

# Thermal Stability of Lightweight Concrete with Incorporated Regranulated Polypropylene Aggregate

L Scheinherrov á<sup>1</sup>, M Z áesk á<sup>1</sup>, M Pavl kov á<sup>1</sup> and Z Pavl k<sup>1</sup>

<sup>1</sup> Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague, Th ákurova 7, 166 29 Prague 6, Czech Republic  
E-mail: pavlikz@fsv.cvut.cz

**Abstract.** Plastic waste and its low recycling rate make a significant contribution towards the pollution of the environment. Therefore, it is essential that plastic waste is utilised in different applications, such as aggregates in concrete. Since the coefficient of thermal expansion of polypropylene (PP) is significantly higher than for the ordinary concrete, the resulting mismatch in thermal expansion behaviour of the lightweight concrete can cause many problems, especially when the external temperatures reach the higher values. In this paper, an investigation of a manufactured plastic aggregate as a partial replacement for natural silica aggregate in concrete is presented. For concrete manufacturing, regranulated polypropylene (R-PP) waste coming from PP pipes production was used for the partial replacement of silica sand in concrete mix composition by 10, 20 and 30 mass % respectively. The studied materials were heated up to 120 °C. The basic physical properties before and after thermal treatment were studied. To analyse the thermal strain and the coefficient of thermal expansion of the studied materials, the horizontal thermodilatometry was applied.

## 1. Introduction

Plastic materials have become a very important part of our everyday life. Their properties, such a low density, strength, user-friendly design, long life and especially low cost make them easily accessible what leads to their growing consumption. Since their commercial development in the 1930s and 1940s they have been widely used in packaging, buildings and constructions, medical delivery systems, communication materials, automotive and industrial applications, or for example in security systems [1, 2]. Global plastic resin production reached about 311 Mt in 2014 which is a 670% increase since 1975 [3]. While plastics production around the world grows steadily, the situation in Europe has been stable within the last several years. It reaches the values around 55–59 Mt per year [3]. The most popular plastic material is polypropylene (19.2% of the total plastics utilization), mainly used for folders, food packaging or car bumpers [3]. The worldwide utilization of plastics brings many problems with their following recycling since there are still many countries where the landfilling is still the first option how to treat plastic waste. Even when the Czech Republic belongs to the list of these countries, it has doubled the volume of plastics being recycled in less than a decade. While it reached only 7% rate of recycling at the beginning of the millennium, it recorded about 30% in 2014. This result put the Czech Republic in the second place in recycling PET bottles and in the fourth place in the whole Europe's overall packaging recycling performance [4]. There is also an increasing amount of companies interested in plastics waste recycling, what helps to improve the numbers of recycled plastics.

The utilization of waste and recycled plastic materials as a part of a concrete structure makes it not only economical, but it also helps to reduce the disposal problems of an increasing amount of plastic



waste. There have been many research works concerned about the use of recycled plastics in concrete as aggregate. One of the most important concrete properties to study are the basic physical properties, which define its structure and can describe expected behaviour of the fresh/hardened concrete mixture. Al-Manaseer and Dalal [5] reported that bulk density of concrete decreases with an increasing amount of plastic aggregates content and that this decrease is directly related to the plastic aggregates content. This trend is one of the reasons why the plastic waste is mostly used in the design of lightweight concrete [6]. The plastic aggregate can reduce not only the weight, but it also reduces the cost of concrete. Besides this, it improves the thermal and acoustic insulation parameters, as documented by many research papers [7-9]. This is given by the fact that plastic waste aggregate has significantly lower thermal conductivity than the natural aggregates [7]. On the other hand, the incorporation of the plastics into the concrete mixtures leads to a decrease of the mechanical properties [7, 9]. Furthermore, since their coefficient of thermal expansion (CTE) is significantly higher than for the plain concrete, the resulting mismatch in thermal expansion behavior can cause many problems when the external temperatures varies from  $-30\text{ }^{\circ}\text{C}$  to  $+40\text{ }^{\circ}\text{C}$  and more [10]. Some research works offered to combine the plastics of the appropriate sizes (nanoscales) with glass fiber reinforcement to reduce the CTE [10, 11].

