Effect of Adhesion Between EPS Granules and Cement Matrix on the Characteristics of Lightweight Concretes

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Abstract. The paper presents the results of examinations of the effect of modification of EPS granulate on the compressive strength of lightweight concrete composites. EPS granulate was used to volumetrically replace mineral aggregate with the amount of 50% and 75%. Modification of EPS granulate consisted in coating with cement slurry and cement slurry with silica dust. It was found that the coating of the EPS granulates followed by preparation of the concrete mix leads to an increase in adhesion of EPS to the cement matrix. This results in significantly higher compressive strength compared to concrete based on unmodified EPS aggregate. Concrete made with 50% of EPS granules previously coated with cement slurry with silica dust obtained an average compressive strength of 18.3 MPa, which was by 18.1% higher than that of concrete with unmodified EPS.

1. Introduction

According to the PN-EN 206 [1] standard, lightweight concrete means a concrete with density in dry state ranging from 0.8 to 2 t/m³. In order to obtain lightweight concrete, light aggregate with grain density in the dry state below 2 t/m³ or bulk density in the loose state below 1.2 t/m³ is used. Aggregates meeting these requirements include: natural pumice, volcanic aggregates, perlite, expanded slate, sintered slate, expanded clay, pollytag, blast furnace slag, etc. Commonly used aggregates for lightweight concretes are characterized by high porosity, and thus high water absorption, which leads to a high value of the effective water content. The effective water content is the difference between the amount of water added to the concrete mix and the amount of water absorbed by the aggregate during mixing (preparation) of the concrete mix. During production of lightweight concretes, it is therefore quite often necessary to pre-saturate the lightweight aggregate in order to reduce the amount of water absorbed.

Lightweight concretes are characterized by appropriate corrosion resistance and very good insulation, but lightweight aggregates, having low density and high porosity, lead to obtaining concretes with relatively low high mechanical parameters. Despite this fact, lightweight concretes have been increasingly used in civil engineering for many years, with the interest in such concretes growing year by year. By using lightweight aggregate and some kind of modifications, it is possible to obtain structural concretes, which can compete with conventional concrete composites. Due to low density of lightweight concretes, they reduce the loads from the mass of the members, which enables the cross-sections of the members to be reduced, thus allowing larger spans to be achieved. Furthermore, lightweight concretes can play a major role in seismic areas as they reduce the risk of damage to the structure due to their mass in the event of an earthquake. Lightweight concretes are not
only characterized by a lower density, but also have a much higher compressive strength to mass ratio and a much lower thermal conductivity coefficient in comparison to conventional cement-bonded concretes [2-4].

More and more often EPS (expanded polystyrene) granulate is used as an aggregate for lightweight concrete. Individual EPS granulates have a spherical shape, contain about 98% air and 2% polystyrene, and, due to their closed structure, are non-absorbent and ultralight. The first explorations and tests of the use of EPS aggregate in concrete were carried out in the 1970s by Cook [5]. Since then, EPS concretes made of polystyrene foam balls have been successfully used as structural components of walls in the form of blocks, as load-carrying layers in floor systems, and for production of foam concretes, floating water structures, energy-absorbing elements, cladding panels and protective walls [6-8]. The energy analysis for a one-storey house concerning the use of wall panels made of EPS concrete was carried out by Dissanayake et al. [8]. Based on the tests, these researchers found that a prefabricated EPS concrete system offers a better solution than conventional ceramics in terms of CO₂ emissions, the speed of construction and labour intensity.

Quite a serious limitation to the use of EPS granules for concrete is their extremely low density and hydrophobicity, which makes it difficult to mix the concrete mix, because these granules tend to flow to the surface of the compacted mixture. Consequently, the concrete obtained is characterized by unstable distribution of EPS granulate and high segregation. In order to limit this effect, EPS granules were subjected to a treatment based on the use of binding additives in the form of epoxy resins. Such a procedure also made it possible to increase the strength of the contact layer between the EPS granules and the cement matrix [10]. The effect of the contact layer between the aggregate surface and the cement matrix on the mechanical properties of conventional concrete composites has been confirmed by many researchers [11]. The contact layer in lightweight concretes between the surface of EPS granules and cement slurry has the same effect on mechanical properties. A slightly different modification of the contact layer of EPS granules with cement matrix was proposed by Kaya et al. [12], who used waste polystyrene foamed together with cement and tragacanth adhesive (resin) in amounts of 0.5%, 1% and 1.5% of the total amount of cement and EPS. EPS granules were dosed in the amounts of 20, 40, 60 and 80 % of the total volume of concrete composite. Based on the study, the researchers concluded that concretes with the use of waste EPS, including tragacanth resins, can be successfully used as a construction material with high thermal resistance. The use of waste EPS, which is a non-biodegradable material, reduces energy consumption in construction and helps solve environmental problems.

