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SCRAP TIRE RUBBER-BASED AGGREGATE IN LIGHTWEIGHT CONCRETE

MARTINA ZÁLESKÁ[1], DAVID ČÍTEK[2], MILENA PAVLÍKOVÁ[1], VOJTĚCH BAZGIER[1], and ZBYŠEK PAVLÍK[1]

[1]*Dept of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague, Prague, Czech Republic*
[2]*Dept of Experimental Methods, Klokner Institute, Czech Technical University in Prague, Prague, Czech Republic*

Reusing rubber particles from used tires is good for the environment and, moreover, the world's population is becoming progressively conscious that a very high demand for natural resources is unsustainable. As the concrete industry consumes high amounts of natural resources, both for clinkering and gravel aggregate production, one must focus on its sustainability, considering environmental and economic issues. Therefore, reuse of waste tire rubber in concrete or in other composite materials is a logical solution for sustainable production of construction materials. Hence, the paper is aimed at the development and testing of lightweight concrete composed of a high volume of crushed waste tire rubber used as partial replacement of natural silica aggregate. In order to access the effect of incorporation waste tire rubber-based aggregate in concrete composition, reference concrete mix based on silica aggregate only is studied as well. The crushed waste tire rubber is characterized by its powder density, specific density, and particle size distribution. Specific attention is paid to thermal transport and storage properties of waste rubber that are examined in dependence on compaction time. For the developed lightweight concrete, mechanical, hygric, and thermal properties are tested. The tested lightweight concrete is found to be alternative and environmentally friendly construction material possessing improved thermal insulation function, interesting hygric parameters and sufficient mechanical resistance.

Keywords: Waste rubber, Mechanical resistance, Thermal insulation, Hygric properties, Construction material, Sustainability.

1 INTRODUCTION

Construction materials in which concrete is modified by the replacement or addition of different constituents have been constantly sought due to both performance and environmental considerations (Bompa *et al.* 2017). According to the U.S. Tire Manufacturers Association (2017), 246.4 million of scrap tires were generated in the United States in 2015, which is equivalent to circa 4.0 million tons. Accordingly, In the UK, it is estimated that 37 million car and truck tires are being discarded annually and this number is set to increase with the growth in road traffic by 63% by 2021, as reported by Cairns *et al.* (2004). The scrap tires are disposed of using various methods like landfilling, to produce carbon black, use as fuel and for pyrolysis. However, the easiest and cheapest method of disposal discarded tires is their burning, which causes a serious fire hazard and moreover emits dense black smoke with toxic gases. One of the most environmentally friendly solutions for the treatment of scrap tires is their use in cement concrete to replace the natural aggregate (Thomas and Gupta 2016). Most of the previous studies investigated the utilization of waste rubber in concrete as aggregate with the results indicated a significant reduction in all mechanical parameters, but the improvement of the thermal and sound insulation properties and reduction of the unit weight (Aliabdo *et al.* 2015, Iqbal 2017, Bompa *et al.* 2017).

The present study aims to evaluate the mechanical, thermal and hygric properties of lightweight concrete containing a different proportion of rubber aggregate as partial replacement of coarse natural aggregate. Developed lightweight concrete with rubber can find utilization in non-structural applications with thermal insulation function.

2 EXPERIMENTAL

Rubber particles of fraction 4/8 mm (Figure 1) were obtained from the crushing of waste tires. First, assessment of basic physical and thermal properties of both natural and tire rubber-based aggregate were done. Then the lightweight concrete with different amount of rubber aggregate was prepared. Portland slag cement CEM II/A-S 52.5 N (Spenner Zementwerk Berlin GmbH & Co. KG, Germany) was used as a binder and silica sand of particle size fraction 0/4 mm and 4/8 mm from gravel-pit Dobříň, Czech Republic, was used as natural aggregate. Silica sand of fraction 4/8 mm has been substituted by scrap tire rubber-based aggregate of fraction 4/8 mm in a proportion of 10, 20 and 30 mass %. Reference concrete samples without rubber aggregate were prepared as well. The concretes composition is shown in Table 1. The water/cement ratio was kept 0.5 for all prepared composites. The casted prismatic samples 40 × 40 × 160 mm and cubic samples with a side dimension of 100 mm were left for 1 day at laboratory conditions and then they were unmolded and cured for 28 days in water.

Table 1. Mix composition of lightweight concrete with waste rubber aggregate.

Mixture	Mass (g)					w/c
	Cement	Natural aggregate 0/4	Natural aggregate 4/8	Rubber aggregate 4/8	Water	
Ref	450	675	675	-	225	0.5
10%	450	675	540	135	225	0.5
20%	450	675	405	270	225	0.5
30%	450	675	270	405	225	0.5

Figure 1. Rubber aggregate of fraction 4/8 mm.

