The impact of expanded polystyrene waste of different fineness on the properties of lightweight composite

D Leonavičius¹, I Pundienė¹, J Prankevičienė¹ and M Kligys¹

¹Vilnius Gediminas Technical University, Scientific Institute of Thermal Insulation, Linkmenu str. 28, LT-08217, Vilnius, Lithuania

E-mail: dainius.leonavicius@vgtu.lt

Abstract. Expanded polystyrene (EP) is widely used as a packaging material for many types of goods. However, once the material is used, it is disposed of in landfills, where it can remain intact for the lifetime of several generations. Recycling of disposed EP packaging is of high relevance worldwide. The main objective of this study is to make a more detailed research into the effect of EP aggregate waste of different fineness and shape on physical and mechanical properties of porous lightweight aggregates concrete (PLWAC) with EP waste aggregates. Tests were done with Portland cement, EP waste of different fractions, resulted from crushing (EPR) and cutting (EPU), metakaolin, superplasticizer and air entraining admixture. Six batches of PLWAC specimens were formed with different EPR/EPU ratios, ranging from 0.5 to 3. The change in EPR/EPU ratio in PLWAC leads to structural changes and density reduction from 550 to 410 kg/m³ after drying. When EPR/EPU ratio in the PLWAC is increased to 2, the compressive strength of the specimens drops from 2.3 to 1.75 MPa and down to 0.55 MPa, when EPR/EPU ratio is increased to 3.

1. Introduction

EP and its aggregates are widely used as packaging materials for many types of goods for inert, closed-cell and ultra-light (up to 95% air by volume) structure. However, once the material is used, it is disposed of in landfills, where it can remain intact for the lifetime of several generations [1, 2]. The problem of reusing or recycling of disposed tare of EP is relevant in the world. EP beads with intact structure are ultralight, hydrophobic and non-water absorbing aggregates [3, 4]. The properties make it possible to use EP aggregates and EP waste for various purposes (reduce density and thermal conductivity) by varying its volume percentage in mortar or concrete [5-8]. Most research on EP containing concretes has shown a decrease in the durability performance and the strength of concrete with increasing the amount of EP aggregate in mixtures [1, 9-11]. One researched [12] found that by increasing EP content in lightweight concrete from (16.7 % to 50 %) by volume of sand, the compressive, tensile and flexural strength decreases to 30.17 %, 37.93 % and 43.3 % respectively. Authors [13] used fly ash (50 % by weight of cement) as additional binding material and 6.3 and 4.8 mm size EP aggregate to produce concrete with the density ranging from 550–2200 kg/m³. They found that mechanical properties of concrete deteriorate with the increase of EP content in mortar compositions. Coarse aggregate replacement by EP waste aggregate by six levels i.e., 5 %, 10 %, 15 %, 20 %, 25 % and 30 % was studied in [11]. Density of 1800 kg/m³ and compressive strength of 9 MP was obtained with the maximum EP content. Authors [14] claim that LWAC with density ranging from

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800 to 1800 kg/m$^3$ and compressive strength ranging from 10 to 25 MPa can be developed by partial replacement of coarse and fine aggregate by EPS beads. Tests showed that EPS concretes, with densities ranging from 1150 to 1350 kg/m$^3$, have strengths ranging from 3.5 to 12 MPa [13].

