The effect of mixing method on capillary moisture content of concretes with recycled concrete aggregates

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Abstract. Recycled concrete aggregate represents a major environmental burden in the affected area and its use as an aggregate in concrete production is widespread in many countries. However, such aggregates have worse characteristics and strength than those of natural aggregate. In particular they have a higher absorption rate than natural aggregates, need much more water for mixing, and cause a high slump loss rate depending on the elapsed time. In this context, it is possible to monitor global extensive research aimed on the elimination of improper properties of alternative aggregates, which are an obstacle to their application in concrete. The sorptivity expressed by capillary moisture content is a characteristic of moisture transport into the material, and recently it has been recognized as an important performance characteristic of durability. The paper is focused on the specific approach to concrete mixing as a way of the improvement of recycled aggregate’s surface using 3 variations of powders as coating materials and 2 kinds of aggregate. The changes in the capillary moisture content are compared and discussed. It is clear that the kind of coating material can influence this performance parameter significantly, so the careful design of mixing process together with the selection of powdery materials is essential. The triple mixing method was found to be promising for recycled concrete aggregate concrete, when fly ash or recycled concrete powder are used in the first stage of mixing. It is a favourable result, taking into account the perspective of the application of secondary raw materials for concrete production.

1. Introduction

Many variables need to be considered for producing the high-quality concrete; they can be considered in the terms of constituent material variables and in the terms of production parameters (mixing course, transportation and handling, as well as temperature).

As for concrete components, the alternative materials play an important role in current concrete technology. Almost three quarters of the volume of concrete is composed of aggregates. To meet the global demand of concrete in the future, it is becoming a more challenging task to find suitable alternatives to natural aggregates for preparing concrete. Therefore, the use of alternative sources for natural aggregates is becoming increasingly important [1]. However, such aggregates have worse characteristics and strength than those of natural aggregates. In particular they have a higher absorption rate than normal aggregate, need much more water for mixing, and cause a high slump loss rate depending on the elapsed time [2–4].

Recycled aggregates are composed of original aggregates and adhered mortar [5]. 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 [6].

The mixing procedure includes the type of mixer, the order of introduction of the materials into the mixer (loading method), the energy of mixing (duration and power) and the discharge method. Those parameters of mixing procedures are generally under wide investigation, evaluating their impact on the concrete properties [7–9].

Various loading methods are investigated worldwide, for the improvement of concrete quality. One of them is triple mixing method (TM); as given in [10], its principle lies in dividing the mixing operation into three steps to further enhance of ITZ and thus the properties of the RCA by surface-coating of pozzolanic materials, such as fly ash, slag and silica fume. It was designed as follows: coarse and fine aggregates are mixed with the addition of a certain amount of water to obtain wet aggregates. Then the additive is added to get the surface-coated aggregates, following by cement. Finally, the rest water together with superplasticizer is added to obtain fresh concrete. Also other authors involve this mixing technique into the investigation process and present the positive effect on the properties of hardened concrete [11,12]. The method primarily works with recycled aggregates and cementitious materials, but possibilities are wider, as presented in [13], when geopolymer slurry was used to coat recycled concrete aggregate, or in [14] when recycled bricks powder was used to coat air cooled blast furnace slag aggregate.

The sorptivity is an index of moisture transport into unsaturated specimens, and recently it has also been recognized as an important index of concrete durability [15]. During the sorptivity process, the driving force for water ingress into concrete is capillary suction within the pore spaces of concrete [16]. Martys and Ferraris have shown that the sorptivity coefficient is essential to predict the service life of concrete as a structural material [17]. Water absorption through capillarity is a phenomenon that occurs due to the difference between the capillary motion force (depending on the surface tension of liquid and wettability of capillary pores) and the gravity force acting on the column of elevated water (the weight of water column), which induces water movement until the balance is established. The height of capillary suction (action) increases with decreasing the capillary diameter of a capillary pore. The process is particularly visible in dry–wet conditions and has the most relevance near the element’s surface [18].

