The Utilization of the Finest Fraction of Recycled Aggregate from CDW for Concrete

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Abstract. The main aim of this study is to verify the use of fine recycled aggregate originating from construction and demolition waste. Fine fraction of aggregate up to 4 mm (sand) is commonly used for ordinary concrete. This research tests the properties of concrete whose sand content has been partially replaced by fine recycled aggregate. The use of these fine particles could reduce the consumption of natural sand. There were also tested samples with a mineral admixture up to 1 mm in size, which appear as dust during the crushing of waste concrete. The use of these fine particles fills pores between larger particles to make the aggregate skeleton of the concrete mixture denser. Furthermore, the fine particles can contain a small amount of unhydrated cement. The results of physical and mechanical and deformation properties of concrete mixtures are presented.

1. Introduction
Concrete is the most widely used construction material. Its production is mostly dependent on primary raw materials such as cement, water, sand, and gravel. Almost ten billion tons of concrete are produced annually [1] and this leads to both high levels of natural resource consumption and large amounts of waste concrete. Waste concrete represents more than one-third of all construction and demolition waste [2,3]. Recycled aggregate, which originates from construction and demolition waste (CDW), can partially or fully replace natural aggregate in the concrete mixture. This is one of the most effective approaches to utilizing CDW.

There are, however, some limitations of recycled aggregate (RA) for concrete, which have been defined in the European Standards [4,5]. Despite there being many studies demonstrating satisfactory results for the full replacement of natural gravel [6–8], according to these standards, it is only possible to partially replace coarse natural aggregate (CAN) with recycled aggregate (CRCA). Furthermore, there are also studies in which natural sand (FNA) was substituted by fine recycled aggregate (FRA) from waste concrete (FRCA) [9–11], waste masonry or bricks (FRMA) [12,13] or waste ceramics [14]. The standards do not allow for the substitution of the fine fraction at all.

The majority of concrete properties are negatively influenced by the partial or full replacement of CAN by CRCA [15] and as a maximal replacement rate of CNA by CRCA has been determined 30% [16,17] or 50% [16,18]. The properties of concrete are most positively influenced if the FNA is partially replaced by FRA [9–11,19,20], which is probably caused by a better fitting optimal grain size curve [20]. Another reason may also be the content of cement paste in the fine particles (up to 1 mm) of FRA. However, the cement paste is responsible for higher water absorption, which negatively influences the
workability of fresh concrete. For this reason, the additional water has to be added to the concrete mixture to compensate for the higher water absorption.

The decline of the mechanical properties of concrete with full replacement of CNA is one of the main barriers to the utilization of CRCA. One of the possible ways to improve the properties of recycled aggregate concrete is to use fine particles of RCA as a mineral admixture. Fine particles up to 1 mm, which arise during the recycling process as dust, fill pores between larger particles to make the aggregate skeleton more dense [21]. Furthermore, it has been found, that it is possible to use a lower ratio of cement by adding cement paste produced from the finest fraction of waste concrete. This contains a high concentration of CaO and is able to bind the aggregate [22].

This study deals with the determination of mechanical and deformation properties of concrete whose content of natural sand was partially or fully replaced by four types of FRA from CDW. The same properties were determined for the concrete with the mineral admixture.

2. Materials and methods

2.1. Materials

The concrete mixtures were designed from natural (NA) and recycled aggregate (RA), Portland cement 42.5 R and water. Four mixtures were designed with replacement of fine recycled aggregate (FRA) of fraction 0–4 mm – fine recycled concrete aggregate (FRCA 1, FRCA 2) used for mixtures REC F C1 and REC F C2, fine recycled masonry aggregate (FRMA) used for mixture REC F M and fine recycled lightweight concrete masonry aggregate (FRLCA) used for mixture REC F LC. Where, the FRCA 1 was crushed in laboratory from waste concrete fragments originated from recycling center, FRCA 2 and FRMA were prepared from C&D waste in recycling center and FRLCA was crushed in laboratory from waste lightweight concrete masonry originated from recycling center. The replacement rate was determined according to the optimal grain size curve. Two mixtures were designed with a mineral admixture 0–1 mm (MAD) from waste concrete combined with – 100% natural aggregate (NA) used for mixture REF MAD and 100% volume replacement of the coarse fraction (4–16 mm) of natural aggregate with recycled concrete aggregate (RCA) used for mixture REC MAD. As a reference mixture, a mixture of 0–16 mm NA was designed. All 6 concrete mixtures were compared to the reference mixture (REF). The properties of used recycled materials are presented in Table 1.

