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Structural, mechanical and hygrothermal properties of lightweight concrete based on the application of waste plastics

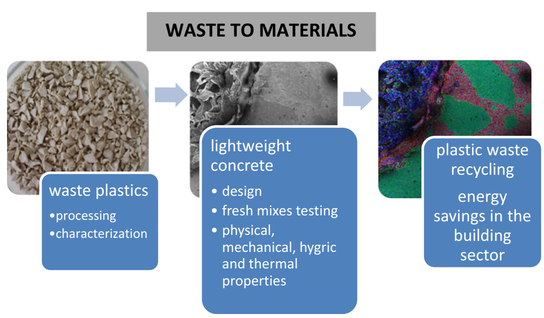
Martina Záleská [a], Milena Pavlíková [a], Jaroslav Pokorný [a], Ondřej Jankovský [b], Zbyšek Pavlík [a,*], Robert Černý [a]

[a] Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7, CZ-166 29 Prague 6, Czech Republic
[b] Department of Inorganic Chemistry, Faculty of Chemical Technology, University of Chemistry and Technology, Prague, Technická 5, 166 28 Prague 6, Czech Republic

HIGHLIGHTS

- Lightweight concrete with different types of plastic waste-based aggregates.
- A wide set of basic physical, thermal, and hygric properties.
- Mechanical parameters satisfactory for non-bearing concrete structures.
- Interesting solution with respect to plastic waste recycling.
- Potential energy savings in the building sector.

GRAPHICAL ABSTRACT



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ABSTRACT

Three different types of plastic waste replacing up to 50% of natural aggregates are used in concrete mix design. A wide set of basic physical, mechanical, thermal, and hygric properties of developed concretes is determined and their assessment is made using a comparison with reference data. The mechanical parameters, though decreasing with the increasing amount of plastic aggregates, are found satisfactory for non-bearing concrete structures. The up to seven times lower thermal conductivity, as compared with the reference material, provides an evidence of greatly improved thermal insulating capabilities. The hygric properties of designed concretes are characterized by an increase of water and water vapor transport parameters and a decrease of water vapor adsorption capacity with the increasing amount of plastic aggregates. Based on the obtained experimental results, a conclusion can be made that the designed lightweight concretes containing plastic waste aggregates present a prospective solution from the points of view of both plastic waste disposal and improvement of buildings' energy efficiency.

1. Introduction

For the past 150 years, plastic materials have been key enablers for innovation and have contributed to the development and progress of society. Plastics meet the needs of a wide variety of markets due to their characteristic features, such as low density, good strength, ease of design, processability, durability, and low cost [1]. The top three markets for plastics are building and construction, packaging, and automotive. However, large amounts of plastic waste exert a pressure on the environment due to its low biodegradability. Several kinds of plastics are produced at present, where most often used are polyethylene terephthalate (PET), polypropylene (PP), polyethylene (PE), melamine, polyvinylchlo-

* Corresponding author.
E-mail addresses: martina.zaleska@fsv.cvut.cz (M. Záleská), milena.pavlikova@fsv.cvut.cz (M. Pavlíková), jaroslav.pokorny@fsv.cvut.cz (J. Pokorný), ondrej.jankovsky@vscht.cz (O. Jankovský), pavlikz@fsv.cvut.cz (Z. Pavlík), cernyr@fsv.cvut.cz (R. Černý).

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ride (PVC), polyurethane foam, polycarbonate (PC), and glass fiber reinforced plastic [2]. The large growth of plastics consumption observed all over the world in recent years and consequently the increased quantity of plastic-related waste requires new forms of recycling, avoiding landfill disposal [3]. The global production of plastics in 2014 was around 311 Mt, with China and Europe as the major consumers with 26% and 20% [4,5]. In recent years in Europe, plastics recycling have increased, but landfilling still constitutes a large part of plastic waste disposal [4]. While eight EU member countries, as well as Norway and Switzerland, landfill less than 10% of their plastic waste, eleven other Member States still landfill more than 50%. The monitoring of plastics waste recycling and recovery performed on behalf of PlasticsEurope and the European Association of Plastics Recycling and Recovery Organisations (EPRO) for the 2016 revealed the following key facts for EU-28 countries plus Norway and Switzerland: collected post-consumer waste reached 25.1 million tons, recovery reached 72.7%, plastics packaging has the highest recycling and recovery rates, for the first time more plastics waste was recycled than landfilled [6]. Accordingly, Žmak and Hartman [7] reported on a significant difference on recycling between different countries in the EU. For example the Netherlands and Belgium recycle 61% and 56% of their plastic waste, respectively. On the other hand, Bulgaria recycles only 6% and Romania 1% of its plastic waste, while the remaining waste ends up on landfills. Based on the given facts of plastics recycling it is evident Europe is losing economically valuable resources by landfilling of plastics waste. This situation is challenging for EU authorities to introduce new policies to increase recycling quotas and to adopt the "Zero plastics to landfills concept" [6].