Research results proved that EP, used separately or in combination with other lightweight aggregates, is a promising filler in foamed concrete. According to studies conducted by other authors [15], foamed lightweight concrete with very small amounts of cement (from 70 to 130 kg/m$^3$), expanded glass and EP used as aggregates has good thermal conductivity coefficient (0.048–0.077 W/(m·K)), but low strength (0.35–0.73 MPa). Other authors [16] report the performance characteristics of super lightweight concrete with bulk density ranging from 300 to 500 kg/m$^3$ and compressive strength ranging from 0.7 to 2.5 Mpa, when normal aggregates were replaced with EP aggregates, while foam was introduced to facilitate manufacture process. Studies [8] on using EP waste in light-weight composites report that recycled EP waste can be used as aggregates in the formulation of heat insulating light-weight cement composites. Such composites have density of 150–170 kg/m$^3$, heat transfer coefficient of 0.06–0.064 W/(m·K), and compressive strength of 0.25–0.28 MPa. Authors [10], who studied heat transfer of similar composites containing EP aggregates, found that in composites with density ranging from 150 to 350 kg/m$^3$, compressive strength ranging from 0.09–0.42 MPa, flexural strength ranging from 0.09–0.39 MPa, heat transfer coefficient changed from 0.048 to 0.095 W/(m·K) in proportion to EP content in the mix. Gypsum slabs containing 50 %–70 % of crushed EP were developed [7]. The density of such composites dropped from 690 to 208 kg/m$^3$ and heat transfer coefficient dropped from 0.240 to 0.183 W/(m·K).

However, the use of EP has limitations as follows: due to low density (12–20 kg/m$^3$) and hydrophobic surface (chemical treatment of EPS surface is required) EP has poor distribution in the mix and the aggregates may float on the surface causing poor workability and lower strength of concrete [14]. The solutions to this limitation are the change of EP aggregates size and content in the mix and the use of different additions. Researchers claim that with smaller EP aggregates size an increase in EP concrete strength is obtained [18]. EP aggregates size effect on compressive strength of EP concrete was tested in [11, 17].

The results of compressive tests showed that the smaller is EP aggregates size, the greater is compressive strength of concrete for the same concrete porosity. Reduction in density (150–500 kg/m$^3$), strength (0.42–2.5 MPa) and heat transfer coefficient (0.048–0.095 W/(m·K)) of PLWAC can be achieved by changing the amount of EP aggregates [10]. It is necessary to create PLWAC with higher values of strength properties seeking to increase the use of different ways resulting EP waste in construction industry. The main objective of this study was to provide a more detailed research on the effect of (EPR/EPU) ratio on physical and mechanical properties of PWLAC. EPR was obtained from crushed EP waste, and EPU was obtained from big size EP sheet milling waste.

2. Materials and methods of testing

Ordinary Portland cement (OPC) CEM I 42.5 R, characterized by the specific surface of 420 m$^2$/kg, bulk density of 1100 kg/m$^3$ was used for testing. Mineral composition of cement, %: C$_3$S – 56.64, C$_2$S – 16.72, C$_3$A – 8.96, and C$_4$AF – 10.59.

EPR aggregates were obtained by crushing household packaging waste in wood shredder BIO-50. Fractions of 0.5/5 mm with bulk density of 9 kg/m$^3$ were produced in the shredding process. EPU aggregates with bulk density of 16 kg/m$^3$ were obtained in big size EP sheet milling process. Particle size distribution of EP waste aggregates is presented in Table 1. Images of EPR and EPU aggregates are presented in Figure 1. Water absorption kinetics for EPR and EPU aggregates is presented in Figure 2.

Milled sand (MS) obtained from AB Anykščių kvartas (Lithuania). 90 % of particles are finer than 45µm. Bulk density 1100 kg/m$^3$. Specific surface area, 490 m$^2$/kg.
Table 1. Particle size distribution of EPR and EPU aggregates.

| Aggregates | Residue on the sieve (mm),% |
|------------|----------------------------|
|            | 5.0 | 4.0 | 2.8 | 2.0 | 1.4 | 1.0 | 0.5 | 0.355 | 0.25 | 0.18 | > 0.18 |
| EPR        | 30.0| 38.0| 21.0| 8.0 | 2.0 | 0.5 | 0.5 | -    | -    | -    | -     |
| EPU        | -   | 0.26| 3.59| 10.51| 25.38| 20.13| 28.46| 5.77 | 2.56 | 1.15 | 2.18  |

Metakaolin (MK) obtained from UAB MC-Bauchemi with specific surface of 885 m²/kg and density of 345 kg/m³ was used in concrete mixtures. Two different admixtures – superplasticizing (SP) admixture based on polyacrilate ester, and air entraining (AE) admixture, (white powder with pH 8.1), were used in concrete mixtures. The amounts of SP (0.55 %) and AE (0.02 %) in concrete mixtures were constant. W/C ratio in compositions (presented in Table 2) was changed from 0.81 to 0.65 with the aim to maintain equal spread of concrete mixtures.