All concrete mixtures have the same amount of cement and the same effective water-cement ratio, which were designed according to the Czech standard CSN EN 206 +A1 [5] (Table 2). The additional water was determined according to the water absorption of aggregate. The materials used to prepare the concrete mixtures are shown in Figure 1.

The samples were designed to test the mechanical properties of the material at the age of 28 days and to determine the elastic modulus. Samples were cured for 28 days and then tested for physical (density), mechanical (compressive strength, flexural strength) and deformation properties (static and dynamic elastic modulus).

| Properties/ Materials | FRCA 1 | FRCA 2 | FRMA | FRLCA | CRCA 4/8 mm | CRCA 8/16 mm | MAD |
|-----------------------|--------|--------|------|-------|-------------|--------------|-----|
| Density [kg/m3]       | 2450   | 2650   | 2250 | 900   | 2400        | 2400         | 2700 |
| Water absorption [%]  | 2.0    | 2.1    | 5.9  | 29.7  | 7.0         | 6.1          | 10.0 |
Figure 1. Materials used to prepare concrete mixtures

Table 2. Recipes of particular mixtures

| The fine aggregate concrete mixture | REF | RECFC1 | RECFC2 | RECFCM | RECFLC | REFMAD | REC MAD |
|------------------------------------|-----|--------|--------|--------|--------|--------|--------|
| Cement CEM I 42.5 R [kg]           | 260 | 260    | 260    | 260    | 260    | 260    | 260    |
| Natural aggregate 0–4 mm [kg]      | 691 | 0      | 293    | 50     | 293    | 465    | 471    |
| Natural aggregate 4–8 mm           | 520 | 533    | 351    | 342    | 351    | 533    | 0      |
| Natural aggregate 8–16 mm          | 609 | 605    | 655    | 657    | 655    | 569    | 0      |
| Recycled concrete aggregate 0–4 mm [kg] | 0   | 545    | 559    | 0      | 0      | 0      | 0      |
| Recycled concrete aggregate 4–8 mm [kg] | 0   | 0      | 0      | 0      | 0      | 0      | 463    |
| Recycled concrete aggregate 8–16 mm [kg] | 0   | 0      | 0      | 0      | 0      | 0      | 574    |
| Recycled brick aggregate 0–4 mm [kg] | 0   | 0      | 0      | 0      | 616    | 0      | 0      |
| Recycled lightweight concrete aggregate 0–4 mm [kg] | 0   | 0      | 0      | 0      | 0      | 422    | 0      |
| Mineral admixture 0–1 mm [kg]      | 0   | 0      | 0      | 0      | 0      | 253    | 247    |
| Water [kg]                         | 169 | 169    | 169    | 209    | 240    | 194    | 232    |
| Water-cement ratio [-]             | 0.65| 0.65   | 0.65   | 0.80   | 0.92   | 0.75   | 0.89   |
| Effective water-cement ratio [-]    | 0.65| 0.65   | 0.65   | 0.65   | 0.65   | 0.65   | 0.65   |
2.2. Methods
The experimental verifications were performed according to valid European technical standards (Compressive strength – CSN EN 12390-3 (2009), Flexural strength – CSN EN 12390-5 (2009), Static modulus of elasticity – CSN EN 12390-13 (2014), Dynamic modulus of elasticity – CSN EN 12504-4 (2005)). Samples of dimensions 150 mm×150 mm×150 mm and 100 mm×100 mm×400 mm were used for testing. Determined elastic modulus is determined from dynamic modulus using a reduction factor according to the class of concrete (see the Czech technical standard CSN 73-2011). Figure 2 shows the particular designed concrete mixtures.

![Figure 2](image1.png)

a) REF  

b) REF F C1  

c) REF F C2  

d) REC F M  

e) REC F LC  

f) REF MAD  

g) REC MAD

Figure 2. Particular mixtures – sample cut at the age of 28 days

3. Results and discussion

3.1. Properties of fresh mixtures
All designed concrete mixtures were tested for workability. Previous tests proved that the workability of fresh concrete was negatively influenced by the utilization of recycled aggregate as a replacement of natural sand. It can be caused by the higher absorption capacity of fine recycled aggregate. As a solution, a higher amount of mixing water was designed to compensate for the higher absorption capacity of FRA. The aim was to maintain the same effective water-cement ratio (Table 2).
3.2. Properties of hardened mixtures

In the research, the properties of concrete with partial sand replacement by FRCA, FRMA or FRLCA and samples with mineral admixtures were tested. Table 3 shows tested properties for all mixtures. In the charts, the compressive strength (Figure 3 and Figure 5) and the elastic modulus (Figure 4 and Figure 6) of the concrete mixtures are shown separately for mixtures with sand replacement by FRA and for mixtures with the mineral admixture.