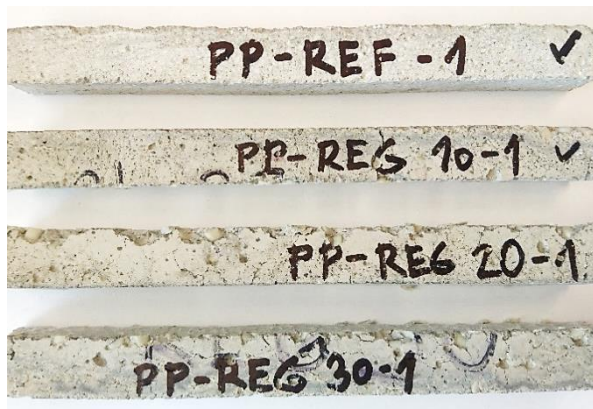
In this paper, the utilization of plastic waste coming from the production of plastic pipes for pressure distribution of water in the design of lightweight concrete is studied. The R-PP waste is used as a partial replacement of natural aggregates by 10, 20, and 30 mass% respectively. The intention of this research paper is to study the influence of plastic particles on the basic physical properties and thermal properties of lightweight concrete after its exposure to the temperature of  $120\text{ }^{\circ}\text{C}$ .

## 2. Experimental

Regranulated waste polypropylene (R-PP) used in this research paper was obtained from the production of plastic pipes for pressure distribution of water, namely from the company FV Plast (Čelákovice, Czech Republic). The plastic waste (see Figure 1) was being cut into small pieces of the 2–8 mm. Its matrix density was determined using automatic helium pycnometer Pycnomatic ATC (Thermo Scientific), and it was found to be  $921\text{ kgm}^{-3}$ .



**Figure 1.** RPP waste used for the preparation of the lightweight concrete mixtures.



**Figure 2.** Studied mixtures with different amounts of RPP waste.

Lightweight concrete was prepared using an ordinary Portland cement CEM I 42.5 R (Czech-Moravian cement, Ltd., HeidelbergCement group, Mokr á plant), silica sand of fraction of 0–2 mm (Filtrační písky Ltd., affiliate Chlum u Doks, Czech Republic), batch water, and R-PP waste which was used as a partial replacement of natural aggregates by 10, 20, and 30 mass% respectively. The water to cement ratio was chosen as 0.5 for all studied mixtures. The composition of the studied materials is summarized in Table 1.

The reference sample without any RPP waste was labelled as REF; the samples containing 10, 20 and 30 mass% of R-PP waste were labelled in accordance to the amount of plastics used in the lightweight concrete structure.

**Table 1:** Mix proportions of lightweight concrete with incorporated PP waste.

Sample	Mass (g)				Water/cement ratio
	Cement	Natural aggregate	Water	PP waste	
REF	450	1350	225	-	0.5
R-PP-10	450	1215	225	135	0.5
R-PP-20	450	1080	225	270	0.5
R-PP-30	450	945	225	405	0.5

From the prepared mixtures specimens with dimensions of  $40 \times 40 \times 160$  mm for the determination of the basic physical properties; and  $15 \times 15 \times 160$  mm for the horizontal dilatometry analysis were casted (see Figure 2). The samples were kept for one day at laboratory conditions and then they were unmoulded and put in water for 28 days. After reaching this age, the samples were carefully dried in a vacuum at  $60^\circ\text{C}$  to constant mass.

### 2.1. Basic physical properties

Basic physical properties of the studied materials, such as bulk density, matrix density and total open porosity were determined. The bulk density was calculated from the measurement of sample size and its dry mass. The matrix density was measured by automatic helium pycnometer Pycnomatic ATC (Thermo Scientific). The total open porosity was calculated on the basis of the knowledge of these two parameters, as it was already described in [12]. The bulk density tests were done on five samples having size  $40 \times 40 \times 160$  mm. Fragments of samples were used for pycnometric measurements. All measurements took place in an air-conditioned laboratory at the temperature of  $23 \pm 1^\circ\text{C}$  and 25–30% relative humidity. Each result represents the average value from five measured values. The relative expanded uncertainty of applied testing method was 5%.

The basic physical properties of examined samples were measured as after 28 days of water curing as well as after their thermal treatment. The particular samples were heated from the room temperature of  $25^\circ\text{C}$  to  $120^\circ\text{C}$  with a heating rate of  $1^\circ\text{Cmin}^{-1}$ .

