The influence of kind of coating additive on the compressive strength of RCA-based concrete prepared by triple-mixing method

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Abstract. The paper deals with the use of alternative powder additives (fly ash and fine fraction of recycled concrete) to improve the recycled concrete aggregate and this occurs directly in the concrete mixing process. Specific mixing process (triple mixing method) is applied as it is favourable for this goal. Results of compressive strength after 2 and 28 days of hardening are given. Generally, using powder additives for coating the coarse recycled concrete aggregate in the first stage of triple mixing resulted in decrease of compressive strength, comparing the cement. There is no very important difference between samples based on recycled concrete aggregate and those based on natural aggregate as far as the cement is used for coating. When using both the fly ash and recycled concrete powder, the kind of aggregate causes more significant differences in compressive strength, with the values of those based on the recycled concrete aggregate being worse.

1. Introduction
There are whole a lot of construction and demolition waste being generated worldwide. Therefore, recycling of the concrete, bricks and masonry rubble as concrete aggregates is an important way to contribute to a sustainable material flow. Conserving natural raw materials such as natural aggregates while reusing construction and industrial wastes for this purpose is the most immediate and obvious way to achieve more sustainable construction. Unfortunately, the composition of these aggregates can vary substantially and consequently the varying properties have a significant influence on the properties of the concrete. In fact, the properties of concrete made with recycled concrete aggregates are inferior to those made with natural aggregates [1].

Recycled aggregates are composed of original aggregates and adhered mortar [2]. The major problems with the use of recycled aggregates in structural concrete are their high water absorption capacity, porosity and lower strength. The presence of RCA and the porous nature of the old cement mortar affect the bond between the RCA and cement paste when used in new concrete. That is why the poorer quality of RCA often limits its utilization [3]. The influence of using recycled aggregate as a replacement of natural aggregate, on the properties of recycled aggregate concrete, has been topic of research by many, from the results of which it was observed that the properties of the RAC were lower than those of the traditional concrete, which has been attributed primarily to the adhered (porous) mortar. With respect to compressive strength, concrete made with 100% of recycled coarse aggregate with lower w/c ratio than the traditional concrete can have a larger compressive strength. When the w/c ratio is the same the compressive strength of concrete made with 100% of recycled aggregate is...
lower than that of traditional concrete [2]. Chai [4] reported that the compressive strength of RAC decreased by 4 to 37% with increase in percentage replacement of coarse RCA. Jian Zhuang Xiao et al. also concluded in 2004 [5] that the compressive strength of recycled aggregate concrete generally decreases with increasing recycled aggregate contents. According to Patel et al. concrete made with recycled aggregate has a compressive strength (28 days) about 27% - 30% less than that of made with natural aggregates [6].

Different mixing methods (double mixing, triple mixing) are presented as a way how to improve the RCA properties directly during mixing in order to improve the behaviour of the whole concrete by [7, 8, 9, 10, 11, 12]. The principle of these methods lies in dividing the mixing process in two/three steps, differing in the order and timing of addition of concrete components. This in principle results in coating of aggregate, thus improving its surface character.

In this study, the recycled coarse aggregate’s surface was coated with fly ash and fine fraction of recycled concrete to improve the quality of concrete. The triple mixing technology was applied for this purpose while RCA was coated in the first stage. The effect of kind of coating material on the compressive strength of concrete after 2 and 28 days of hardening is evaluated.

2. Materials and methods

The triple mixing method (TM) was presented and proved by [9] with the aim of enhancement of interfacial transition zone (ITZ) quality between RCA and binder paste. The principle of this mixing is given in figure 1. The purpose of this mixing is to achieve the coating of the aggregate with a thin layer of paste in the first phase, the paste being made of pozzolanic materials such as fly ash, granular blast furnace slag or silica fume. Thus, the triple mixing method is a way how to improve the surface quality of RCA directly during mixing the concrete.

![Figure 1. The principle of triple mixing method according to Kong [9].](image1)

In presented experiment, TM method given by Kong was slightly modified to be useful for intended purposes. The mixing procedure mainly differs in sequence of adding aggregate (only coarse portions of RCA are of subject for testing and therefore they only will be coated in the first stage of mixing), method of calculation of coating layer volume as well as method for the calculation of \( W_1 \) and \( W_2 \) (see figure 2). The amount of water for the first stage of mixing is increased by a value corresponding to the absorption capacity of RCA, i.e. the “effective w/b ratio” is applied.

The calculation of a particular recipe is based on the proposed thickness of the coating layer in the first mixing step: \( \delta = 0.15 \mu \text{m} \). The volume of the paste for the coating as well as the volume of the paste to fill the gap between the grains is calculated by the Kennedy method. Subsequent weight of both the coating additives and cement is calculated on the base of their density. The mixing procedure for this experiment is given in figure 2.

![Figure 2. Experimental triple mixing procedure.](image2)
Two kinds of additives are tested for the coating of RCA: fly ash (FA) and recycled concrete powder (RCP). The characteristics of the materials used are as follows:

- **Aggregates:**
  - Fraction 0/4: natural aggregate (NA) is used for all recipes.
  - Fraction 4/8 and 8/16: recycled concrete aggregate (RCA) is used in this study. The 0/32 fraction of RCA was obtained from a company dealing with C&DW treatment (ENVIRONCENTRUM Ltd., Slovakia). Within the experiment, it was crushed and sorted to standard fractions. NA is also used as reference aggregate.

- **Coating additives:**
  - Fly ash (FA): coming from the energy segment of the steel-making factory from Eastern Slovakia. The original grain size of fly ash is \( d_{0.9} = 95 \, \mu m \).
  - Recycled concrete powder (RCP): this material was prepared with the idea of using fine portion of RCA which is otherwise difficult to recycle in concrete production. Particles under 125 \( \mu m \) were separated by sieving from the material that remained after the sorting of above mentioned fractions 4/8 and 8/16.

