Influence of increasing amount of recycled concrete powder on mechanical properties of cement paste

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Abstract. This paper deals with using fine recycled concrete powder in cement composites as micro-filler and partial cement replacement. Binder properties of recycled concrete powder are given by exposed non-hydrated cement grains, which can hydrate again and in small amount replace cement or improve some mechanical properties. Concrete powder used in the experiments was obtained from old railway sleepers. Infrastructure offer more sources of old concrete and they can be recycled directly on building site and used again. Experimental part of this paper focuses on influence of increasing amount of concrete powder on mechanical properties of cement paste. Bulk density, shrinkage, dynamic Young’s modulus, compression and flexural strength are observed during research. This will help to determine limiting amount of concrete powder when decrease of mechanical properties outweighs the benefits of cement replacement. The shrinkage, dynamic Young’s modulus and flexural strength of samples with 20 to 30 wt. % of concrete powder are comparable with reference cement paste or even better. Negative effect of concrete powder mainly influenced the compression strength. Only a 10 % cement replacement reduced compression strength by about 25 % and further decrease was almost linear.

1. Introduction
The need for construction and maintenance of the infrastructure takes a large amount of funds and natural resources and yearly produces a great amount of construction and demolition waste based on concrete and asphalt. Asphalt materials can be directly processed on site with the help of mobile recycling units and incorporated into new structural layers. It is mainly because the material is homogenous and does not need much effort to sort and modify. In railway structures the concrete is mostly contained in sleepers or slabs for tram tracks. Sleepers and boards can be reused but recycling on the site is more complicated because they contain reinforcement [1].

Sorted waste based on concrete and asphalt can be applied to new asphalt mixtures [2,3]. Old concrete is in its simplest form used as an alternative to crushed stone backfilling and soil treatment. It can also be used as sub-base layers of the roads [4,5] or unpaved road surfaces [6,7]. Recycled concrete is also used as fine and coarse aggregate in new concrete [8,9,10]. Problematic part of recycling process is remaining concrete powder < 1 mm, which is mostly composed of old cement paste. One option is to use it as fillers or partial binder replacement in cement composites.

In this paper the high speed mill was used to crush old cement grains and exposed their non-hydrated core. Exposed non-hydrated core can hydrate with water again and therefore can be used as partial cement replacement. Also particles of old cement are smaller after milling and thus can be used...
as microfiller. This way of using rest of recycled concrete could help to reduce the amount of accumulating construction waste. Based on previous research, the amount of recycled concrete powder (RCP) was limited to 50 wt. % [11]. Replacement of the cement behind this level is inefficient and unfeasible.

2. Materials and samples
The samples were made of the Portland cement CEM I 42.5 produced in Radotín, the Czech Republic. Recycled concrete powder was produced by LAVARIS Ltd. by using a high speed mill. The old concrete was obtained from old railway sleepers of type PB2 and SB8. Six mixtures with 0%, 10%, 20%, 30%, 40% and 50% of RCP, by weight, were prepared (Table 1). W/b ratio was different due to deteriorated workability caused by increasing amount of RCP. Each set contained 6 prismatic samples having dimensions of $40 \times 40 \times 160$ mm. The samples were removed from their casts after 2 days. After that the samples were cured for 28 days in laboratory conditions at the temperature of $21 \pm 2$ °C and relative humidity of $50 \pm 5$ %. After 28 days the testing of the samples was performed.

| Mixture   | Cement [g] (CEM I 42.5 R) | RCP [g] | Water/mixture ratio | Slump flow test [mm] |
|-----------|---------------------------|---------|---------------------|----------------------|
| CEM (ref) | 1500                      | 0       | 0.35                | 130 ± 5              |
| RCP 10    | 1350                      | 150     | 0.36                | 130 ± 5              |
| RCP 20    | 1200                      | 300     | 0.37                | 130 ± 5              |
| RCP 30    | 1050                      | 450     | 0.38                | 130 ± 5              |
| RCP 40    | 900                       | 600     | 0.39                | 130 ± 5              |
| RCP 50    | 750                       | 750     | 0.40                | 130 ± 5              |

