

LOS ANGELES INDEX AND WATER ABSORPTION CAPACITY OF CRUSHED AGGREGATES

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Abstract: The mechanical and physical properties of the crushed aggregate have been studied. The properties of crushed aggregate, which produced from recycled aggregate concrete is not discussed in the literature yet despite it could be a choice in some circumstances like in case of demolishing the structures that already constructed by recycled aggregate concrete. Twenty-two types of self-compacting high-performance concrete made by coarse natural aggregate and coarse recycle concrete aggregate have been crushed and their properties have been studied. The main findings of the present study that, the Los Angeles index and water absorption of crushed aggregate is affected by the coarse recycled concrete aggregate dosage in its parent concrete, as well as, incorporating cement replacing materials in parent concrete help to enhance the abrasion resistance of crushed aggregate.

Keywords: Los Angeles index, Water absorption, Crushed aggregate, Recycled aggregate concrete, Cement replacing materials

1. Introduction

Aggregate is the most fundamental component of construction, which uses as an unbound material. It constitutes the majority of the volume of concrete and it is one of the most frequent materials within recycling, thus the focusing on reusing of crushed concrete should be on the high level of priority as one of the logical options [1], [2]. Using coarse Recycled Concrete Aggregate (RCA) as a partial replacement of coarse Natural Aggregate (NA) for producing Recycled Aggregate Concrete (RAC) has been

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much investigated and already validated with very satisfactory results, especially regarding its mechanical performance [3], [4]. However, as new concrete structures are made with RCA, these will eventually reach the end of their service life and consequently will be demolished and new crushed aggregate will be produced. This new aggregate will have different properties that need to be assessed [5]-[7]. It is Multiple Recycle Concrete Aggregate (MRCA), which means an aggregate produced as a result for crushing a RAC. Studying this kind of aggregate has to be supported and promoted to produce new concretes and therefore can be considered as a new environmental, economic and technological perspective.

It is concluded that the properties of MRCA are deteriorated as the number of recycling cycle's increases, due to the increasing of the amount of adhered mortar, where this observation is also applied on the RCA at the first generation comparing to the NA. The density of the MRCA tends to decrease by increasing the number of recycling cycles, while the water absorption tends to increase [8]-[11]. Some of the researchers studied the properties of concrete produced by using crushed aggregate, but just a few of them attempt to propose relations that link the properties of crushed aggregate to the properties of its parent concrete [12]-[14].

Several methods were proposed for assessing the abrasion resistance of aggregates; however, Los Angeles test is the most common method. It is a measure of toughness, degradation, and abrasion resistance of standard grading aggregates as a result of combining actions of abrasion and grinding in a rotating steel drum containing a specified number of steel spheres [1], [15]. Los Angeles index gives an indication to the quality and competence of any type of aggregate where higher Los Angeles index means less abrasion resistance. Most of the researches declared that the resistance of crushing and abrasion of RCA is relatively lower than that of NA with a higher Los Angeles index, that is because of the separation and crushing of adhered mortar in addition to the loss of original aggregate [16], [17].

Water absorption capacity is one of the most important properties of aggregate especially in case of RAC, which it has to be determined at early stages like in job mix design stage [18]. It affects the porosity of the produced concrete and thus affects the mechanical and durability properties of concrete. The water absorption of MRCA, has been observed to be higher than in case of RCA and NA [19].

The possibility for reusing of RAC deserves more attention, which promising a sustainable future. Thus, the present study aims to investigate the properties of crushed aggregate (RCA and MRCA) and attempts to find out some relations between its properties and the properties of its parent concrete. That is through testing the Los Angeles and water absorption for twenty-two different crushed aggregate samples, which their parent concrete's properties are already known. As well as studying the effect of using Cement Replacing Materials (CRMs) as a partial replacement of cement in parent concrete in order to enhance the properties of its crushed aggregate. The parent concrete was Self-Compacting High Strength Concrete (SCHSC), thus its porosity is low and has a high binder volume.