In this study, the own course of TM method is presented, as well as its influence on the capillary water content of concrete. For finding the advantages of triple mixing technology, the adequate samples and tests were performed using the normal mixing approach. Two kinds of aggregates were tested (recycled concrete aggregate and natural aggregate), as well as two kinds of additives (fly ash and recycled concrete powder) were used to coat the coarse fraction of RCA in the first step of mixing. While fly ash is considered worldwide to be a standard additive, recycled concrete powder is not widely used; even it represents a problematical part of recycled concrete. It was involved into the experiment from environmental reasons to check whether it would be suitable to play the role of the coating material within the triple mixing technology. For comparison, cement as a coating material was used, too. The paper is focused on the evaluation of changes in capillary water content of concrete from three points of view: mixing technique, kind of aggregate and kind of coating material.

2. Materials and methods

Six kinds of concrete mixtures were tested, depending on the kind of aggregate and the kind of coating powder, while samples were prepared in two series: using triple mixing (TM) and normal mixing (NM). While the standard mixing involves the pre-mixing of dry components first, following by the addition of water with plasticizer, the principle of triple mixing lies in dividing the mixing process into three steps, differing in the order and timing of concrete’s components addition. It results in coating the aggregate in the first stage of mixing by specific coating material, thus improving the surface character of aggregate. In this experiment, the own course was applied (see figure 1). The materials and their parameters were as follows:

- Aggregates:
Natural aggregate (NA): fraction 0/4 was used in all mixtures (water absorption 1.2% and apparent density $\rho_0 = 2650$ kg/m$^3$).

Recycled concrete aggregate (RCA): fractions 4/8 (water absorption 6.8% and apparent density $\rho_0 = 2200$ kg/m$^3$) and 8/16 (water absorption 5.3% and apparent density $\rho_0 = 2300$ kg/m$^3$).

- Coating materials:
  - Cement CEM I 42.5 R, $\rho_0 = 3100$ kg/m$^3$.
  - Fly ash (FA): the energy segment of the steel-making factory. The original granulometry of fly ash was $d_{0.9} = 95\ \mu m$; $\rho_0 = 2100$ kg/m$^3$.
  - Recycled concrete powder (RCP): Particles under 125$\mu m$ were separated from unsorted C&DW by sieving.

- Binder: Cement CEM I 42.5 R, $\rho_0 = 3100$ kg/m$^3$.

- Admixture: polycarboxylate type of superplasticizer.

The triple mixing method given by Kong [10] was slightly modified. The actual mixing method (see Figure 1) mainly differs in the following aspects: the sequence of adding aggregate (coarse aggregate in the first stage of mixing, fine aggregate in the third one), the method of calculation of the coating layer volume, and the method of calculation the water amounts ($W_1$ and $W_2$). Two kinds of powdery materials were tested for coating of RCA in the first stage of mixing: fly ash and recycled concrete powder. As a control mixture, concrete of standard composition was tested too, having natural aggregate (NA) and cement (CEM); in the TM cement meets two functions: coating the coarse aggregate and filling the voids between grains. To see the effect of triple mixing, samples of the same compositions were prepared by normal mixing (Figure 2).

The compositions of concrete were designed keeping the limiting amounts of cement and water for specific class of exposure, in accordance to standard for concrete production (min 300 kg of cement and max w/c ratio = 0.5). The amounts of real mixing water ($W_1$ and $W_2$) were adjusted taking into account the actual absorption capacity of aggregates, i.e. the effective amount of water $W_{ef}$ was increased by water absorption value during mixing. For calculation of the additive amount, the thickness of coating layer was considered as $\delta = 0.150$ mm. The compositions were calculated taking into account densities of individual components to keep the constant volume 1m$^3$. The compositions of concrete mixtures are given in Table 1.

![Figure 1. Experimental triple mixing procedure.](image-url)
Figure 2. Experimental normal mixing procedure.

