Mixed Low-density Demolition Waste in Production of Lightweight Cement-based Composites

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Abstract. Lightweight concretes are traditionally used composites intended for non-bearing applications. In their composition, various types of lightweight natural as well as industrially produced aggregates are employed. Regard to the considerable aggregates consumption, the potential application of mixed low-density demolition waste (MDW) in production of cement-based composites was studied in this paper. In mixes with maintained workability, silica sand was replaced by MDW in the amount of 0 – 100 vol. %. On hardened developed composites, basic physical properties, strength properties and dynamic moduli were determined and compared with control material after 28 days of water curing. Due to reduced weight of waste aggregate compared with the silica sand, hardened composites showed importantly lower bulk density. However, their increasing porosity induced by higher MDW additions led to the decrease of compressive and flexural strengths and dynamic moduli values. With respect to the maintaining of mechanical resistance, quantities of incorporated MDW not exceeding 25 % were chosen as an optimal replacements ratio.

1. Introduction

Due to the constant economic growth of last years, the construction industry is still developing area consuming a considerable amount of natural non-renewable resources [1]. Its estimated that about 50 % of extracted nature commodities is utilized for this purpose. With nature resources depletion, the governments all over the world are driven to support environmental policies and look for alternative materials [2]. New developer projects as well as increasing urbanization connected with meeting of human needs bring additional impacts on the environment. Accordingly, over 859.5 million tons of construction and demolition waste (CDW) is generated across the EU annually [3]. In view to the European directives, produced CDW cannot be disposed in landfills. The major CDW amounts should be recycled and reused [4]. For this reason, recycled concrete and ceramic aggregates found the applications as subbase layers or filling material of low strength composites. CDW often includes other materials, such as packaging materials, plastics, insulating materials, etc. whose source separation is necessary to maintain their utility value [5]. Nevertheless, in some cases the separation process can be problematic or highly financially demanding and thus different blends with inferior properties are formed.

With the aim to reduce the amount of unseparated waste from construction industry, this work is focused on the potential application of mixed low-density demolition waste (MDW) in the
manufacturing of cement-based composites. The results pointed out to the possibility of the production of environmentally friendly lightening materials.

2. Experimental

2.1. Used materials

In composites production, CEM I 42.5 R (Českomoravský cement, Ltd., Czech Republic), meeting the specifications given in the EN 197-1 [6] standard, was applied. Its oxides composition and basic material properties, available from the producer, are summarized in Table 1 and 2. Natural silica sand (Filtráční písky, Ltd., Czech Republic), in the fraction 0.0/2.0 mm, was used as reference aggregate. This silica sand was substituted by mixed low-density demolition waste (MDW) in the amount from 0 % up to 100 vol. %. The material blend was consisted from cotton-polyester mix, paper-based packaging materials, polyethylene and cellulose in the concentrations of 56.0 wt. %, 24.4 wt. %, 12.2 wt.% and 7.1 wt. % respectively. Moreover, polyether urethane was found in the concentration less than 1 wt.%. The particle size distribution of both sand and its preplasing material are introduced in Table 3. From indicated data, higher occurrence of rougher MDW particles in the interval from 1.0 mm to 2.0 mm are visible.

| Table 1. Oxides composition of CEM I. |
|--------------------------------------|
| Oxide composition (wt.%)              |
| SiO₂ 19.62                           |
| Al₂O₃ 4.80                           |
| Fe₂O₃ 3.34                           |
| CaO 63.70                            |
| MgO 1.42                             |
| K₂O 0.75                             |
| Na₂O 0.19                            |
| SO₃ 3.10                             |
| Cl⁻ 0.04                             |

| Table 2. Material properties of applied binder. |
|------------------------------------------------|
| Powder density (kg·m⁻³) | Specific density (kg·m⁻³) | Specific surface area (m²·kg⁻¹) | Loss on ignition at 1000°C (wt.%) |
|--------------------------|---------------------------|-------------------------------|-------------------------------|
| 980                      | 3 110                     | 408                           | 3.42                          |

| Table 3. Particle size distribution of sand and replacing aggregate. |
|---------------------------------------------------------------|
| Material | d₁₀ (mm) | d₅₀ (mm) | d₉₀ (mm) |
| Sand     | 0.20     | 0.72     | 1.67     |
| MDW      | 0.17     | 1.05     | 1.80     |

