

Effect of Waste Expanded Polypropylene-Based Aggregate on Mechanical and Thermal Properties of Lightweight Concrete

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Abstract. Resource efficiency and building energy consumption is in recent years an open question for construction industry. Recycled plastic aggregate can be used as an alternative aggregate to produce lightweight concrete with low environmental impact of both concrete and waste plastic and moreover, the obtained lightweight concrete is characterized by improved thermal insulation properties. In the present study, waste expanded polypropylene (EPP) aggregate is used for partial replacement of natural aggregate to produce lightweight cement-based composites containing synthetic coagulated amorphous SiO₂ as supplementary cementitious material. For the applied EPP, basic physical properties were measured and specific attention was paid to thermal transport and storage properties that were studied in dependence on compacting time. The effect of EPP content on the mechanical characteristics and on the thermal properties of developed material was investigated for 28 and 90 days water cured samples. Composite with incorporated EPP aggregates exhibits enhanced thermal insulation properties with sufficient mechanical resistance and can be considered as promising material for building subsoil or floor structures.

1. Introduction

The building industry has consumed a vast amount of natural resources and also been responsible for a significant energy usage. This is expected to increase further with economic development where more people will need quality housing. Therefore, any building material that minimizes the usage of natural resources or use waste materials to a certain extent could have promising future [1].

Since the 20th century, plastics have been used increasingly in a large range of products because of their favourable properties, including low density, high strength-to-weight ratio, high durability, ease of design and manufacture, and low cost [2]. The top three markets for plastics are packaging, building and construction and automotive. However, large amounts of plastic waste give much pressure on the environment due to very low biodegradability of plastics [3]. The global production of plastics in 2014 was around 311 Mt. In 2014 in Europe, 25.8 Mt of post-consumer plastic waste ended up in the waste upstream. Plastic waste recycling in Europe have increased to almost 30 %, however landfilling and energy recovery still constitutes a large part of plastic waste disposal [4].

Reuse of waste and recycled plastic materials in concrete mix is able to combine both economic growth and environmental protection. A large number of studies undertaken on concrete containing waste plastic particles have demonstrated that plastic aggregate can reduce the cost and significantly improve unit weight and the thermal and acoustic insulation parameters of developed composites [5], [6], [7]. On the other hand, many studies reported on worsening of mechanical properties of concrete with incorporated plastic waste aggregate [2], [6], [8].



Since most of the published literature is focused on the use of polyethylene terephthalate (PET) and high density polyethylene (HDPE) aggregates, and because the recycle ratio for polypropylene (PP) is only 0.6 %, which makes it one of the least recycled post-consumer plastics [9], this paper is concerned to study the effect of expanded PP particles as partial silica sand replacement for the development of lightweight concrete with improved thermal insulation properties.

2. Experimental

Expanded polypropylene used in this study was obtained as shredded waste from aircraft model production. Basic physical and thermal properties of EPP aggregate were measured at first. Lightweight concrete was then prepared using Portland cement CEM I 42.5 R (Czech-Moravian cement, Ltd., HeidelbergCement group, Mokrplant), silica sand (Filtrační písky, Ltd., affiliate Chlum u Doks), synthetic coagulated amorphous SiO₂ (Silica VP4, AV EKO-COLOR, Ltd.), water and EPP waste, which was used as partial replacement of silica sand of 60 % by volume. Dynamon SX 45 (Mapei Ltd.) superplasticizer was used to achieve good workability. As ultra-lightweight aggregate tends to float and can result in a poor mix distribution and segregation [10], Silica VP4 as admixture for improvement of dispersion of EPP particles in the cement matrix was used. The silica sand was mixed from three size of sand with granulometry PG1 (0.06 3/0.5 mm), PG2 (0.08/1 mm) and PG3 (1/2 mm) respectively in weight ratio 1:1:1. The water/cement ratio was 0.5 for all investigated mixtures. For comparative reasons, the reference sample without EPP was prepared as well. Table 1 gives chemical characteristics of cement and silica VP4. In Table 2, composition of tested mixtures is shown.

Table 1. Chemical composition of cement and silica VP4.

Chemical composition (mass %)	Cement CEM I 42.5 R	Silica VP4
SiO ₂	19.5	91.1
Al ₂ O ₃	4.7	0.1
Fe ₂ O ₃	3.2	0.03
CaO	64.2	0.00
MgO	1.3	0.00
Na ₂ O	0.09	0.78
K ₂ O	0.78	< 0.01
SO ₃	3.2	0.00
Loss on ignition (LOI)	3.3	4.75

Table 2. Mix design of studied lightweight concretes.