- **Cement:** type CEM I 42.5 R.

- **Admixture:** polycarboxylate type of plasticizer.

Six recipes were tested (see table 1), which varied from each other by the kind of coarse aggregate (RCA and NA) and by the kind of coating additives (FA and RCP). Coating of coarse aggregates by cement was performed for comparison. Fraction 0/4 was the same in all tested mixtures (NA). The samples of cubes shape with dimensions 100x100x100 mm were prepared with standard methods. Samples were demoulded after one day and consequently cured in water under standard conditions until the test execution. The standard test of compressive strength was executed after 2 and 28 days of setting and hardening, according to [13].

| Component | RCA - coarse aggregate | NA - coarse aggregate |
|-----------|------------------------|----------------------|
| CEM I 42.5 R [kg] | [kg] | [kg] |
| CEM | 310 | 310 | 310 | 336 | 336 | 336 |
| FA | 898 | 898 | 898 | 896 | 896 | 896 |
| RCP | 3-RA_CEM | 3-RA_FA | 3-RA_RCP | 3-NA_CEM | 3-NA_FA | 3-NA_RCP |
| NA | 4/8 | - | - | 269 | 269 | 269 |
| 8/16 | - | - | 627 | 627 | 627 |
| RCA | 4/8 | 224 | 224 | 224 | - | - | - |
| 8/16 | 545 | 545 | 545 | - | - | - |
| Coating material [kg] | 80 | 68 | 68 | 55 | 47 | 47 |
| Admixture [kg] | 2.5 | 2.5 | 2.5 | 2.7 | 2.7 | 2.7 |
| Water content [kg] | W_1 | 84 | 78 | 78 | 36 | 33 | 33 |
| W_2 | 166 | 166 | 166 | 179 | 179 | 179 |

3. Results

Compressive strength of concrete mixes which were produced by substitution of natural aggregates with recycled concrete aggregates is shown in table 2. No differences in type of failure were witnessed. It is evident that all of the tested samples had the same compressive strength time development (increase) while the rate of increase is quite significant. The increase is expressed in % and is also given in table 1. Although the values of all samples are within a narrow range (48%-54%),
clear positive effect is visible in the case of using FA and RCP for coating, comparing CEM. The well-known long-term strength development of pozzolanic materials has also appeared here. The highest compressive strength after two days of curing obtained sample 3-NA$_{\text{CEM}}$ (19.4 MPa), while after 28 days it was 3-NA$_{\text{FA}}$ (38.2 MPa) – it corresponds with strength class C30/37, following the [14]. The lowest compressive strength reached mixture 3-RCA$_{\text{RCP}}$; 11.7 MPa after 2 days and 25.6 MPa after 28 days - it corresponds with class C20/25.

There is no very important difference between samples based on RCA and corresponding samples based on NA as far as the cement only is used for coating the aggregate (3-RCA$_{\text{CEM}}$ and 3-NA$_{\text{CEM}}$). Once the additives (FA and RCP) are used for coating, the difference between the RCA and NA based samples is more significant with the values of those based on RCA are worse. Comparing the kind of coating material, FA and RCP additives give worse results comparing the cement and FA gives better results than RCP. The influence of coating material change is seen in the table 2, where differences between values of compressive strength are given for particular combinations of coating materials (CEM/FA, CEM/RCP and FA/RCP). Results are grouped by the kind of aggregate.

### Table 2. Compressive strength of samples and differences in values resulting from kind of coating material.

| Coarse aggregate | Time  | $f_c$ - compressive strength [MPa] | Differences of values by the change of coating material [%] |
|------------------|-------|------------------------------------|--------------------------------------------------------|
|                  |       | CEM | FA | RCP | CEM/FA | CEM/RCP | FA/RCP |
| RCA              | 2 days| 18.3| 13.4| 11.7| 27     | 36     | 13     |
|                  | 28 days| 37.0| 27.7| 25.6| 25     | 31     | 8      |
| Increase in time [%] | 51 | 52 | 54 | - | - | - |
| NA               | 2 days| 19.4| 17.6| 15.7| 9      | 19     | 11     |
|                  | 28 days| 37.0| 38.2| 34.1| 3      | 8      | 11     |
| Increase in time [%] | 48 | 54 | 54 | - | - | - |

### 4. Conclusions
The triple mixing technology was applied for improvement the quality of concrete based on RCA, while effect of different kinds of coating additives are evaluated. Both the fly ash and the fine fraction of recycled concrete were used for coating in the first stage of triple mixing, as well as cement as the reference material. For the same reason, samples with natural aggregate instead of RCA were tested as well. Compressive strength is evaluated based on the results obtained after 2 and 28 days of setting and hardening. Following conclusions can be formulated:

- all samples show positive time development of compressive strength;
- FA and RCP have better effect on the rate of increase the compressive strength in time than the cement;
- comparing the kind of coating material, FA gives higher values of compressive strength than RCP;
- there is no very important difference between samples based on RCA and NA as far as the cement is used for coating the aggregate;
- in case that both the FA and RCP are used for coating, the kind of aggregate causes the more significant differences in compressive strength, with the values of those based on RCA being worse.

Generally, testing the alternative powder additives (FA and RCP) for coating the coarse RCA in the first stage of triple mixing resulted in decrease in compressive strength comparing the cement.
However, the results that have been achieved (27.7 MPa and 25.6 MPa) are at practically useful values. This approach is open for next optimization of presented principle and is very promising for saving cement and supporting the RCA consumption, while keeping the technical limits for concrete production and application.

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