| Property                        | Recycled mat. | - | Concrete | Masonry | Mineral Admixture |
|---------------------------------|---------------|---|----------|---------|------------------|
|                                 | Unit          | REF| REC F C1 | REC F C2 | REC F M         | REC F LC | REC MAD | REC MAD |
| Replacement rate                | [%]           | 0 | 37       | 30      | 17              | 14       | 81       |
| Density                         | [kg/m³]       | 2244 | 2245 | 2276 | 2151 | 1813 | 2182 | 2093 |
|                                 | σ             | 18.59 | 7.72 | 11.70 | 14.36 | 14.32 | 7.05 | 10.02 |
| Static elastic modulus          | [GPa]         | 27.6 | 26.6 | 29.2 | 23.5 | x | 21.7 | 20.6 |
|                                 | σ             | 0.71 | 1.61 | 0.62 | 0.42 | x | 0.87 | 0.98 |
| Dynamic elastic modulus         | [GPa]         | 36.8 | 32.4 | 35.1 | 29.4 | 23.9 | 28.4 | 27.1 |
|                                 | σ             | 1.72 | 1.22 | 1.65 | 2.91 | 1.40 | 1.43 | 1.06 |
| Determined elastic modulus      | [GPa]         | 29.8 | 26.9 | 29.2 | 23.8 | 14.8 | 21.6 | 20.6 |
|                                 | σ             | 1.39 | 1.01 | 1.37 | 2.36 | 0.87 | 1.09 | 0.81 |
| Flexural strength               | [MPa]         | 4.90 | 4.95 | 4.71 | 4.70 | 3.16 | 3.90 | 3.70 |
|                                 | σ             | 0.29 | 0.37 | 0.42 | 0.62 | 0.29 | 0.35 | 0.16 |
| Compressive strength            | [MPa]         | 31.55 | 34.86 | 34.31 | 31.59 | 13.46 | 23.89 | 23.60 |
|                                 | σ             | 0.90 | 0.71 | 0.67 | 0.89 | 0.48 | 0.22 | 0.17 |

The compressive strength for mixtures with sand replacement by FRA increases for mixtures with FRCA in comparison with reference mixture REF. The differences in compressive strength between two types of FRCA are minimal. The increase of strength in comparison with REF is around 10%. The compressive strength of reference concrete mixture with natural aggregate and concrete mixture with FRMA is slightly the same. The compressive strength of concrete mixture with FLCA decreases in comparison with REF and the increase is more than 50%. The reason is probably high water absorption and low mechanical resistance of FLCA (see Figure 3).

The results of elastic modulus for mixtures with FRCA are similar or slightly better than REF. It was measured the highest modulus of elasticity for concrete with FRCA 2, which was prepared in the recycling center. The elastic modulus of concrete mixture with FRMA decreases in comparison with REF. The decline is 15%. The static elastic modulus of concrete mixture with FRLCA was not measured due to low compressive strength. The static elastic modulus is determined from dynamic elastic modulus and the decline is around 50% in comparison with REF (see Figure 4).
Figure 3. Compressive strength at the age of 28 days for concrete with sand replacement

Figure 4. Elastic modulus at the age of 28 days for concrete with sand replacement

The compressive strength for mixtures with mineral admixture from fine particles of waste concrete decreases for both mixtures with admixture. The decline of strength in comparison with REF is around 25%. The compressive strength of both mixtures with mineral admixture REF MAD (concrete mixture with coarse natural aggregate) and REC MAD (concrete mixture with coarse recycled concrete aggregate) is similar (see Figure 5).

The results of static elastic modulus for mixtures with mineral admixture are similar for both mixtures with mineral admixture. The modulus of elasticity decreases for both MAD mixtures in comparison with REF. The differences are up to 25%.
Figure 5. Compressive strength at the age of 28 days for concrete with mineral admixture content

Figure 6: Elastic modulus at the age of 28 days for concrete with mineral admixture content

4. Conclusion
The following conclusions can be drawn from this experimental verification. The mechanical and deformation properties of mixtures with the content of FRA show similar or slightly better results in comparison with reference mixture. The mechanical and deformation properties of mixtures containing mineral admixture are negatively influenced by MAD. However, there are no differences between concrete with CNA and CRCA, and both mixtures with MAD meet the requirements defined in the standard for the designed concrete mixture. Although the experimental verification of tested concrete mixtures shows satisfactory results, especially for mixtures with FRA, and allows the use of FRA in concrete, it is necessary to verify the conclusions of this research before putting them into practice.

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