	CEM (g)	VP4 (g)	Sand (ml)	EPP (ml)	Water (g)	Dynamon (g)	w/c
Ref	1387.5	112.5	3300	0	750	30	0.5
EPP	1387.5	112.5	1300	2000	750	30	0.5

The casted prismatic samples 40 × 40 × 160 mm and cubic samples with side dimension of 70 mm were left for 1 day at laboratory conditions and then they were unmoulded and cured for 28 days (Ref28, EPP28) resp. 90 days (Ref90, EPP90) in water.

2.1. EPP aggregates

For the basic physical characterization of EPP grains, their powder density, matrix density and grain-size distribution were measured. The matrix density was determined using automatic helium pycnometer Pycnomatic ATC (Thermo Scientific) with fully integrated temperature control with precision of ± 0.01 °C and real multi volume density analyser. The matrix density achieved value of 105 kgm^{-3} , which ranks EPP aggregates among artificial ultra-lightweight (density of less than 300 kg/m^{-3}) nonabsorbent aggregate as classified by Babu and Babu [10]. The grain-size analysis was realized using standard sieve method with sieves of following mesh dimensions: 0.063; 0.125; 0.25; 0.5; 1.0; 2.0; 4.0; 8.0; 16.0; 31.5 and 63.0 mm. Obtained results shows that size of all EPP particles is below 8 mm, what is favourable for their use as partial replacement of natural aggregate.

To determine thermal insulation properties of EPP aggregates, powder density and thermal properties namely thermal conductivity λ ($\text{Wm}^{-1}\text{K}^{-1}$), volumetric heat capacity C_v ($\text{Jm}^{-3}\text{K}^{-1}$) and thermal diffusivity a (m^2s^{-1}) of EPP particles were measured in dependence on compacting time. During the measurement, EPP aggregate was put into graduated cylinder and compacted using the vibration exciter. From the known mass of the sample in cylinder and its volume, the powder density was evaluated. To determine thermal parameters, the commercially produced device ISOMET 2114 (Applied Precision, Ltd.) was used as a representative of transient impulse methods [11], [12]. The measurement is based on an analysis of the temperature response of the analysed material to the heat flow impulses. For the measurement of EPP aggregate, needle probe was used. The measurement accuracy was 5 % of reading + 0.001 W/mK for the thermal conductivity in the range $0.015\text{-}0.70 \text{ Wm}^{-1}\text{K}^{-1}$ and 10 % of reading for the thermal conductivity ranging from $0.70 \text{ Wm}^{-1}\text{K}^{-1}$ to $6.0 \text{ Wm}^{-1}\text{K}^{-1}$. The accuracy of the volumetric heat capacity was 15 % of reading + $1 \times 10^3 \text{ Jm}^{-3}\text{K}^{-1}$.

2.2. Basic physical characteristics

As fundamental physical characteristics of prepared composites, bulk density, matrix density and total open porosity were measured. Samples were first dried in a vacuum drier at 60 °C. The matrix density was measured using automatic helium pycnometer as described above. The bulk density was determined using the measurement of sample sizes and dry mass of the sample according to EN 12390-7 [13]. The total open porosity was determined on the basis of bulk density and matrix density measurement. The relative expanded uncertainty of porosity test was 5 %.

2.3. Mechanical properties

The mechanical properties of casted materials were evaluated on $40 \times 40 \times 160$ mm prismatic samples, which were cured 28 resp. 90 days in water. Mechanical resistance of researched concretes was characterized by compressive strength, flexural strength and Young's modulus. The flexural strength was tested according the standard EN 12390-5 [14]. The compressive strength was determined by following the standard EN 12390-3 [15] on the broken halves of samples from the flexural strength tests. The loading area was 40×40 mm. The relative expanded uncertainty of the both testing methods was 1.4 %. The Young's modulus was obtained on a dynamic principle using the pulse ultrasonic method. This method is based on the measurement of travel time of ultrasonic wave launched from the device and passing through the material. The measurement was done on $40 \times 40 \times 160$ mm prismatic samples in a longitudinal direction using device DIO 562 (Starman's Electronics) working on the frequency of 50 KHz [16]. Before the ultrasonic measurement, the samples were dried in a vacuum drier at 60 °C. The relative expanded uncertainty of the dynamic Young's modulus measurement was 2 %.

2.4. Thermal properties

In order to quantify the influence of the plastic aggregates on improvement of heat transport and storage properties of prepared composites, their thermal conductivity, volumetric heat capacity and thermal diffusivity were obtained using device ISOMET 2114 (see above). Before the particular tests, the samples were dried at 60 °C in a vacuum drier until their constant mass was achieved.