Concrete mixtures (compositions are presented in Table 2) were prepared as follows: at first, water was mixed with OPC, SP, and AE for 2 minutes. Then, MK and MS were added and the mixtures were mixed for 3 minutes. Afterwards, the necessary amounts of EPR and EPU were added to the mixture and mixed for 5 more minutes. The prepared concrete mixture was poured into steel moulds (100×100×100) mm and slightly compacted with a wooden board (so as not to damage the structure of aggregates) and additionally compacted for one minute on a vibrating plate. All concrete mixtures were prepared in a laboratory mixer with a vertical rotation axis by forced mixing at a speed of 125 rpm. The moulds were kept in hermetic plastic bags for two days, then the specimens were demoulded and kept before treating for 2, 7 and 28 days (50 % RH at 20±5°C) in laboratory conditions.

Table 2. PLWAC compositions.

| Batch | Used materials, % |
|------|-------------------|
|      | OPC | MK | MS | EPR | EPU | EPR/EPU | SP* | AE* | Water* | W/C |
| K0.5 | 50  | 20 | 25 | 1.70| 3.30| 0.5      | 0.2 | 0.025| 40.3   | 0.81 |
| K1   | 50  | 20 | 25 | 2.50| 2.50| 1.0      | 0.2 | 0.025| 38.4   | 0.77 |
| K1.5 | 50  | 20 | 25 | 3.00| 2.00| 1.5      | 0.2 | 0.025| 35.0   | 0.70 |
| K2   | 50  | 20 | 25 | 3.30| 1.70| 2.0      | 0.2 | 0.025| 33.8   | 0.67 |
| K2.5 | 50  | 20 | 25 | 3.60| 1.40| 2.5      | 0.2 | 0.025| 33.0   | 0.66 |
| K-3  | 50  | 20 | 25 | 3.75| 1.25| 3.0      | 0.2 | 0.025| 32.5   | 0.65 |

* Above dry solids content

Particle size distribution of aggregates, bulk density, for EP were measured in accordance with standard tests (EN 933-1, EN 1097-6+AC, EN 12664). The microstructure of EPU aggregate was inspected using SEM Helios NanoLab 650.

The macrostructure of EPR and EPU samples was inspected using an optical microscope, equipped with a digital camera and connected to the computer. Dry density, compressive strength of PLWAC specimens was measured in accordance with standards EN 1602, EN 12089 and EN 826. Changes in the structure of PLWAC specimens were measured by the ultrasonic pulse velocity method using the device Pundit 7 (range from 0.1 to 6553 µs, resolution 0.1 µs, and frequency of transducers 54 kHz). The final test result was taken as the average value calculated out of at least 5 successful measurements. The measuring surface of standard cylindrical heads was pressed against the specimen at two strictly opposite points. Vaseline was used to ensure a good contact. Ultrasonic pulse velocity (UPV) was calculated from the equation (1):

\[ V = \frac{l}{\tau} \times 10^6 \]  

where \( l \) is the length of the tested PLWAC concrete specimen (distance between cylindrical heads), \( \tau \) is time of pulse propagated.
3. Results and discussions

As it is seen in Figure 1, EPR aggregates are of different size and have a spherical form. The surface of some aggregates is damaged. EPU aggregates have irregular form, there are damages on the upper layer, closed-cell structure is not intact. These irregularities are clearly seen in EPU microstructure tests.