2. Method

The main goal of the present study is to investigate the properties of different types of crushed aggregate by taking into consideration the properties of its parent concrete, which is either NA concrete or RAC. To do so, twenty-two concrete mixtures of SCHSC incorporating RCA and different CRMs were designed, mixed, cast, and tested for their mechanical properties at different ages. The rubble of the specimens after testing has been crushed and saved up to six months in the laboratory condition; in order to eliminate the effect of proceeding hydration as much as possible and confirm the behavior with the normal situation for using aggregate in the reality. Then it sieved to consider just the coarse fraction of aggregate, where the produced crushed aggregates were mainly four groups:

1. RCA is a recycled concrete aggregate produced by crushing NA concrete in the laboratory after testing;
2. MRCA25 is a multiple recycled concrete aggregate produced from the first generation of RAC, which was originally prepared with 25% replacement of NA by RCA;
3. MRCA50 is a multiple recycled concrete aggregate produced from the first generation RAC, which was originally prepared with 50% replacement of NA by RCA;
4. MRCA100 is a multiple recycled concrete aggregate produced from the first generation RAC, which was originally prepared with 100% replacement of NA by RCA.

As a final step, the aggregate samples have been prepared for testing both the water absorption capacity and Los Angeles abrasion.

2.1. Parent concrete

Parent concrete mixtures have been designed and produced to achieve the purpose of producing high strength concrete with high flow-ability by utilizing waste granular and powder materials. Thus, twenty-two SCHSC mixtures with 500 kg/m³ cement (powder) content and 0.35 water to binder (*w/b*) ratio were the types of the parent concrete for the next stage (crushed aggregate). The main differences between the mixtures are the RCA and CRMs substitution of NA and cement respectively, the cement substitution ratios by CRMs were 0%, 15%, and 30%, whereas the NA substitution ratios by RCA were 0%, 25%, 50%, and 100% by mass of NA. CRMs were three waste powder materials delivered to the laboratory for use in the testing program without any processing, which they were:

1. Unprocessed Waste Fly Ash (WFA) collected from a coal power station in Hungary (Visonta coal-fired thermal power station);
2. Waste Cellular Concrete Powder (WCC) collected from a factory for cutting cellular concrete masonry in Hungary;
3. Waste Perlite Powder (WPP), an amorphous volcanic silicate/alumina rock originating from raw perlite resulting from the cutting of raw perlite rock. It was

exported with high and low specific surface areas (WPP-c and WPP-s). WPP-c and WPP-s were used by 50% of each as WPP.

The water absorption of the used RCA was 5.6% by mass, which is high due to the adhered mortar, thus, extra water were added to compensate the water absorption of RCA where it has been used in air dry situation. Los Angeles index of RCA was relatively higher than that of NA owing to the low strength of the adhered mortar in RCA, which was 36.11 for RCA and 26.3 for NA, however, all aggregates blends have been tested to meet the requirements of BS EN 12620:2002+A1 [20]. The mixes were divided into four series, depending on the substitution ratios of NA; *Table I* shows the mixing proportions for all mixtures.

Table I

Concrete mixing proportioning

| Name of mixture | Proportions in kg/m ³ | | | | | | | | |
|---------------------------------|----------------------------------|------|-----|-----|----------------|------------------|-----|-----------------|-------|
| | CEM I 42.5 N | CRMs | | | Fine aggregate | Coarse aggregate | | Super-plastizer | Water |
| | | WFA | WCC | WPP | N. Sand | NA | RCA | | |
| | | | | | 0/4 | 4/16 | | | |
| Series I: 0% RCA | | | | | | | | | |
| RA0 | 500 | 0 | 0 | 0 | 783 | 939 | 0 | 1.5 | 175 |
| F15RA0 | 425 | 75 | 0 | 0 | 767 | 920 | 0 | 2 | 175 |
| F30RA0 | 350 | 150 | 0 | 0 | 751 | 901 | 0 | 3 | 175 |
| C15RA0 | 425 | 0 | 75 | 0 | 766 | 919 | 0 | 1.7 | 175 |
| C30RA0 | 350 | 0 | 150 | 0 | 750 | 899 | 0 | 3.25 | 175 |
| P15RA0 | 425 | 0 | 0 | 75 | 774 | 928 | 0 | 3 | 175 |
| P30RA0 | 350 | 0 | 0 | 150 | 766 | 918 | 0 | 3.75 | 175 |
| Series II: 25% RCA replacement | | | | | | | | | |
| RA25 | 500 | 0 | 0 | 0 | 783 | 704 | 230 | 1.5 | 175 |
| F15RA25 | 425 | 75 | 0 | 0 | 767 | 690 | 226 | 2 | 175 |
| F30RA25 | 350 | 150 | 0 | 0 | 751 | 475 | 221 | 3 | 175 |
| C15RA25 | 425 | 0 | 75 | 0 | 766 | 690 | 225 | 1.7 | 175 |
| C30RA25 | 350 | 0 | 150 | 0 | 750 | 674 | 220 | 3.25 | 175 |
| P15RA25 | 425 | 0 | 0 | 75 | 774 | 697 | 228 | 3 | 175 |
| P30RA25 | 350 | 0 | 0 | 150 | 766 | 688 | 225 | 3.75 | 175 |
| Series III: 50% RCA replacement | | | | | | | | | |
| RA50 | 500 | 0 | 0 | 0 | 783 | 470 | 460 | 1.5 | 175 |
| F15RA50 | 425 | 75 | 0 | 0 | 767 | 460 | 251 | 2 | 175 |
| F30RA50 | 350 | 150 | 0 | 0 | 751 | 451 | 442 | 3 | 175 |
| C15RA50 | 425 | 0 | 75 | 0 | 766 | 459 | 451 | 1.7 | 175 |
| C30RA50 | 350 | 0 | 150 | 0 | 750 | 451 | 442 | 3.25 | 175 |
| P15RA50 | 425 | 0 | 0 | 75 | 774 | 464 | 455 | 3 | 175 |
| P30RA50 | 350 | 0 | 0 | 150 | 766 | 459 | 450 | 3.75 | 175 |
| Series IV: 100% RCA replacement | | | | | | | | | |
| RA100 | 500 | 0 | 0 | 0 | 783 | 0 | 920 | 1.5 | 175 |