2.1 Characterization of Used Natural and Rubber-Based Aggregate

In order to assess used aggregate in terms of physical properties, its specific density, powder density, and particle size distribution were determined. Automatic helium pycnometer Pycnomatic ATC (Thermo-Scientific) was used for specific density measurement. The grain-size curve was obtained using the standard sieve method with sieves of 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. For the purpose of evaluation of possible changes in thermal properties of both natural and rubber aggregates of fraction 4/8 mm during sample preparation, their thermal conductivity λ (W/m·K), volumetric heat capacity C_v (J/m^3·K) and thermal diffusivity a (m^2/s) as well as their powder density were measured in dependence on compaction time. For these tests, a high-frequency vibrating table VSB-15 (Brio) was used. For thermal parameters determination, the commercially produced device ISOMET 2114 (Applied Precision, Ltd.) was used as a representative of transient impulse methods (Záleská *et al.* 2017). In the thermal parameter tests, needle probe was applied.

2.2 Basic Physical Properties

Lightweight concrete specimens were first dried in a vacuum drier at 60 °C. Matrix density measurement was performed using an automatic helium pycnometry as described above. The bulk density was accessed on a gravimetric principle following the standard EN 12390-7 (2009). This method is based on the measurement of sample size and its dry mass. Calculation of the total open porosity was then done from the bulk and matrix density values. The relative expanded uncertainty of the applied measuring method was approx. 5 %.

2.3 Mechanical Resistance

After 28 days of water curing were on the prismatic specimens of dimension 40 × 40 × 160 mm applied the strength tests. The flexural strength was measured according to the standard EN 12390-5 (2009). Halves of broken specimens were used for compressive strength testing following the standard EN 12390-3 (2009). The loading area was 40 × 40 mm. The Young´s modulus was accessed on the dynamic principle using the pulse ultrasonic method on the prismatic samples dried at 60 °C. Device DIO 562 (Starman Electronic) was used for the measurement.

2.4 Thermal Properties

In order to understand the influence of the rubber aggregate on the improvement of thermal insulation properties of the developed lightweight concretes, their thermal conductivity λ (W/m·K) was accessed using commercially produced device ISOMET 2114 (see above) equipped with a surface probe. The measurement was conducted in dependence on moisture content at the dry state and at the full water saturated state on the cubic samples with a side dimension of 100 mm.

2.5 Water Transport Parameters

To access performance of the developed lightweight concrete with rubber aggregate in terms of capillary suction, experimental test for determination of water absorption coefficient A (kg/m^2·s$^{1/2}$) was carried out. Dried prismatic samples were cut into half and water and vapor-proof insulated by epoxy resin on all lateral sides. Then they were exposed by their 40 × 40 mm face to the distilled water. The weight change of the samples in time was monitored and registered. On the basis of experimental data, the capillary water absorption coefficient was calculated as originally proposed by Hall (1989).

3 RESULTS AND DISCUSSION

The grain-size curves of used both natural and rubber-based aggregates are given in Figure 2. Rubber aggregate was found to be slightly finer compared to the natural aggregate of fraction 4/8, especially for grain size ranging from 1 to 3 mm.

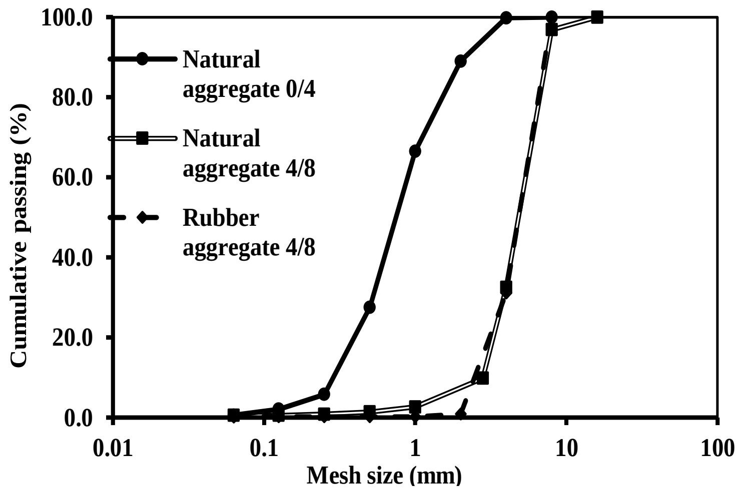

Figure 2. Grain-size analysis of used natural and rubber aggregates.

Thermophysical properties of both natural and rubber-based aggregates of fraction 4/8 are given in Table 2. The specific density was 1174 kg/m^3 for the rubber aggregate and 2662 kg/m^3 for the natural aggregate of fraction 4/8 respectively. We can see that the thermal performance of rubber particles is better in comparison with silica sand. As expected, with compaction time the thermal conductivity, as well as the volumetric heat capacity, increased for both rubber and natural aggregates due to the reduced amount of air gaps between aggregates particles.