3. Experimental methods
The dynamic Young’s modulus was determined by using the impact resonance method, based on nondestructive measurements of the basic natural frequency of longitudinal vibration of the sample (Figure 1) and the basic natural frequency of flexural vibration of the sample (Figure 2) of the samples. The dynamic Young’s modulus was evaluated by basic longitudinal natural frequency of the samples according to the standard equations for prismatic sample [12]. The basic flexural natural frequency of the samples was used for verification of results. Weight and dimension of each sample was measured before testing. The samples were supported by a soft elastic pad at the nodal points.

![Figure 1. Configuration of measuring the basic natural frequency of longitudinal vibration of the sample by impact resonance method.](image1)

![Figure 2. Configuration of measuring the basic natural frequency of flexural vibration of the sample by impact resonance method.](image2)
The measurement of dynamic Young’s modulus was carried out by a measuring assembly Brüel & Kjaer containing the measuring station type 3560-B-120, the acceleration transducer type 4519-003, the impact hammer type 8206 and a control notebook. The measuring station recorded excitation signal and response signal. Using the Fast Fourier Transform, the signals were transformed from the time domain to frequency domain and graph of Frequency Response Functions (FRF) as a ratio of a response and an excitation force in the frequency domain was evaluated by Software PULSE LabShop version 14.0.1. From the FRFs the appropriate basic natural frequencies were evaluated (Figure 3).

![Graph of Frequency Response Functions (FRF)](image)

**Figure 3.** Graph of Frequency Response Functions (FRF) obtained by Software PULSE LabShop version from measurement of the basic natural frequency of longitudinal vibration of the sample.

The flexural and compressive strength were determined on the 28 days old samples using the Heckert device, model FP100. The testing was displacement controlled at a constant rate of 0.1 mm/s in the case of three-point bending and 0.3 mm/s during the compression test. The distance between supports during the three-point bending test was equal to 100 mm. The uniaxial compressive test was performed on the broken halves of the specimens with effective dimensions of 40 × 40 × ~80 mm.

### 4. Experimental results

Bulk density was evaluated before measurement of dynamic Young’s modulus. As can be seen in Table 2, bulk density decrease is directly proportional to the increasing amount of recycled concrete powder. Bulk density of the samples with 50 % of RCP decreased by about 18 %.
Table 2. Bulk density of the samples with different cement replacement.

| Samples       | Bulk density [kg/m$^3$] | Samples       | Bulk density [kg/m$^3$] |
|---------------|-------------------------|---------------|-------------------------|
| CEM (ref)     | 1919 ± 9                | RCP 30 (30 wt. %) | 1790 ± 9                |
| RCP 10 (10 wt. %) | 1851 ± 1              | RCP 40 (40 wt. %) | 1709 ± 4                |
| RCP 20 (20 wt. %) | 1839 ± 7              | RCP 50 (50 wt. %) | 1566 ± 3                |

The dynamic Young’s modulus of the samples with RCP up to 20 % was within standard deviation comparable with reference sample (Figure 4). Dynamic Young’s modulus of the samples with RCP above 20 % decreased with increasing amount of RCP. Modulus of samples with 50 % of RCP was about 38 % lower compared with reference sample.

![Figure 4. Dynamic Young’s modulus of cement paste with increasing amount of RCP.](image)

In Figure 5 the results of compression strength are shown. Samples with 10 % of RCP exhibit lower compressive strength by about 35 % compared to reference samples. But with 20 % replacement, the compressive was lower by only about 25 %. The amount of RCP about 20 % was high enough to reach improvement of compression strength due to microfiller and binder effect and also sufficiently low to limit the decrease of strength caused by lower amount of cement and higher porosity. Compression strength of the samples with RCP above 20 % decreased with increasing amount of RCP.