Another method of modification of EPS granules was proposed by Kan and Demirbog [13]. They modified the waste EPS granules by heat treatment by heating them in the furnace at 130°C for 15 minutes. Thermally modified EPS granules were used to replace the mineral aggregate by dosing them in quantities of 25, 50, 75 and 100% of the volume of conventional aggregate. In this way, very satisfactory values of concrete compressive strength (from 12.5 to 23.3 MPa) were obtained. The increase in the content of EPS in concrete mixes caused deterioration in their workability and difficulties with its compaction. Deterioration in the degree of fluidity of concrete mixes with an increase in the content of EPS and an obvious decrease in mechanical properties was also observed. Tests carried out for 300 cycles of freezing and thawing did not confirm their low-temperature resistance. The decline in strength after 300 cycles ranged from 52 to 68%. Despite the negative evaluation of low temperature resistance, concretes made with the use of thermally modified waste EPS granules can be successfully used as a construction and insulation material. Furthermore, such use of recycling waste brings measurable benefits of reduced disposal costs.

Ganesh Babu et al. [14] attempted to increase the strength of concretes made with EPS aggregate by using silica dusts in the amount of 3, 5 and 9% of cement mass. Based on the conducted research, they concluded that the addition of silica dust has a positive effect on the rate of development of compressive strength and that the mechanical parameters are affected by the size of the EPS balls. Concrete strength increased with the decrease in the diameter of EPS balls [7,14]. Mileda et al. also conducted research on the effect of EPS granulate size on mechanical properties of concrete [15].
They performed strength testing of concrete made of EPS granules with diameters of 1mm, 2.5mm and 6.3mm, and found that as the size of the granules increased, the compressive strength declined. Similar results were presented in the paper [16], in which the authors used cements with fly ash and silica dust to make lightweight concretes with EPS. In the study [17], an additive in the form of fly ash in the amount of 50% of cement mass was added to EPS concretes. This allowed to obtain very satisfactory results of compressive strength. After 28 days, EPS concretes were characterized by strength above 18 MPa, while 90-day strength exceeded 23 MPa. These mechanical parameters represent the basis for the use of EPS concretes as construction materials. Fernando et al. [18] carried out testing of EPS concretes with the addition of 25% of fly ashes [18], used to obtain lightweight 2400 mm high concrete wall panels. They used 50% new EPS granules and 50% recycled EPS granules from foamed polystyrene boards used as packaging material for concrete. After the recycled EPS was fragmented in special crushers, it was added to the production of wall panels. Based on the tests, the authors found that foamed concrete with the addition of new and recycled EPS granulate can be used for wall panel production using double-sided cement-fibre boards. These panels had satisfactory bending strength of 1.64 MPa and compressive strength specified on full-size panels of 2.89 MPa. The study [4] confirmed the usefulness of EPS as a recycling material for the production of lightweight concretes. It was found that the amount of EPS granules has a large impact on the workability of the concrete mix, its density and shrinkage. The shrinkage in conventional concretes is essentially affected by the strength of the cement matrix and the aggregate, which represents a hard (rigid) filling of the composite. In case of using aggregate in concrete in the form of elastic EPS granules, they constitute a small obstacle to the shrinkage of the matrix. Bing Chen et al. [19] proposed to reduce the shrinkage of concrete with EPS granules by adding a 25 mm long steel fibre. They showed that EPS concrete with a density of 0.8 to 1.8 t/m$^3$ with the addition of silica dusts can increase compressive strength to 25 MPa, whereas steel fibre limits concrete shrinkage.

In the paper [20], the attempt was made to use EPS granules for self-compacting concretes (SCC). Aggregate in the form of EPS was used in quantities of 10, 15, 22.5 and 30% by volume to replace conventional mineral aggregate. The results obtained in the study showed that mixtures with an EPS content of up to 22.5% met the criteria for self-compacting concretes. Another use of lightweight concretes made of EPS aggregate was proposed in the study [21], where EPS concrete was used to build external concrete barrier layers between traffic lanes. Concrete with the addition of EPS granules made it possible to obtain a material with an increased ability to absorb energy during a road collision compared to conventional concrete. Replacement of 15, 30 and 45% by volume of coarse aggregate with EPS granulate resulted in a decrease in concrete strength by 55, 64 and 79 % compared to conventional concrete, respectively. Nevertheless, the concrete which dissipated the impact energy during the accident was obtained. In tests with simulated impacts at speeds ranging from 50 to 130 km/h for control concrete without EPS, its deformations were much greater than those recorded for EPS concretes. The authors believe that increasing the content of EPS granulate to more than 50% would allow for the increase in energy dissipation to more than 95%.

2. Range of tests
The presented literature analysis shows that cement composites made on EPS aggregate have been widely used not only as insulating concretes but also as structural concretes. In most cases, one problem in obtaining high strength of such concretes is to ensure or even increase adhesion between the surface of the EPS granulate and the cement matrix, which directly affects their mechanical properties.

