Testing thermophysical and mechanical properties of cement-based composites with plastic and horse manure

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Abstract. Cement-based composites change their properties in dependence on added materials. Scientific papers display results on changes in various mechanical and thermophysical properties. In this paper, the effect of different amount of plastic in two shapes (granules and fibers) and horse manure on thermophysical and mechanical properties of cement-based composites are tested. To understand the structural changes 1-D process of water uptake and porosity measurements were done. The economic growth brings new possibilities for industry development but also increasing problem with waste disposal. Our tests were aimed at finding the optimal balance between plastic disposal in cement based materials and changes in some important properties. The best results of thermophysical properties were for plastic and natural fibers, where horse manure samples had even better mechanical properties than plastic ones.

1. Introduction

The 20th century witnessed substantial growth in the consumption of plastic, which is considered the most significant innovation of this century. In the 21st century, plastic belongs to the top 25 environmental concerns. Plastic recycling in concrete is often given as a good example of help with plastic disposal problems [1, 2].

The idea of plastic recycling or its disposal in cement based materials is based on the following facts. Cement-based composites are the most widely used materials in building construction. Available plastic polymers have a number of vital properties which could be beneficial for construction needs, e.g. corrosion resistance, good sound and heat insulation properties [3, 4]. Plastic is already used in concrete reinforcing as one kind of fibers (steel fiber, glass fiber, natural fiber, synthetic fiber) [5].

Several review articles, e.g. [6,7] have dealt with the contemporary state of knowledge in the properties of cement-based composites with some kind of plastic. The increase of concrete production means the increased amount of required mineral aggregates. Hence some researchers started with plastic waste substitution of mineral aggregates. The substituted amount was from 3-50% [7]. The measurements showed improvement in thermophysical properties, but decrease in mechanical properties. Plastic has different affinity to water and entraps air molecules, so the porosity changes [7]. Our approach was different. We did not replace the sand; plastic waste was added in two shapes: granules and fibers.

When testing fibers’ addition, the plastic fibers were often compared to the natural ones. Natural fibers are biodegradable and it means shorter service life. New kinds of plastic fibers were produced and so the initial idea of recycling led to increased production of plastic. Therefore we also used horse manure, which fibers harden with time, and we compare it to plastic fibers. Our initial testing with plastic waste from recycled polyethylene (LDPE) Bralen Na7-25, Slovnaft, Bratislava, Slovakia, previously used for packaging (plastic bags, plastic films, containers including bottles, etc.) in the form of the granules with the size Φ4x4 mm showed the improvement of thermophysical properties. The results were better for the
samples with 20 percent of waste granules and the same was true after the artificial ageing (to test changes in the course of time) [8]. The aim of this work is to compare influence of added materials on thermophysical properties.

2. Materials and Methods

Plastic waste in the form of the granules with the size \( \Phi 4x4 \) mm was obtained from recycled polyethylene (LDPE) Bralen Na7-25, Slovnaft, Bratislava, Slovakia, previously used for packaging (plastic bags, plastic films, containers including bottles, etc.). Plastic fibers (PP) with the length 12-18 mm were made by Adfill Co., Hull, Great Britain. Horse manure was taken from the horse training center Carpathia, Bratislava, Slovakia. We used Cement Ladce (Portland-composite cement) CEMII / B-M (S-L) 32.5R, Bratislava, Slovakia and the finest fraction sand, Bratislava, Slovakia with the diameter <0.064 mm.

Samples with 10% (calculated from volumetric amount of cement and sand together) of plastic granules, plastic fibers and horse manure were tested on thermophysical and some mechanical properties. The densities of samples can be seen in table 1 and the composition of samples can be seen in table 2.

Table 1. Density of components.

| Component | Cement (kg\( m^{-3} \)) | Sand (kg\( m^{-3} \)) | Water (kg\( m^{-3} \)) | LDPE (kg\( m^{-3} \)) | PP (kg\( m^{-3} \)) | HM (kg\( m^{-3} \)) |
|-----------|--------------------------|------------------------|-------------------------|-----------------------|-------------------|-------------------|
| Density (kg\( m^{-3} \)) | 1292 | 1717 | 1000 | 560 | 338 | 153 |

Table 2. Composition of samples.

| Sample           | Cement (cm\(^3\)) | Sand (cm\(^3\)) | Water (cm\(^3\)) | Additive (cm\(^3\)) |
|------------------|-------------------|-----------------|------------------|---------------------|
| Pure concrete    | 350               | 1050            | 350              | 000 (none)          |
| C. with 10 % LDPE| 350               | 1050            | 350              | 140 (granules)      |
| C. with 10 % PP  | 350               | 1050            | 350              | 140 (fibers)        |
| C. with 10 % HM  | 350               | 1050            | 350              | 140 (manure)        |

The samples were prepared according to the norm BS EN 12390-1:2012, dried for 30 days, and afterwards put into the oven with ventilation at the temperature 90°C for 7 days. The surfaces of all samples were polished to achieve smooth surfaces. LDPE = recycled polyethylene, PP = polypropylene, HM = horse manure, C. = concrete.