### 2.2. Thermal properties

One of the main motivations of this paper was the determination of the influence of R-PP waste on the thermal properties of the designed lightweight concretes. Since the thermal strain is one of the most important parameters in case of sun exposure of materials' surface, the horizontal thermodilatometry was chosen for this analysis. This method is in accordance with EN 13471 [13]. For the measurement, a unique horizontal thermodilatometer designed by Clasic CZ, Ltd. (Řevnice, Czech Republic) was used. The apparatus consists of a furnace for placing the studied material. It is heated using a resistance heating and the temperature distribution is controlled using a thermocouple type S. The temperature is displayed using Orbit Merret OM 351. The Sylvac ms229 digital indicator having resolution  $0.001$  mm and repeatability  $2\ \mu\text{m}$  measures the length changes, and its calibration is provided by Micro Precision Calibration Inc. accredited according ISO 17025 [14]. The calibration was done using an alumina rod. Rectangular prisms having dimensions of  $15 \times 15 \times 160$  mm were used for the measurement. The analysis was performed in a horizontal arrangement under a static air atmosphere within the temperature interval from  $25^\circ\text{C}$  to  $120^\circ\text{C}$  with a heating rate of  $1^\circ\text{Cmin}^{-1}$ . The length changes (%) of the studied materials were measured as a function of temperature. The results were used for the calculation of the linear thermal expansion coefficient  $\alpha$  ( $^\circ\text{C}^{-1}$ ), as described in equation (1)

$$\alpha = \frac{d(l_T / l_0)}{dT} = \frac{d\varepsilon}{dT}, \quad (1)$$

where  $l_0$  is the original length of the sample (m),  $l_T$  is the temperature dependent length (m),  $T$  is the temperature (°C or K), and  $\varepsilon$  the thermal strain (-) of the studied sample.

Three samples of the each designed material were used for the analysis. The mean value was then determined and presented in this study.

### 3. Results and discussion

#### 3.1. Basic physical properties

The results of the basic physical properties, such as matrix density, bulk density and total open porosity of examined materials before and after thermal treatment are summarized in Table 2 and Table 3, respectively. The matrix density of the reference material was  $2508 \text{ kgm}^{-3}$ . The results of the materials with incorporated R-PP waste indicate that the matrix density tends to decrease by 12%, 19%, and 26% for R-PP-10, R-PP-20, and R\*PP-30, respectively, compared to the reference samples. This trend is attributed to the density of the plastic waste which is significantly lower than the sand used which is in accordance with data reported in literature [15]. The matrix density values did not change after the heating up to  $120^\circ\text{C}$ . The bulk density of REF samples reached value of  $2064 \text{ kgm}^{-3}$ . The bulk densities significantly decreased with an increasing amount of R-PP waste in the studied mixtures and reached values in the range between  $1533\text{--}1837 \text{ kgm}^{-3}$ . Therefore, in accordance to the standard EN 206-1 [16] these materials can be classified as lightweight concretes having the bulk density values lower than  $2000 \text{ kgm}^{-3}$ . The total open porosity was also calculated and was found to be lower than 18% for all studied mixtures. The materials R-PP-10 and R-PP-20 reached lower porosity values compared to the reference samples; while the samples having 30 mass% of the RPP waste had a slightly higher total open porosity. However, the differences in porosity were in the range of measuring uncertainty. The lower amounts of RPP waste (up to 20 mass%) caused that the nonporous structure of this plastic waste decreased the total open porosity of cement composite, whereas the workability and therefore air absorption in the structure of the fresh mixes were not negatively affected. On the other hand the higher amount of plastic waste slightly increased the porosity due to its bigger particles what led to the general coarsening of composites inner structure [17]. This “formation a new type of porosity” is discussed also in [18].

**Table 2.** Basic physical properties of tested materials before thermal treatment.

Material	Matrix density ( $\text{kgm}^{-3}$ )	Bulk density ( $\text{kgm}^{-3}$ )	Total open porosity (%)
REF	2508	2064	17.7
R-PP-10	2202	1837	16.6
R-PP-20	2035	1690	17.0
R-PP-30	1865	1533	17.8