![Figure 1. Structure: (a) – EPR macrostructure, (b) – EPU macrostructure, (c) – EPU microstructure.](image)

The analysis of water absorption kinetics (Figure 2) of EPR and EPU aggregates showed that EPR had a less damaged structure and water absorption in these aggregates increased from 39 % to 96 % throughout the entire testing time (up to 28 days). The cell structure of EPU waste is disrupted; therefore, water fills in all cavities and their water absorption during the measurement increases from 200 % to 382 %.

![Figure 2. Water absorption kinetics in EPR and EPU aggregates after 10, 60 minutes, 7 and 28 days.](image)

The density of PLWAC specimens (Figure 3) after 28 days of curing decreased about 1.4 times (from 720 to 490 kg/m³) when the EPR/EPU ratio was increased. These density values confirmed the findings of water absorption tests indicating that due to its structure EPU absorbed more water and thus the density of specimens increased. The dry density of PLWAC specimens revealed similar trends. When EPR/EPU ratio reached 2, the decrease of density values slowed down. With lower content of fine aggregates water absorption in specimens also decreased and subsequently, with higher EPR content in the mix, there was a little change in density.

The compressive strength of cementitious materials directly depends on the compressive strength of aggregates used. When normal aggregate in concrete was replaced by the porous one (EPR and EPU), the compressive strength of concrete reduced due to the lower strength of aggregates used and due to poor adhesion of cement paste and porous aggregate [18, 19]. After two days of hardening the compressive strength of PLWAC specimens changed from 1.5 to 1.1 MPa with a continuous increase in EPR/EPU ratio up to 2 (Figure 4).
When EPR/EPU ratio reaches 2.5 and 3, the compressive strength of PLWAC specimens significantly decreases down to 0.65 and 0.4 MPa. The growth in compressive strength (50%–67%) was observed in all PLWAC specimens after 7 and 28 days. In our case the compressive strength of the specimens with lower EPR/EPU ratio was higher because in concrete mixtures smaller EPU aggregates filled the voids between larger EPR aggregates in the cement paste and the developed structure led to increased compressive strength of the specimens. On the other hand, higher W/C ratio can negatively influence the compressive strength of PLWAC specimens, as was observed in other studies [20, 21].

The density and compressive strength of PLWAC specimens after curing is also characterised by ultrasonic pulse velocity (UPV) measurement. The UPV in the specimens (Figure 5) was the highest (1880 m/s) when EPR/EPU ratio was the lowest 0.5. With higher EPR content in the mixture UPV reduces down to (1250 m/s). It is known that UPV depends on the density and stiffness of the material, so it increases with an increase of EPU amount in concrete mixture [22, 23].
4. Conclusions

- The effect of the EPR/EPU ratio (which varied from 0.5 to 3) on the properties of PLWAC specimens containing OPC, MK, MS, superplasticizer and air entraining admixtures was investigated.
- It was observed that EPR and EPU differ by their structure and thus have different water absorption kinetics. During 28 days water absorption of EPR reached 96%, whereas water absorption of EPU reached 382%.
- When EPR/EPU ratio in the PLWAC increased to 2, compressive strength of the specimens dropped from 2.3 to 1.75 MPa and density dropped from 720 to 530 kg/m$^3$. The increase of EPR/EPU ratio up to 3 causes a slight drop in density down to 490 kg/m$^3$, and a significant drop in compressive strength down to 0.55 MPa. The reduction of compressive strength is caused by different structure of EPR and EPU, varying W/C and structural changes in PLWAC, which are observed from UPV tests. When EPR/EPU ratio in concrete mixture composition reaches 3, UPV drops to 40% compared to the specimens where EPR/EPU ratio is 0.5.
- The tests revealed that with the increase of EPR/EPU ratio in the mixture from 0.5 to 3, the dry density of PFAC specimens decreased from 550 to 410 kg/m$^3$.

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