The samples with the base 100 x 100 mm and prescribed thickness (ranging from 14 to 15 mm) of the individual parts were measured for thermophysical properties at the temperatures: -30°C, -15°C, 0°C, 15°C and 30°C. The resulting values of the quantities were determined by the arithmetic average of ten measurements on four samples. The reproducibility for thermal conductivity measurement is 3% of reading + 0.001 W/m.K and for specific heat 3% of reading + 1 J/kg.K.

The principle of pulse transient method is in figure 1. The samples and additives are shown in figures 2-3.

Figure 1. Principle of the pulse transient method where \( T = \) temperature and \( t = \) time.
Figure 2. Samples (left picture: upper left - pure concrete, upper right - concrete with spheres, lower left - concrete with fibers, lower right - concrete with horse manure).

Figure 3. Additives (left - spheres, middle - fibers, right - dry horse manure). Caliper is depicted for size comparisons of additives.

The thermophysical parameters - specific heat, thermal diffusivity, and thermal conductivity - are calculated according to the following relations [9]: specific heat \( c = \frac{Q}{\sqrt{2\pi\rho hT_m}} \), thermal diffusivity \( a = \frac{h^2}{2T_m} \) and thermal conductivity, \( \lambda = acp \), where \( Q = R t_0^2 \), \( R \) is the electrical resistance of the heat source, \( t_0 \) is the width of the current pulse, \( \rho \) is the sample density, \( I \) is the heating current of planar heat source, \( h \) is the width of the sample, \( T_m \) is the temperature increase of the sample, as defined in figure 1 and \( e \) is Euler’s number.

Expected uncertainty for each of the properties is 5% depending on pore size distribution. The diameter of thermocouple is about two orders of magnitude higher than the ones of material pores and so the distribution of pores under the thermocouple might be slightly different.

Thermophysical measurements were carried out before and after artificial ageing in climatic chamber BINDER MKF (E3) after 60 temperature and humidity cycles of 12 hours, or 30 days in total, table 3. We tested the longevity of achieved properties. The results are in figures 4-6.

Table 3. The regime of climatic chamber - number of cycles 60 times 12 hours = 30 days total.

| Section | 1   | 2   | 3   | 4   |
|---------|-----|-----|-----|-----|
| Time (hours) | 3   | 3   | 3   | 3   |
| Temperature (°C) | -10 | 20  | 60  | 20  |
| Humidity (%)   | 0   | 70  | 70  | 80  |

Water sorptivity measurement using a free water intake experiment as described in Hall [10] was performed. The water absorption coefficient \( A \), defined as the slope of the initial stage of the cumulative mass of water versus square root of time curve.

The effective pore volume and open porosity were measured and calculated. The whole volume of samples was put into the water and boiled for 50 minutes. After cooling at room temperature the samples were weighted. From the weight difference, before and after boiling, the open porosity was calculated [11]. The results are in the table 4.

The samples for flexural and compressive strength with dimensions 40 x 40 x 160 mm were tested according to the norm EN 196-1 „Cement testing“. Flexural strength was tested with Controls Model 65-L0019B apparatus at loading force 50 N/s. Compressive strength was tested using the Controls Model 1551246001 apparatus at loading force 2000 N/s. Measured quantities are in the table 5.
3. Results
Samples with 10% plastic granules, plastic fibers and horse manure were tested on thermophysical properties.

![Figure 4. Thermal diffusivity values of concrete and concrete with 10% of different additives before and after ageing.](image)

Thermal diffusivity in the temperature range -30 to 30 degrees of Celsius decreased by 12 to 17% for concrete based composites and increased by 17% for concrete. The decrease of thermal diffusivity means higher thermal inertia. The ageing process did not influence the temperature dependence of thermal diffusivity for concrete with additives (figure 4).