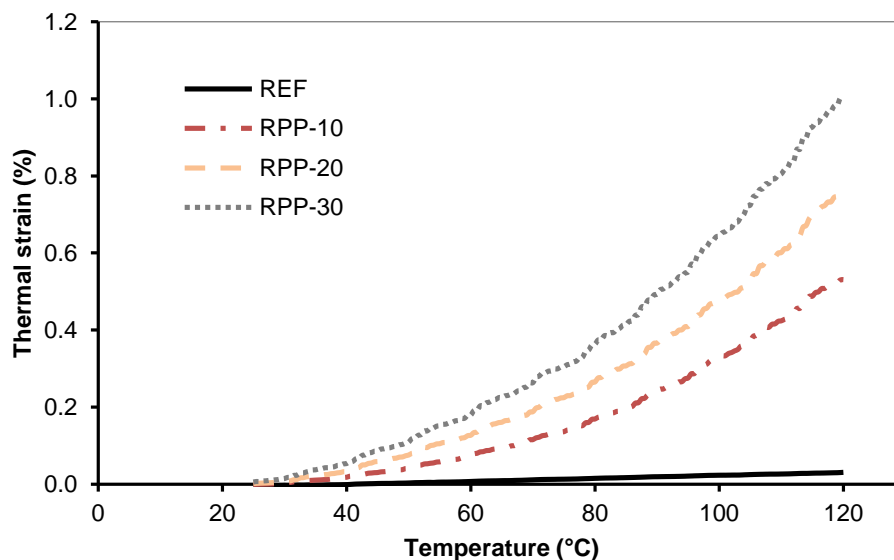
The basic physical properties of the developed composites were studied also after the thermal treatment. Because there was no obvious difference in the results when the samples were cooled down to the room temperature, the bulk density and total open porosity were calculated from the known parameters during heating at the maximal temperature of  $120^\circ\text{C}$ . The mass change in this temperature range was not expected to be changing because the samples were dried before the tests were done. The size of the samples changed mainly in the horizontal direction during the horizontal thermodilatometry measurements. Based on the new maximal lengths of the samples, new characteristics were calculated. The results are summarized in Table 3. As it can be seen from the obtained results, the bulk density of the studied materials slightly decreased with the temperature applied which led to the increase of the total open porosity. Increasing values of the total open porosity then can cause a decrease in the mechanical properties, which has been widely discussed in literature [15, 19-21].

**Table 3.** Basic physical properties of tested materials after thermal treatment.

Material	Bulk density (kgm <sup>-3</sup> )	Total open porosity (%)
REF	2063	17.7
R-PP-10	1827	17.0
R-PP-20	1679	17.5
R-PP-30	1518	18.6

From the results of the basic physical properties before and after thermal treatment from 25 °C to 120 °C, it can be concluded that this temperature interval does not significantly affect these material characteristics.

### 3.2. Thermal properties

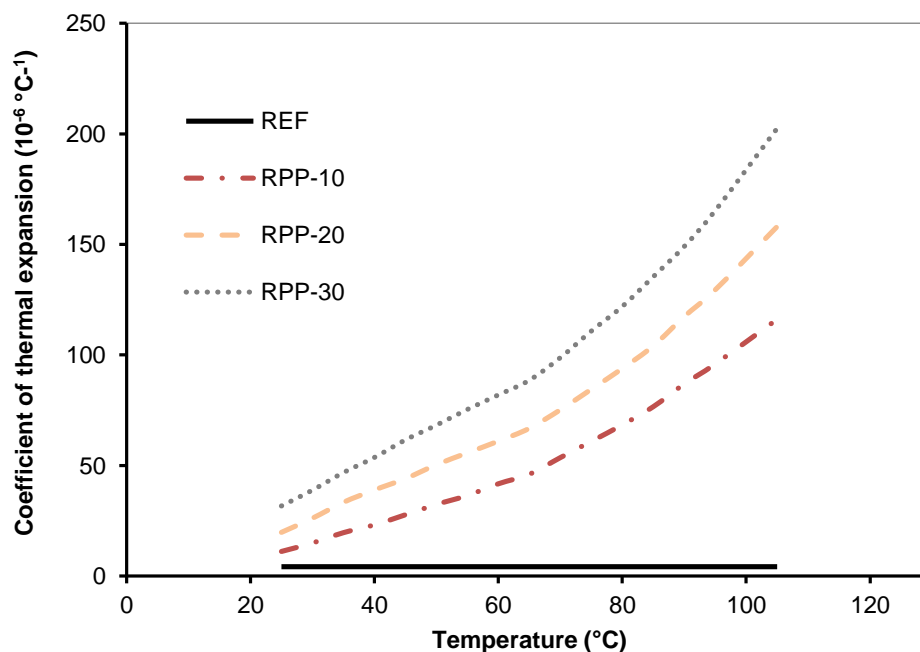
**Figure 3.** Thermal strain curves of the studied lightweight concrete mixtures as functions of temperature.

The results of the thermal properties obtained from the horizontal thermodilatometry are shown in the Figure 3 and 4, respectively.