The cement used throughout the experimental program was CEM I strength class 42.5 N, the chemical and physical properties of the cement and CRMs are shown in

Table II, which they were tested in accordance with DIN EN 197-1; DIN EN 196-2; MSZ EN 525-12 [21]-[23]. However, Fig. 1 shows the sieve curves for the cement and CRMs and depicts that UWFA, WCCP and WPP-c had larger grain distributions than cement but WPP-s had a finer grain distribution.

Table II

Chemical compositions and physical properties of cement and CRMs

| Measured property | CEM I | WFA | WPP | WCC |
|---|-------|-------|-------|-------|
| Density (g/cm ³) | 3.02 | 2.15 | 2.33 | 1.96 |
| Specific surface area (cm ² /g) | 3326 | 4323 | 2347 | 2513 |
| Loss on ignition | 3.0 | 1.95 | 2 | 9.25 |
| SiO ₂ | 19.33 | 43.02 | 73.5 | 54.28 |
| CaO | 63.43 | 15.07 | 1.1 | 22.81 |
| MgO | 1.45 | 3.14 | 0.16 | 1.15 |
| Fe ₂ O ₃ | 3.42 | 14.17 | 2.1 | 2.16 |
| Al ₂ O ₃ | 4.67 | 15.6 | 15.2 | 5.09 |
| SO ₃ | 2.6 | 3.56 | - | 4.90 |
| Chloride content | 0.04 | 0.02 | - | 0.02 |
| Free CaO | 0.71 | 0.37 | - | - |
| K ₂ O | - | - | 3.75 | - |
| Na ₂ O | - | - | 2.08 | - |
| TiO ₂ | - | - | 0.87 | - |
| Insoluble part in dilute hydrochloric acid and sodium carbonate | 0.26 | 49.72 | 89.13 | 33.02 |

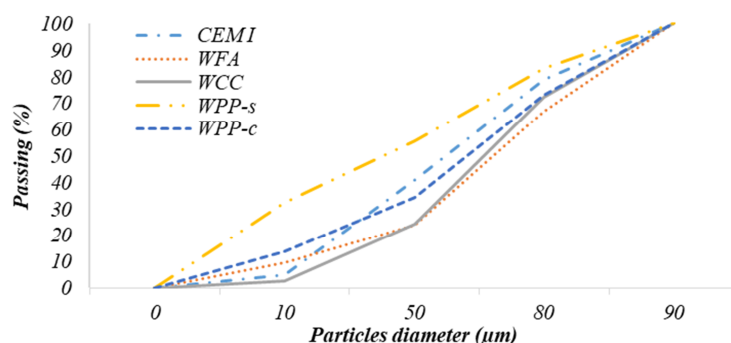


Fig. 1. Grading curves of cement and CRMs

The X-ray diffraction profile for the cement, WFA, WCC and WPP is shown in Fig. 2. where A: Alite (C₃S). B: Belite (C₂S). C: Brownmillerite (C₄AF). D: Gypsum (CSH₂). E: Gypsum Un-Hydrated (CS). H: Hematite. K: Kaolinite. P: Plagioclase (Lattice). Q: Quartz. R: Phyllosilicates. S: Plagioclase (Anorthite). T: Tobermorite. A high absorption factor was recorded for iron, which meant a long time required for completing the hydration process of WFA. Considerable SiO₂ was present in amorphous

form and burned albite. The hydrated phase in the cement was gypsum (dehydrate), but it was anhydrite in WFA. The crystalline phases could be identified as follows:

1. CEM I: Ca_3SiO_5 (C_3S , alite, hattrurite) as main crystalline component; Ca_2SiO_4 (C_2S , belite, larnite) presence could not be excluded; - $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (CSH_2 , gypsum); - $\text{Ca}_4\text{Al}_2\text{Fe}_2\text{O}_{10}$ (C_4AF , brownmillerite);
2. WFA: - $\alpha\text{-SiO}_2$ (S, α -quartz) as main crystalline component; - Fe_2O_3 (F, hematite) also dominating crystalline component; - CaSO_4 (CS, anhydrite); - plagioclase (feldspar, most probable heat-treated albite);
3. WCC: - $\alpha\text{-SiO}_2$ (S, α -quartz) as the main crystalline component; - CaSO_4 (CS, anhydrite); - hydrated mineral, called tobermorite 11A seemed to explain several diffraction peaks;
4. WPP: - SiO_2 (Ca-, Al-bearing cristoballite) as main crystalline component; - plagioclase (feldspar, most probable anortite); - occurrence of various zeolitically hydrated minerals could not be excluded.

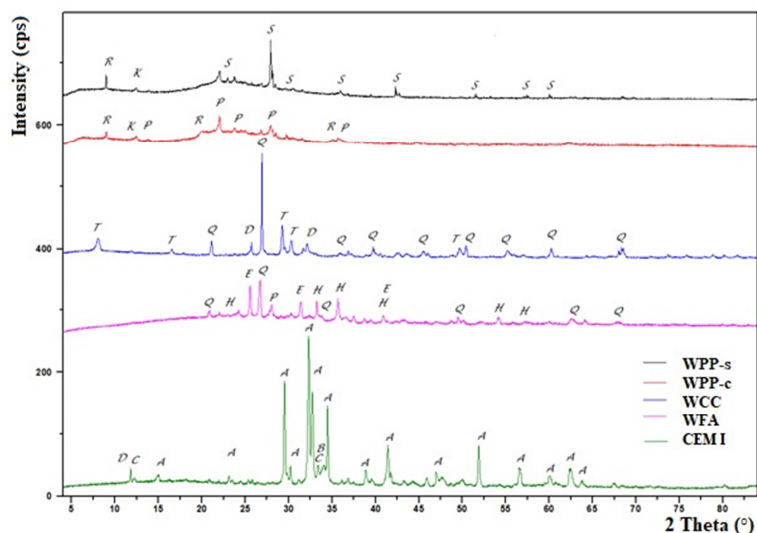


Fig. 2. X-ray diffraction profile of cement and CRMs

To achieve the same range of flow-ability for the concrete mixtures and produce workable mixtures with the same *w/b* ratio, a considerable amount of high range water reducing admixture was used (Sika ViscoCrete-5 Neu). River quartz sand (0/4 mm) was used as fine aggregate in all the concrete types, whereas the coarse aggregate was the main variable with two coarse aggregate (4/16 mm) types: NA and RCA.

2.2. Crushed aggregate

After testing the mechanical properties of all the twenty-two concrete types, their rubble saved at the laboratory conditions for up to six months. Then the rubble for each

type of concrete has been crushed and sieved to consider the coarse fraction of the crushed aggregate and prepared for testing both Los Angeles and water absorption capacity of the new crushed aggregate. Twenty-two types of the crushed aggregate have been produced, where mainly they were RCA and MRCA with different CRMs.

2.3. Los Angeles index of crushed aggregate

The most common method of assessing the abrasion resistance of aggregates is the Los Angeles abrasion test, which determines the relative competence or resistance to abrasion of aggregates according to BS EN 1097-2 [24]. The standard testing procedure for the Los Angeles index requires the measurement of mass passing a 1.6 mm sieve after 500 revolutions of a drum, which is a hollow steel cylinder that is closed at both ends. The graded aggregate sample is placed into with eleven of steel spheres weighing approximately 420 g each and having a diameter of 47 mm. The interior of the cylinder has a shelf that picks up the sample and spheres during each rotation and then drops them on the opposite side of the cylinder, thereby subjecting the sample to abrasion or attrition.