2.2. Mixes design and sampling

The overview of compositions of prepared composites is listed in Table 4. Control mix was comprised from 487.8 kg of Portland cement per 1 m³ and three times higher amount of silica sand. In the case of other four mixes, sand was replaced by MDW in the quantity up to 100 % by volume with the step of 25 %. Silica sand replacing material disposed a considerable water absorption of 360 % (about 0.85 % measured for sand) and thus was left to soak with water in the plastic container for 24 hours before the application. In this context, the amount of added water was different in order to kept the constant value of spreading of 160 × 160 ± 10 mm (EN 1015-3 [7]) for all fresh composites.
From fresh mixes, prismatic samples with dimensions of $40 \times 40 \times 160$ mm and 100 mm cubes were casted and compacted with the help of a vibrating table (Matest, S.p.A, Italy) for 60 s. Placed tested specimens were covered by plastic foil and left under the laboratory conditions at $20 \pm 1 \, ^\circ\text{C}$ and $45 \pm 5$ \% of relative humidity for 24 hours. Subsequently, demoulded hardened specimens were cured under water at conditions mentioned above for other 27 days.

Table 4. Compositions of developed mixes.

| Mix       | CEM 1 (kg·m$^{-3}$) | Sand (kg·m$^{-3}$) | MDW (kg·m$^{-3}$) | Water (kg·m$^{-3}$) |
|-----------|---------------------|--------------------|-------------------|---------------------|
| Control   | 487.8               | 1 464.4            | -                 | 243.9              |
| MDW-C 25  | 490.5               | 1 103.7            | 37.2              | 147.2              |
| MDW-C 50  | 493.1               | 739.8              | 74.8              | 98.6               |
| MDW-C 75  | 495.8               | 372.0              | 112.8             | 49.6               |
| MDW-C 100 | 498.4               | -                  | 151.1             | -                  |

2.3. Measured properties

2.3.1. Particle size distribution. Particle size distribution (PSD) of aggregates was measured with the usage of sieving analysis according to the standard EN 933-1 [8] on dried aggregates samples. Each sample was sieved through the set of sieves having mesh size of 2.0; 1.0; 0.5; 0.25; 0.125 and 0.063 mm and shaken by vibratory apparatus Retsch AS 200 (Germany).

2.3.2. Basic physical properties. Basic physical properties measured after 28 days on hardened samples, bulk density, saturated water content and open porosity under vacuum conditions, were determined. Bulk density measurements were performed following procedure described in the standard EN 1015-10 [9]. The relative expanded uncertainty of the density tests was 2.7 \%. The saturated water content and further open porosity were measured with the gravimetric method according to the EN 1936 [10]. In both cases, the expanded uncertainty did not exceed 5 \%. Moreover, powder densities of aggregates were measured in the agreement with the EN 1097-3 [11].

2.3.3. Strength parameters and dynamic moduli measurements. Flexural and compressive strengths tests were performed with the usage of hydraulic press Servo Plus Evolution (Matest, S.p.A., Italy) with disposing loading capacity of 300/15 kN accordingly to the EN 1015 – 11 [12]. Prismatic samples with dimensions of $40 \times 40 \times 160$ mm in three-point bending setting were tested. Further, maximum compressive forces were recorded on the broken halves of prisms [13]. The expanded measuring uncertainty of both mentioned procedures was 2.5 \%. Moreover, dynamic moduli measurement with the device Dio 562 NLF (Starmans Electronics) was carried out. The relative expanded uncertainty of the dynamic moduli measurements of 2.4 \% was recorded.

