% styrodur addition were 36.71% lower than for the control composite. The compressive strength values tested for the composite with 30% styrodur added were 21.05% lower than for the control composite. Relating the observed results to the flexural strength test and to the observations made at that time, it can be concluded that the result of this test was also predictable. What is noteworthy here, however, is the high strength of the composite itself, in which the styrodur waste was used as the only aggregate. The value of 33.7MPa is high and allows such a composite to be classified as structural concrete.

Relating the results of this study to those taken from the literature for polystyrene concrete also confirms the validity of using styrodur for this type of composites. The results presented for polystyrene concretes show the composites which have strength of 12 MPa at a volume density of about 1300 kg/m^3. The presented XPS100 composite at a slightly higher density had a significantly higher compressive strength value of 33.7MPa. The result of this study can be considered as a confirmation of the thesis that the use of this type of waste for lightweight cement composites is justified.

CONCLUSIONS

According to the conducted analyses and obtained research results, the extruded polystyrene (XPS) wastes generated during thermal modernization works can be used as a filler for cement concretes. The use of this type of wastes in the crushed form makes it possible to obtain the cement composites with high strength parameters. The composites made with XPS waste have higher compressive strength than similar composites made with EPS polystyrene regranulate. The results of research work proved that the composite made with only wastes of extruded polystyrene as the only filler can have the compressive strength which classifies it to structural concretes. Taking into account the above, it can be recommend the production of this type of composites under industrial conditions. The proposed use of such lightweight concretes may be as insulation layers of buildings, which will also carry loads. Such composites can be used in such elements as floors on the ground, ceilings or roof layers.

REFERENCES

1. EN 12390–3:2006. Concrete testing – Part 3: Compressive strength of test specimens.
2. EN 12390–5:2005. Concrete testing – Part 5: Flexural strength of test specimens.
3. EN 12390–7:2009 Testing hardened concrete – Part 7: Density of hardened concrete.
4. Frankiewicz, D., Łysiuk, B. 2006. Selecting materials, tools and equipment for thermal insulation. NationalResearchInstitute. Radom.
5. Hind A., Mahdi K. , Kareem A., Jasim A. , Shaban H. 2019.Manufacturing and improving the characteristics of the isolation of concrete composites by additiveStyrofoamparticulate, Energy Procedia, 157, 158–163.
6. Mores E.G., Sangiacomo L., Novaes de Oliveira A. 2019. innovative thermal and acoustic insulation foam by using recycled ceramic shell and expandable (EPS) wastes, Waste Management, 89, 336–344.
7. Mrozik Ł., Pawel P. 2016. Practical possibilities of production and application of lightweight concretes using EPS regranulate. Sustainable Construction. UTP University Publishing House, 172–177.
8. Piekarski P., Mrozik Ł., Grzybowska A. 2017. Properties of lightweight concretes based on expanded polystyrene regranulate. Building Materials 537(5), 98–99. DOI: 10.15199/33.2017.05.42.
9. PN EN 933-4. Testing of geometrical properties of aggregates. Part 4: Determination of grain shape.
10. EN 1097–6. Testing of the mechanical and physical properties of aggregates – Part 6: Determination of grain density and water absorption.
11. PN-EN 1097–7:2001. Testing of mechanical and physical properties of aggregates – Part 7: Determination of density of filler.
12. PN-EN 933–1:2012. Testing of geometrical properties of aggregates.
13. Radziszewska-Zielina E., 2009. Comparative analysis of parameters of thermoinsulating materials applied as insulation of external walls. Przegląd budowlany, 80, 32–37.
14. Szmigiera E., Łukowski P., Jemioło S. 2015. Concrete and structures from concrete – research, Oficyna Wydawnicza Politechniki Warszawskiej, Warsaw.
15. Wesołowska M., Szczapaniak P., Gajewski J. 2018. “NZEBs built of elements based on styrofoam regranulate”. IOP Conference Series: Materials Science and Engineering, 415, 1–8.
16. Wim N., Wandee T., 2019. Fabrication and Mechanical Properties of Hybrid Composites between Pineapple fiber/StyrofoamParticle/Paper Tissue, Materials Today, 17(4), 1444–1450.