![Figure 5. Compression strength of cement paste with increasing amount of RCP.](image)
Results of flexural strength (Figure 6) show that replacement of 10 to 20 % of cement by RCP cause increase of strength by about 25 to 40 %. But high standard deviation needs to be considered. It was likely caused by the same influences as in case of compression strength. All of this contributed to a reduction in cohesiveness of the cement paste and led to increase of flexural strength. Samples with RCP above 20 % were comparable with reference samples.

![Figure 6. Flexural strength of cement paste with increasing amount of RCP.](image)

5. Discussion
This study evaluated the effects of recycled concrete powder (RCP) on mechanical properties of cement paste. Samples of cement paste contained 0 to 50 wt. % of RCP. From presented results can be summarized those findings.

Bulk density of samples decreased with increasing amount of RCP mostly because of higher water/mixture ratio that caused higher porosity. Partial negative influence can also be attributed to lower density of old cement paste in the RCP. Decrease of dynamic Young’s modulus of the samples with > 30 wt. % of RCP was related to lower modulus of elasticity of the old cement paste and higher porosity caused by higher water to binder ratio that cause mentioned higher porosity. But on the other hand, the microfiller and binder effect of RCP retained the dynamic Young’s modulus of the samples with RCP up to 20 % on the same or slightly higher level than in case of reference cement paste. Compression strength of samples decreased with increasing amount of RCP, but samples with 20 wt. % of RCP showed better results than samples with 10 wt. % of RCP. Samples with 10 to 20 wt. % of RCP had higher flexural strength than reference cement paste, samples with more than 20 wt. % of RCP had comparable flexural strength as reference samples. According to results of dynamic Young’s modulus, compression and flexural strength, the optimal rate of replacement was defined around 20 to 30 wt. % of RCP. Such replacement level allows some improvements due to microfiller and binder effect of RCP and also allows to minimize the negative influence of higher porosity caused by higher water to binder ratio.

The paper focused on using recycled concrete powder and eventually brick powder [13,14] confirmed possibility of using recycled concrete powder as partial cement replacement. Compared with the paper by Šeps and Broukalova [15], the trend of decreasing bulk density according to higher amount of micro-ground recycled concrete was similar. Also the compressive and flexural strength had similar trend. In cited paper, the values of all investigated properties were higher than in this paper. This difference was probably caused by curing in water that provided better conditions during hardening. Also better compaction of samples during molding could have resulted in higher bulk density that primary influenced compressive strength.

Other authors used recycled concrete powder as heat treated binder [16,17] or as replacement of natural ingredients in the mixture for cement production [18]. Those methods require large amounts of energy and produce high CO₂ release although less than in the case of conventional cement clinker.
Only methods using recycled concrete in its raw form can be considered as sustainable and environmentally friendly. Using RCP in geopolymer based binder [19] or as microfiller and partial cement replacement belongs to these sustainable methods.

6. Conclusions

This study evaluated the effects of recycled concrete powder (RCP) on mechanical properties of cement paste. Samples of cement paste contained 0 to 50 wt. % of RCP. From presented results can be summarized those findings:

- Bulk density of samples decreased with increasing amount of RCP mostly because of higher water/mixture ratio that caused higher porosity and partially because of lower density of old cement paste in the RCP.
- Decrease of dynamic Young’s modulus of the samples with > 30 wt. % of RCP was related with lower modulus of elasticity of the old cement paste and higher porosity caused by higher water/mixture ratio.
- Compression strength of samples decreased with increasing amount of RCP, but samples with 20 wt. % of RCP showed small improvement.
- Samples with 10 to 20 wt. % of RCP had higher flexural strength than reference cement paste.
- Optimal rate of replacement was defined around 20 to 30 wt. % of RCP. Such replacement allows some improvements due to microfiller and binder effect of RCP and also allows to minimize negative influence of higher porosity caused by higher water to binder ratio.

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