3. Results and discussion

The data on matrix density, bulk density and porosity of tested materials is given in Table 3.

Table 3. Basic physical properties of tested materials.

Material	Matrix density (kgm^{-3})	Bulk density (kgm^{-3})	Porosity (%)
Ref28	2306	1984	14.0
EPP28	1798	1437	20.1
Ref90	2320	1998	13.9
EPP90	1800	1443	19.8

The bulk density of samples containing EPP aggregates reached value of 1800 kgm^{-3} ; this composite can be therefore classified as lightweight concretes (bulk density $< 2000 \text{ kgm}^{-3}$) in D2.0 class according to the standard EN 206-1 [17]. As expected, the matrix and bulk density values were for samples after 90 days of curing slightly greater than for specimens after 28 days of curing and conversely, porosity decreased with age of samples. In accordance with the literature [8], the use of plastic aggregate resulted in the increased porosity compared to the reference mixture due to the addition of materials with an extremely heterogeneous morphology, which modified workability and amount of entrained air in the mixture.

The mechanical properties of the tested composites are introduced in Table 4.

Table 4. Material properties of tested materials.

Material	Compressive strength (MPa)	Flexural strength (MPa)	Young's modulus (GPa)
Ref28	53.6	9.7	25.7
EPP28	20.8	5.1	8.1
Ref90	54.3	10.7	25.8
EPP90	21.4	5.9	10.9

Babu and Babu [10] stated that the strength of concrete is mainly influenced by the strength of the aggregate. This finding together with the higher porosity and with the low bond strength between the surface of EPP particles and the cement paste resulting from the hydrophobic nature of EPP led to the decrease in mechanical resistance of the developed EPP lightweight concrete in comparison with concrete without plastic aggregate. These results are in accordance with results of other studies, where plastics were used as aggregate for production of concretes/mortars (e.g., [2], [5], [6], [7], [18]). As expected, all mechanical characteristics increased with curing time for both reference samples and samples with incorporated EPP, due to the prolonged hydration time and development of denser concrete structure.

Thermal parameters of plastic waste aggregate together with corresponding powder density are presented in Table 5. With increasing powder density, the thermal conductivity as well as the volumetric heat capacity increased. This is due to the reduction of air gaps during compaction that can be anticipated during preparation of light-weight concrete with incorporated EPP aggregate. Generally, the EPP aggregate had significantly better thermal properties than silica aggregates commonly used in the concrete industry [19].

Table 5. EPP aggregate properties in dependence on compacting time.

Compaction time (s)	Powder density (gcm ⁻³)	λ (Wm ⁻¹ K ⁻¹)	C_v ($\times 10^6$ Jm ⁻³ K ⁻¹)	a ($\times 10^{-6}$ m ² s ⁻¹)
0	0.0189	0.042	0.049	0.96
10	0.0224	0.043	0.055	0.80
30	0.0233	0.044	0.058	0.75
60	0.0239	0.044	0.061	0.72
180	0.0243	0.047	0.062	0.69

Table 6 gives the thermal properties of the investigated composites in the dry state.

Table 6. Thermal properties of tested materials.

Material	λ (Wm ⁻¹ K ⁻¹)	C_v ($\times 10^6$ Jm ⁻³ K ⁻¹)	a ($\times 10^{-6}$ m ² s ⁻¹)
Ref28	1.86	1.81	1.09
EPP28	0.69	1.58	0.47
Ref90	1.88	1.82	1.10
EPP90	0.71	1.66	0.50

The presence of EPP particles with advantageous thermal properties caused substantial reduction in the thermal conductivity of the developed lightweight concrete. The replacement of silica sand by EPP aggregates of 60 % in volume is resulting in a 63 % reduction in the thermal conductivity compared to the reference material. Similarly, Herrero et al. [5] stated that 20 % in mass addition of PE waste aggregate leads to the thermal conductivity below one half of its original value. The data obtained show the positive effect of EPP aggregates content on the moderation of heat transport in the developed material.

4. Conclusions

The paper has reported the results of experimental study on the mechanical and thermal properties of lightweight concrete with incorporated waste EPP-based aggregate. These results indicate that use of plastic aggregates decreases the mechanical resistance of the developed materials. However, for intended application in multi-layered floor structures or as the core of sandwich panels the mechanical parameters of EPP modified material are quite sufficient. Lightweight concrete with EPP exhibits enhanced thermal insulation properties, which indicates promising potential for future development in terms of building energy efficiency as well as plastic waste disposal.

5. References

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