3. Results and discussion

Powder density measurements performed on both aggregate samples pointed out to importantly lower value of 150 kg·m$^{-3}$ attributed to artificial aggregate. On the other hand, used common silica sand had approximately tenfold higher powder density (1 492 kg·m$^{-3}$, detected in loose state). Significantly different values of powder density thus influenced the obtained basic physical properties given in Table 5. At first sight, the gradual decrease in bulk density caused by the increased incorporation of MDW is visible. Already at MDW addition of 25 vol. \%, the bulk density of hardened specimens was dropped under 1 800 kg·m$^{-3}$ which is the limiting value for lightweight concretes according to the EN 206-1 [14]. On contrary, open porosity was detected to be considerably higher for MDW composites. Control samples average values of absorbed water was detected to be 189 kg·m$^{-3}$ and these samples exhibited average value open porosity of 19.8 \%. With the substitution of natural silica sand with MDW, saturated water content and open porosity started to increase. Fully substituted composite, MDW-C 100, showed more than three times higher values of these physical quantitates in the comparison with the control
sample. In this sense, the application of MDW promoted an important weight reduction of produced composites bringing benefits like decrease of transportation costs of precast products, reduction of structural dead loads, etc.

Table 5. Basic physical properties measured on hardened composites.

| Mix       | Bulk density (kg·m³) | Saturated water content (kg·m³) | Open porosity (%) |
|-----------|----------------------|--------------------------------|-------------------|
| Control   | 2 055                | 189                            | 19.8              |
| MDW-C 25  | 1 723                | 295                            | 30.9              |
| MDW-C 50  | 1 424                | 407                            | 40.5              |
| MDW-C 75  | 1 162                | 480                            | 48.4              |
| MDW-C 100 | 760                  | 625                            | 62.7              |

Mechanical properties, flexural strength, compressive strength and dynamic moduli values, obtained on tested samples are summarized in Table 6. As a consequence of growing open porosity of waste aggregate dosed composites, the continuous decrease of strength performance was recorded. Flexural strengths values of MDW-C 25, MDW-C 50, MDW-C 75 and MDW-C 100 were detected to be lower for 19 %, 45 %, 60 % and 78 %, respectively, in the comparison with control sample. Likewise, the considerable decrease compressive strengths values were calculated. In the comparison with control sample, values of compressive strength were detected to be lower for 47 %, 79 %, 88 % and 95 % of MDW-C 25, MDW-C 50, MDW-C 75 and MDW-C 100, respectively. From reported values, it is visible that the decrease of compressive strength was more noticeable. Less steep decrease of flexural strength values could be ascribed to the partial reinforcing capability of cellulose and cotton fibres occurring in the artificial aggregate blend as reported e.g. in [15]. Similarly, with higher representation of MDW in produced composites, the dynamic moduli values dropped dramatically. The observed trend is in line with previous research done by Malešev et al. [16] in which it was described that the usage of lower density aggregates resulted in decrease of dynamic moduli. From quantitative point of view, all MDW applications exceeding 25 vol. % adversely influenced mechanical properties.

Table 6. Mechanical properties measured on 28 days cured samples.

| Mix       | Flexural strength (MPa) | Compressive strength (MPa) | Dynamic moduli (GPa) |
|-----------|-------------------------|---------------------------|----------------------|
| Control   | 8.0                     | 56.6                      | 35.6                 |
| MDW-C 25  | 6.5                     | 29.9                      | 18.6                 |
| MDW-C 50  | 4.4                     | 11.9                      | 8.0                  |
| MDW-C 75  | 3.2                     | 7.0                       | 4.7                  |
| MDW-C 100 | 1.8                     | 3.0                       | 2.0                  |

4. Conclusions
The influence of low-density demolition waste from construction industry as a potential alternative of silica sand in manufacturing of lightweight cement-based composites was studied. Applied replacing aggregate had importantly reduced powder density compared to silica sand and thus considerable lightening of produced composites was achieved even for samples with the lowest of sand replacement. However, high rate of open porosity up to 62.7 %, attributed to MDW modified samples, resulted in important strengths losses. The compressive strength measured for MDW-C 100 was reduces of about 95 % with respect to the control material. In view of examined properties and to maintain acceptable strength performance of produced composites, an optimal amount of MDW seems to fall in the range from 0 to 25 vol. %. Nevertheless, the increasing open porosity of modified tested samples may improve thermal performance of designed composites. This will be further investigated in the subsequent research.
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