The existence of a serious worldwide energy problem is now generally recognized by governments and industry leaders. Buildings are responsible for approximately 40% of energy consumption and 36% of CO_2 emissions in the EU [8]. The 2010 Energy Performance of Buildings Directive [9] and the 2012 Energy Efficiency Directive [10] are the EU's main legislation promoting the improvement of the energy performance of buildings within the EU. According to an update of the Energy Performance of Buildings Directive approved on 19 December 2017, new buildings must be nearly zero-energy buildings by 31 December 2020. In residential sector, air conditioning system takes the biggest portion of overall energy consumption to fulfil the thermal comfort need [11]. In addressing the issue, thermal insulation is one efficient technology to utilize the energy in providing the desired thermal comfort by its environmentally friendly characteristics Therefore, the close interrelationships between building materials and energy should be well addressed and investigated [12]. The indoor climate of buildings and the energy losses are strongly affected by the hygrothermal performance of building envelopes and their airtightness. For the improvement of energy efficiency of buildings, there is necessary to focus on advanced technical solutions of building design resulting in building envelopes with high thermal resistance. To obtain buildings with preferable thermal attributes and optimum energy performance, the development and use of materials with suitable thermal insulation properties should be taken into consideration [13]. The topicality of buildings energy efficiency issues clearly characterizes a number of recent review papers on insulation materials for energy conservation in buildings [11,14,15].

The construction industry, acknowledging the importance of environmental issues, has sought to find solutions that are able to combine both economic growth and environmental preservation. One of the methods, with a particular attention to the consumption of natural raw materials for concrete aggregates, is the substitution of sand by recycled plastic aggregates in cementitious materials (mortars or concretes) [16]. Plastic waste may be incorporated into concrete or mortars in varying amounts and in various forms: (i) fibers or aggregates (flakes, pellets, small pieces); (ii) one type of polymer waste or mixture of plastics; (iii) crushed waste or regranulated waste; (iv) various particle size distribution, which usually differs from sand, whereas their addition has a number of beneficial effects on the material properties of resulting compound. Several authors explored the use of lightweight aggregate based on polymeric waste as a material reducing the cost and unit weight of building materials, such as concrete or mortars, and improving their thermal and acoustic insulation parameters, as well as absorption of mechanical energy [1,17–20]. On the other hand, many authors reported worsening of rheological and mechanical properties of concrete containing plastic aggregates [17,2]. This material behavior is probably affected particularly by the shape and size of used plastic particles. In that respect, the main possible non-bearing application of these materials is in the form of lightweight concretes with enhanced thermal insulating properties for building subsoil or floor structures, sandwich panels for prefabricated enclosures, fence panels, or as a part of anti-noise barriers [1]. Polyethylene terephthalate (PET) and high density polyethylene (HDPE) were the most frequently used plastic aggregates in concrete mix design to date. Polypropylene (PP) and glass fiber reinforced plastics (GFRPs) were utilized relatively scantly for that purpose. Moreover, they were often used in mixtures with other types of plastic or with another waste as fly ash or wood [2,3,21–23].

As PP and GFRPs were only scantly studied as possible aggregate in lightweight concrete mix, three types of PP wastes originating from PP tubes production are used in this paper for the development of lightweight cement-based composites with enhanced thermal insulation properties. The main intention of this work is to study the effect of plastic particles used as a partial sand substitution on the basic physical, mechanical, thermal, and hygric properties of cement-based composites. Such complex analysis comprising assessment of hygrothermal performance of the developed composites and its linking with structural parameters was not presented yet, as most of the published papers dealing with waste plastics-based aggregate is focused on mechanical resistance and thermal properties assessment only. For detailed information on materials performance in real environmental and indoor conditions is such complete set of experimentally tested material parameters necessary both for material research and practical use of examined materials. The application of PP waste in lightweight concrete can be considered as an interesting solution with respect to plastic waste recycling, and potential energy and material savings in the building sector.

2. Materials and methods

2.1. Materials

Lightweight concrete samples were prepared using an ordinary Portland cement CEM I 42.5 R (Heidelberg Cement Group, Mokrá plant, Czech Republic); the chemical composition and the main physical properties of the cement are presented in Table 1.

The silica sand of fraction 0–2 mm (Filtrační písky Ltd., Chlum u Doks, Czech Republic) was mixed from three subfractions in a weight ratio of 1:1:1. As a partial replacement of natural aggregates, crushed polypropylene random copolymer (CPPR), regranulated polypropylene random copolymer (RPPR) and crushed glass fiber reinforced polypropylene (CPPGF) was employed. PP waste used in this research was obtained from the PP tubes production in company FV-Plast, a.s., Czech Republic. The PP waste was crushed in the production plant and used in concrete mixtures as received, without any further treatment. The waste plastics were not contaminated by any impurities, chemicals, dust, etc. For mixed silica sand and PP waste particles, grain-size distribution curves were measured. The grain size analysis was realized using the standard sieve method EN 933-1 [24] with sieves of the 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. The grain size distribution of natural and PP waste aggregates is given in Fig. 1. All plastic particles were smaller than 8 mm, which was favorable for their incorporation into the composite mixes.