Table 2. Aggregate properties in dependence on the compaction time.

Compaction Time (s)	**Rubber Aggregate 4/8**				**Natural Aggregate 4/8**			
	Powder Density (kg/m^3)	**λ (W/m·K)**	**$C_v\times10^6$ (J/m^3·K)**	**$a\times10^{-6}$ (m^2/s)**	**Powder Density (kg/m^3)**	**λ (W/m·K)**	**$C_v\times10^6$ (J/m^3·K)**	**$a\times10^{-6}$ (m^2/s)**
0	0.445	0.0951	0.2580	0.3684	1.408	0.315	1.4040	0.2246
10	0.460	0.0954	0.2542	0.3753	1.539	0.348	1.4195	0.2451
20	0.465	0.0957	0.2558	0.3741	1.581	0.369	1.4432	0.2559
180	0.465	0.0963	0.2623	0.3671	1.603	0.388	1.4260	0.2720

In Table 3, there are presented results of bulk density, matrix density, and open porosity tests performed for lightweight concretes with incorporated rubber aggregate. The bulk density values of prepared concrete containing rubber are between 1500-2000 kg/m^3, they can be therefore classified as lightweight concretes in classes LC 1.6, LC 1.8 and LC 2.0 respectively, according to the standard EN 206-1 (2014). Rubber has much lower specific density than natural aggregate, so its replacement with rubber consequently reduces the density of the developed rubber concrete (Shu and Huang 2014). The porosity of developed lightweight concrete increased with increased rubber content, this can be explained by the higher content of entrained air in concrete mixes and pores present in rubber particles (Girskas and Nagrockienė 2017).

Table 3. The basic physical characteristic of lightweight rubber concrete.

Material	Bulk density (kg/m^3)	Matrix density (kg/m^3)	Open porosity (%)
Ref	2134	2453	13.0
10%	1914	2249	14.9
20%	1760	2101	16.3
30%	1543	1902	18.9

Results of mechanical strength tests are summarized in Table 4. We can see that mechanical resistance significantly decreased with increasing amount of rubber-based aggregate in the mixture. These results are in accordance with the findings of other authors (Shu and Huang 2014, Thomas and Gupta 2016, Girskas and Nagrockienė 2017). The bond between the non-wetting rubber surface and cement paste is probably the main parameter that controls the reduction in mechanical concrete properties (Aliabdo *et al.* 2015).

Table 4. Mechanical properties of lightweight rubber concrete.

Material	Compressive strength (MPa)	Flexural strength (MPa)	Young´s modulus (GPa)
Ref	61.5	6.8	39.0
10%	26.0	5.1	17.0
20%	13.0	2.7	5.2
30%	4.5	1.7	3.1

The thermal conductivity values in the dry and full water-saturated state are presented in Table 5. The thermal conductivity of concrete is sensitive to many factors, such as concrete density, which is primarily related to the type and density of the contained aggregates and moisture condition of specimens (Iqbal 2017). With the increased rubber substitution rate, the thermal conductivity value of rubberized concrete significantly decreased, this observation was also reported in many recent studies (Aliabdo *et al*. 2015, Iqbal 2017). With increased moisture content the thermal conductivity value increases for all samples. Rubber particles in present of moisture still reduce the thermal conductivity value compared to the reference sample but in opposite direction is the higher porosity associated with higher moisture presence in concrete porous space.

Table 5. The thermal conductivity of lightweight rubber concrete in the dry and fully water saturated state.

Material	λ (W/m·K)	
	Dry state	Saturated state
Ref	1.776	2.378
10%	1.275	1.899
20%	0.857	1.205
30%	0.653	1.123

Results of the water absorption coefficient test are given in Table 6. The water transport behavior of lightweight rubber concrete is mainly influenced by the non-wetting character of the used rubber aggregate and by the porosity of the sample, which acts against each other.

Table 6. The water absorption coefficient of lightweight rubber concrete.

Material	***A*** **($kg/m^2{\cdot}s^{1/2}$)**
Ref	0.0197
10%	0.0168
20%	0.0187
30%	0.0171

4 CONCLUSIONS

This study aimed at the evaluation of scrap tire rubber-based aggregate with different replacement levels in lightweight concrete in terms of mechanical, thermal, hygric and basic physical properties of the developed materials. The obtained results have shown that application of the rubber aggregate in the building industry can lead to an environmentally friendly material with improved thermal insulation function that can increase the energy efficiency of buildings whereas its mechanical parameters are suitable for non-structural applications.

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