Table 1. Mix proportions of concrete samples for TM approach.

| Component [kg.m⁻³] | RCA - coarse aggregate | NA - coarse aggregate |
|--------------------|------------------------|----------------------|
|                     | CEM RCA | FA RCA | RCP RCA | CEM NA | FA NA | RCP NA |
| CEM I 42.5 R 0/4    | 310     | 310    | 310     | 336    | 336   | 336    |
| NA 4/8              | 898     | 898    | 898     | 896    | 896   | 896    |
| 8/16               | -       | -      | -       | 627    | 627   | 627    |
| RCA 4/8             | 224     | 224    | 224     | -      | -     | -      |
| 8/16               | 545     | 545    | 545     | -      | -     | -      |
| Material for coating| 80      | 68     | 68      | 55     | 47    | 47     |
| Plasticizer        | 2.5     | 2.5    | 2.5     | 2.7    | 2.7   | 2.7    |
| Water Wₑ₁         | 39.8    | 33.8   | 33.8    | 27.4   | 23.2  | 23.2   |
| Water Wₑ₂         | 155     | 155    | 155     | 168    | 168   | 168    |
| Total              | 232     | 226    | 226     | 203    | 198   | 202    |

Cube samples of 100x100x100 mm were prepared and cured under standard conditions. After 28 days, the capillary moisture (water) content was tested. The capillary absorption test allows the characterization of the porous structure of concrete and it is an indicator of the concrete durability. Samples were dried to constant mass, and then one face of the specimens is immersed in water at a depth of 5–10 mm for a specific period of time (normally 10 and 90 min). For this evaluation, the values in 90 min are discussed. Capillary moisture content \( m_c \) is characterized by water absorption coefficient \( A_w \) according to [19,20].

\[
m_c = A_w \cdot \sqrt{t} \tag{1}
\]

- \( m_c \) is the capillary moisture content (kg/m²).
- \( A_w \) is the water absorption coefficient (kg/m² s¹/²).
- \( t \) is the time (s).

Water absorption coefficient (\( A_w \)):

\[
A_w = \left( \frac{m_t - m_i}{A \sqrt{t}} \right) \tag{2}
\]

- \( A_w \) is the water absorption coefficient (kg/(m² s¹/²)).
- \( m_t \) is the mass of the specimen after time \( t \) (kg).
- \( m_i \) is the initial mass of the specimen (kg).
- \( A \) is the liquid contact area of the specimen (m²).
- \( t \) is the time (s).
3. Results and discussion
The comparison of capillary moisture content of the tested concretes prepared by various mixing methods after 28 days of curing is shown in Figure 3. The figure is organized in terms of mixing method, kind of aggregate and kind of coating material.

![Figure 3. Capillary moisture content of concrete samples.](image)

**Evaluation in terms of mixing method:**
In most cases, the triple mixing method gives better results than that of normal mixing. Looking at samples with RCA, the triple mixing process gives better results when aggregate is coated by FA and RCP. For coating with cement, the normal mixing seems to be more favorable.

For samples with NA, the triple mixing process gives better results when aggregate is coated by CEM and RCP while the normal mixing seems to be more favorable for coating with FA.

**Evaluation in terms of kind of aggregate:**
The samples with RCA have usually higher capillary water content than that of the samples with NA. The only exceptions are samples having RCA when coated with FA and prepared by TM, and the samples having RCA when coated with CEM and prepared by NM.

**Evaluation in terms of kind of coating material:**
There is no clear dependence in capillary moisture content in terms of coating material. Those additives affect differently in individual cases of the mixing method and the kind of aggregate. In 2 of 4 cases (when normal mixing was applied), the RCP gives the highest values; this corresponds with the character of the material, as it has no premise to have some pozzolanic/hydraulic character. However, the values themselves are so far from the ones of other coating materials.

4. Conclusion
The concretes prepared by two mixing methods (triple and normal) with 2 kinds of aggregate and 3 kinds of coating materials were tested. The capillary water content was measured as a durability parameter. The triple mixing method is promising for recycled concrete aggregate concrete, when fly ash or recycled concrete powder are used in the first stage of mixing to coat the coarse grains. It is a favourable result, taking into account the perspective of the application of secondary raw materials for concrete production.
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