The graded aggregate sample in the testing of the coarse aggregates was 5000 g of the confined aggregates between 10 and 14 mm sieves (passing the 14 mm sieve and returning via the 10 mm sieve). To determine the amount of degradation that occurred during the test; the crushed aggregate, which was coarser than the 1.6 mm sieve, had to be separated and weighed (G_{500}). The abrasion loss as percentage of the original mass of the test sample after 500 revolutions was calculated according to Eq. (1).

$$K500 = \frac{G_0 - G_{500}}{G_0} \cdot 100, \quad (1)$$

where $K500$ is the abrasion loss after 500 revolutions in %; G_0 is the original sample mass in g; G_{500} is the sample mass after 500 revolutions in g.

2.4. Water absorption capacity of crushed aggregate

Water absorption is an important physical property of aggregates, and despite the many differences between the NA and the crushed aggregates, methods, which were used to measure the water absorption in NA were still applicable for RCA [18]. Determination of water absorption capacity based on Saturated Surface Dry (SSD) of the aggregate's particles was used for figuring out the water absorption of the crushed aggregate in the present study. SSD means the condition in which the permeable pores of an aggregate's particles are filled with water without free water on their surfaces.

In determining the water absorption capacity based on the concept of SSD, the following steps, which are recommended by most standards, had to be followed. Eq. (2) was used to calculate the water absorption capacity.

1. The aggregate was saturated by soaking in water for usually 24 hours or more at atmospheric pressure;

2. The film of water covering the surface was removed with a towel, and the SSD mass was weighed. Towelling the surface of the aggregates allowed for achieving the SSD state according to the followed standards;
3. The sample was dried until it reached a constant mass, and the oven-dry (OD) mass was measured by saving in a ventilated oven at $110 \pm 5 \text{ }^{\circ}\text{C}$ for usually 24 hours.

$$\text{Water absorption capacity} = \frac{M_{SSD} - M_{OD}}{M_{OD}} \cdot 100, \quad (2)$$

where *water absorption capacity* is in %; M_{SSD} is the SSD mass in g; M_{OD} is the OD mass in g.

3. Results

All mechanical properties of the parent concrete mixtures have been tested at the age of 28, 90 and 270 days, the authors published the results as green versions of SCHPC [25]. Where it was concluded that by incorporating waste materials in the concrete production could provide sustainable, economic and high-performance versions of concrete [26]. The compressive strength of the parent concrete mixtures is presented in *Fig. 3* which shows that the incorporating a high quality of RCA enhanced the compressive strength of SCHPC due to the high roughness, porosity and specific surface of the RCA, which contributed to enhancing the interconnection and better mechanical bonding between the RCA and the new mortar [27], [28]. As well as incorporating up to 15% of WPP or UWFA improved the compressive strength of RAC due to their pozzolanic activity and their grading fractions, which contributed to filling the micro-crack of RCA, where the coal fly ash has a positive influence on compressive strength development of the tested concrete samples [29]. However, WCC was not a good choice as a CRM, where it caused a reduction in the compressive strength of SCHPC.

3.1. Los Angeles index

An investigation of the relationships between the Los Angeles indices of the crushed aggregate and the compressive strength for its parent concrete revealed no general relationship as it is shown in *Fig. 3*. However, a strong regression was possible for each type of concrete (regarding the binder type), but it could not be generalized.

Fig. 4 shows the Los Angeles indices of the crushed aggregate at the age of 180 days for all SCHSC mixtures. The Los Angeles indices are grouped into three for determining the effect of the RCA and CRMs in their parent concrete. The first, second and third are normal RCA, MRCA25 and MRCA50, respectively.

Findings also showed that using any of the proposed CRMs in the parent concrete enhanced the abrasion resistance of RCA or MRCA. In general, the use of CRMs improved the wear resistance of the mortar in the concrete. The enhancement of wear resistance of the crushed aggregate by the use any of WFA, WCC, WPP in its parent

concrete could be related to the hydration, which occurred with age for the adhered mortar that was attached to the crushed aggregate.