EPS was modified in order to increase the strength of the contact layer between these phases (EPS granulate and cement matrix). It consisted in previous coating of EPS granules with cement slurry. EPS granules had diameter ranging from 4 to 5 mm. The granules were immersed and mixed in separately prepared cement slurry (and cement slurry with silica dust) for about 5 minutes. After this time, they were drained from the slurry and distributed on a metal worktop so that they would not stick to each other. For the next 3 hours, they were also blown with air. EPS granules prepared in such a
way were used to make concretes. For comparison purposes, control concretes were prepared, made of granulate without modification (series E) and of granulate which had previously been coated with cement slurry (series ME). Furthermore, the series in which EPS granules were coated with cement slurry with the addition of silica dust (SME series) were made. Modified EPS granules are shown in Figure 1.

![Modified EPS granules (coated with cement slurry).](image)

The mass proportions of the components from which the slurry was prepared for granule coating were identical to those used in the subsequent series of concrete. The water-cement ratio in all series was W/C=0.47, including the liquid plasticizing admixture. BASF's Master Ease 3002 admixture in the amount of 0.9% of cement mass was used for all separately prepared cement slurries (to be coated with EPS) and to make concrete mixes. Silica dusts were dosed into concrete mixes and separately prepared slurries for EPS coating in the amount of 7.5% of cement mass.

Concretes were made, in which natural aggregate was replaced by modified and unmodified EPS granules with the amounts of 50% and 75%. CEM II/A-V 42.5R Portland multi-component cement was used for all series. Concrete compositions are presented in Table 1.

### Table 1. Concrete compositions in kg/m³.

| Series | Cement | Water | Silica dusts | Liquefying admixture | Natural aggregates | EPS granules | Volume of EPS in total aggregate volume, % |
|--------|--------|-------|--------------|----------------------|-------------------|--------------|------------------------------------------|
| E 50   | 390    | 181.5 | -            | 3.5                  | 914               | 6.9          | 50                                       |
| E 75   | 390    | 181.5 | -            | 3.5                  | 457               | 10.4         | 75                                       |
| ME 50  | 390    | 181.5 | -            | 3.5                  | 914               | 6.9          | 50                                       |
| ME 75  | 390    | 181.5 | -            | 3.5                  | 457               | 10.4         | 75                                       |
| SME 50 | 390    | 181.5 | 29.3         | 3.5                  | 914               | 6.9          | 50                                       |
| SME 75 | 390    | 181.5 | 29.3         | 3.5                  | 457               | 10.4         | 75                                       |

For all series of concretes, compression strength tests after 7 and 28 days of maturation and density tests in dry state were performed.

### 3. Results

Compressive strength tests were carried out on cubic specimens with an edge of 150 mm according to PN-EN 206-1 [1] and PN-EN 12390-3 [22]. Volumetric density tests were performed using the
hydrostatic method in accordance with PN-EN 12390-7 [23]. The results of the tests are presented in Table 2.

| Series | Mean compressive strength f_{cm}, MPa | Density, kg/m³ |
|--------|--------------------------------------|---------------|
| E 50   | 8.1                                  | 1547          |
| E 75   | 5.4                                  | 989           |
| ME 50  | 9.3                                  | 1558          |
| ME 75  | 6.3                                  | 1009          |
| SME 50 | 10.0                                 | 1553          |
| SME 75 | 6.9                                  | 994           |

After 28 days, concrete of E50 series made of EPS aggregate without modifications, which replaced 50% of natural aggregate volume, yielded the average compressive strength of f_{cm}=15.9 MPa. Modification of EPS by coating the granulate with cement slurry resulted in an increase in the average concrete strength of the ME50 series by 14.8% after 7 days and by 8.4% after 28 days compared to the strength of the control concrete of the E50 series. Similar relationships were found for concrete made of granulate coated with cement slurry containing micro-silica. The SME50 series concrete achieved an average compressive strength increase of 23.5% after 7 days and 18.1% after 28 days compared to the E50 series control concrete. Replacement of natural aggregate with 75% EPS granulate resulted in lower average strength of concretes, but also significantly lower densities compared to similar concretes with 50% of EPS granules. The mean compressive strength of concrete (ME75) with EPS granulate modified by coating it with cement slurry increased by 16.7% after 7 days and by 14.2% after 28 days compared to the control concrete of the E75 series. Concrete of SME75 series with 75% of EPS granulate, coated with cement slurry and silica dust was characterized by higher strength, by 27.7% after 7 days and 15% after 28 days compared to control concrete of E75 series.

4. Conclusions
The tests conducted in the study lead to the following conclusions:
- EPS granules can be successfully used as a substitute for mineral aggregate for the production of lightweight structural concretes of medium compressive strength of above 18 MPa,
- the strength of concrete with EPS granules depends on the strength of the cement matrix and on the contact layer between the EPS and the cement matrix,
- concretes made of modified granules (coated with cement slurry and cement slurry with silica dust) achieved significantly higher compressive strength compared to concretes with the same percentage of unmodified granules,
- concrete with 50% of the EPS granulate coated with cement slurry with silica dust was characterized by higher strength after 28 days of maturation by 18.1% compared to concrete with unmodified EPS. Similar to the concrete with 75% of granulate, the increase in strength was 15%,
- the production of the coating from cement slurry around the EPS granulate leads to a significant improvement in the adhesion of the EPS to the cement matrix, and consequently, to an increase in mechanical properties.

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