The results of the thermal strain (calculated in %) of the REF samples were significantly lower than in case of the samples having R-PP waste in the mix. The strain of the designed mixtures is strongly linked to the expansion of the aggregates, as aggregates represent about 75-80% of the volume of concrete [22]. Recently, in the study presented by Koňáková et al. [23], the influence of basalt and silicate aggregates on the thermal expansion of cement-based composites was studied. They confirmed that the basalt aggregates are more stable in the term of thermal expansion in a comparison to the silica aggregates. On the other hand, the thermal strain of both studied aggregates in their study was almost the same in the temperature interval from 25 °C to 120 °C, which is the scope of this study. The thermal strain of the REF samples achieved the highest value of 0.03% of the initial length at the temperature of 120 °C. The trend of the obtained curve was almost linear with no significant increase, which is in a good accordance with the fact that the samples were dried before the thermal treatment, and there was no water evaporation occurred. The effect of the sand aggregates is usually observed at

higher temperatures [24]. Since the other materials presented in our study contained up to 30 mass% of R-PP waste, which is thermally not stable and expands more significantly than the plain concrete under a thermal load, the results of the thermal strain are mainly in accordance to the behaviour of polypropylene [10]. The maximal thermal strains of the samples labelled as RPP-10, RPP-20, and RPP-30 were determined as 0.53%, 0.76%, and 1.00%, respectively. These values are almost ten times higher than for the REF samples what should be taken into account in their further applications. Nevertheless, these results show that the cementitious materials produced from R-PP waste achieved better thermal properties than other PP modified materials, as it can be seen in literature [25].

Since the coefficient of thermal expansion is calculated from the thermal strain values, it also highly depends on the type of aggregates used in the mixture [24, 26]. The CTE of cement paste is usually between  $11.0 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$  and  $20 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ , while the CTEs of lightweight concretes are around  $7 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$  and  $13 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ , respectively. These values depend on many other factors besides the type of aggregates; mainly on how the hardened concrete is cured, its relative humidity, the proportion of the coarse versus fine types of aggregates, the mineral admixtures, and some small fluctuations can be observed due to age of samples [24, 26-30]. Thermal strain/CTE can be also affected with varying water to powder ratio (the fine material content, including cement), as observed in [24]. It shows that the thermal behaviour of concrete is in accordance to its air void system, which is the result of the porosity and the water to cement ratio of concrete. The system of voids in concrete can lead to the decrease of the internal pressure of the material resulting in a lower thermal strain. This is probably one of the reasons why the thermal strain of the REF material was found low in our study. Since the thermal strain was found to be almost a straight line in the temperature interval from 25  $^{\circ}\text{C}$  to 120  $^{\circ}\text{C}$ , the CTE was considered as a constant value based on its determination from equation (1). It was  $4.23 \times 10^{-6}$  which is in accordance with the results of the self-consolidating normal aggregate concrete designed in [24]. The content of R-PP waste has a significant impact on the results of the CTE of studied materials, as it can be seen in Figure 4. The higher amount of R-PP waste leads to an increase of the CTE. In a contrary to the REF material results, the CTE of the materials with the R-PP waste increases with the temperature in the entire studied temperature range.



**Figure 4.** CTE curves of the studied lightweight concretes as functions of temperature.

The CTEs of the studied materials at chosen temperatures are summarized in Table 4. The CTEs of R-PP-10, R-PP-20, and R-PP-30 were calculated as  $11.13 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ ,  $19.76 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$  and  $31.70 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ , at the temperature of 25  $^{\circ}\text{C}$ , respectively. It is challenging to find a literature dealing with the

same plastics waste like in our case to compare our results. To our best knowledge, the closest results were found in [25], where 30 mass% talc-filled PP composites reached values of  $50 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ .

**Table 4.** CTEs of tested materials at selected temperatures.

Temperature ( °C)	Coefficient of thermal expansion ( $\times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ )			
	REF	R-PP-10	R-PP-20	R-PP-30
25	4.22	11.13	19.76	31.70
65	4.22	46.03	66.80	88.56
105	4.22	116.14	158.06	202.48

The replacement of silica sand by RPP waste aggregates of 30 mass% is resulting in a significant increase of the thermal strain and the CTEs of studied materials which has a negative effect on the thermal stability of the designed materials.

#### 4. Conclusions

In this research study, the effect of the use of R-PP waste as a partial replacement of silica sand in concrete mixture composition on chosen properties of lightweight materials was studied. The plastic waste coming from PP pipes production was used for the partial replacement of silica sand in concrete mix composition by 10, 20 and 30 mass% respectively. To observe thermal stability of R-PP modified materials, they were heated up to 120 °C. From the results of the basic physical properties, it can be concluded that the higher R-PP content decreases the bulk density, which is mostly related to the low weight of R-PP. The total open porosity of the studied materials was lower than 18%. These characteristics were almost not affected by the thermal exposure to 120 °C.

Replacing the silica sand with R-PP waste increases both the thermal strain rate and the CTE of the hardened lightweight materials. The extension effect increases with increasing volume of R-PP waste in the mixture. Therefore, an improvement of the thermal stability of the studied materials is necessary to allow their wider use.

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