![Figure 5. Specific heat values of concrete and concrete with 10% of different additives before and after ageing.](image)

The difference between specific heat of concrete and concrete with additives was 60%. The smallest increase of specific heat value within temperature interval (-30, 30°C) was for concrete with 10% of plastic fibers (2%). Temperature changes of specific heat (after ageing) within the tested temperature range were by 5% (statistically not significant) except for concrete with horse manure (17%) (figure 5).
Figure 6. Thermal conductivity values of concrete and concrete with 10\% of different additives before and after ageing.

Thermal conductivity values decreased for all samples with additives within the tested temperature range by 9\%-28\%. Best observed improvement was for concrete with horse manure. Only for plastic granules thermal conductivity increased compared to pure concrete by 15\% at -30°C. The thermal conductivity of materials depends upon many factors, including their structure, material mixture proportioning, size and type of added materials, density, porosity, the way of mixing, air content etc. Higher volume of plastic waste results in higher air contents, thereby decreasing the unit weight of the composite and its thermal conductivity. It might be due to the non-polar nature of granules and their tendency to entrap air in their rough surfaces. Also the tendency of plastic molecules to repel water enables air adherence to the granules. As for the best results for samples with horse manure they correlate with highest open porosity values of horse manure samples. The values of thermal conductivity after artificial ageing did not change significantly (6\%-8\%) within the tested temperature interval (figure 6).

Table 4. Water absorption coefficient A and open porosity of non-aged concrete and concrete with 10\% of different additives.

| Property                | Pure concrete | C. with 10 \% LDPE | C. with 10 \% PP | C. with 10 \% HM |
|-------------------------|---------------|---------------------|-------------------|------------------|
| Density (kg/m³)         | 2045          | 1845                | 1701              | 1586             |
| Open porosity (-)      | 0.195         | 0.204               | 0.322             | 0.362            |
| A (kg.m².s⁻¹/²)         | 0.075         | 0.061               | 0.127             | 0.193            |

Water absorption and porosity measurements were carried on to understand the material structure. The results are in table 4. Test so far hint to the following understanding. Plastic granules disrupt the capillaries, which leads to lower sorptivity value, but also smaller porosity. Fibers do not change the capillary structure so much and their sorptivity and porosity values are higher. As for 52\% differences in sorptivity value between natural and plastic fibers we suppose the reason is “breathing” of natural fibers. They absorb and release water sooner. Mechanical properties’ testing is important for the future usage of cement based materials. According to density values, we had lightweight concrete samples. Flexural and compressive strength of our samples are listed in table 5.
Table 5. Strength of the samples.

| Sample          | Flexural strength (MPa) | Compressive strength (MPa) |
|-----------------|-------------------------|-----------------------------|
| Pure concrete   | 4.9                     | 21.1                        |
| C. with 10 % HM | 3.5                     | 13.3                        |
| C. with 10 % PET| 2.4                     | 8.2                         |

4. Discussion
Putting the results together we can say that adding plastic waste and horse manure improved thermophysical properties before artificial ageing and after it the results were even better. The best improvement of thermophysical properties was for horse manure fibers then plastic fibers and the least improvement was for plastic granules. Horse manure fibers also proved to have better compressive and flexural strength values.

From the point of environmental concern let us do one simple calculation, which strongly depends on available data, which can vary from source to source, but it is just the basic idea. The annual production of concrete is 25 billion tons [12]. The annual production of plastic is around 350 million tons [13]. Assuming horse population of 58 million [14] and 17 kilograms of horse manure per day per horse [15], the annual production of horse manure is about 350 million tons. Assuming the whole plastic waste would be put into the concrete, its content should be 1.4 wt. %. Assuming the whole horse manure would be put into the concrete, its content should be 1.4 wt. %. Another 8.3 billion tons of plastic waste is already in the landfills [16]. If the plastic content could be increased to 4 wt. %, in about 12 years the plastic waste in the landfills could be eliminated. As the production of plastic grows about 3.3% annually, the elimination time would be prolonged to about 18 years. Assuming hard plastic density of 72 kg/m³, and concrete density around 830 kg/m³ [17] and horse manure density around 830 kg/m³ [18], this translates to 16 vol. % of plastic in concrete to eliminate annual plastic waste production, respectively 46 vol. % of plastic in concrete to eliminate the plastic waste form landfills or 1.4 vol. % of horse manure to eliminate annual horse manure production. There are some drawbacks of these calculations. We did not exclude the high performance concrete production, where addition of plastic is not appropriate, secondly, there are different types of plastic (PP, HDPE, LDPE) with different material properties which determine the feasibility of their use [19].

5. Conclusion
Thermophysical properties of concrete with added horse manure fibers, plastic fibers and granules were measured. Best improvement was for horse manure fibers, where compressive and flexural strength values were also better.

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