The Los Angeles index of MRCA increased comparing to the Los Angeles index of RCA and NA, however, the increasing value was affected by the replacement amount of RCA in its parent concrete. In the case of using 50% of RCA in the parent concrete, the Los Angeles value was higher than that in the case of using 25% or 75%; therefore, 50% is the critical point where the Los Angeles index was retaining to decrease after increasing behavior. Fig. 5 shows a stable binomial relationship ($R^2 = 0.99$) between the Los Angeles indices of MRCA and the replacement amount of NA by RCA in their parent concrete.

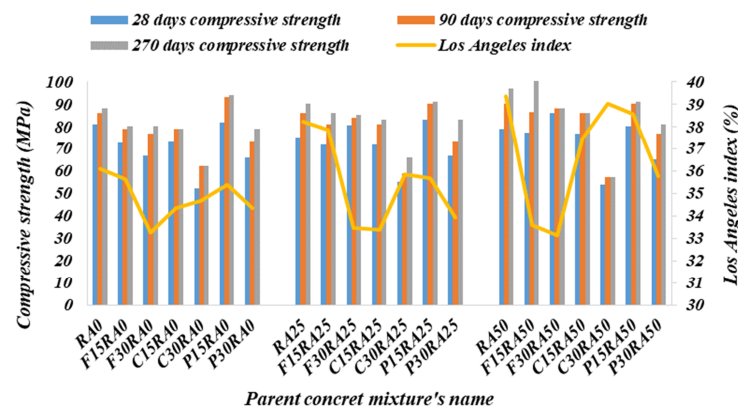


Fig. 3. Compressive strength of parent concrete mixtures and Los Angeles values for their crushed aggregate

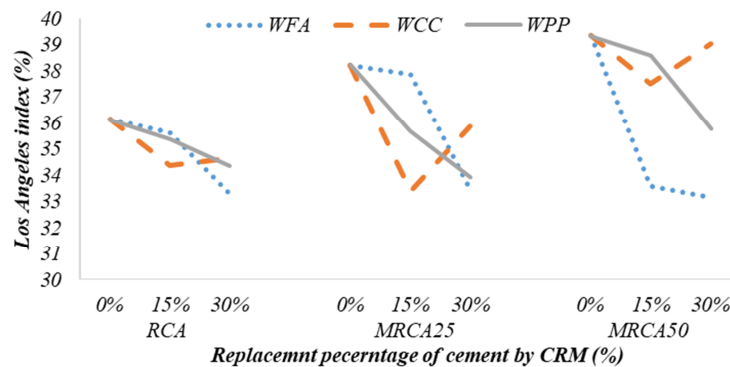


Fig. 4. Los Angeles indices for the crushed aggregate

This relationship could be justified by the homogeneity of the aggregate mixture in the parent concrete, which affected the distribution of aggregates inside the mixtures. The homogeneity of (25% RCA + 75% NA) mixture differed from that of (50% RCA +

50% NA) mixture. Meanwhile, 50% replacement of NA by RCA in the parent concrete mixture changed the dominant type of aggregate; otherwise, the homogeneity was improved.

The rise in the amount of the adhered mortar, which increased by the recycling generations and/or the replacement amount of RCA in the parent concrete, was the main reason for the increase of the Los Angeles indices. Therefore, enhancing the abrasion resistance of the mortar of the parent concrete (then the adhered mortar in the crushed aggregate) could enhance the abrasion resistance of RCA or MRCA, which was produced from it.

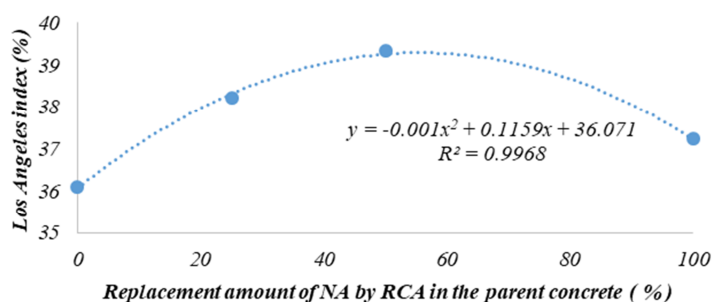


Fig. 5. Relationship between the Los Angeles index of crushed aggregate and the replacement amount of RCA in its parent concrete

3.2. Water absorption capacity

A linear relationship ($R^2 = 0.93$) could be expressed by the absorption capacity of MRCA with regard to the replacement amount of the NA by RCA in its parent concrete, as it is shown in Fig. 6. This relationship was expected due to the increase of the adhered mortar by the increasing RCA dosage in the parent concrete, which was the main reason for the increasing of the absorption capacity of crushed aggregate.

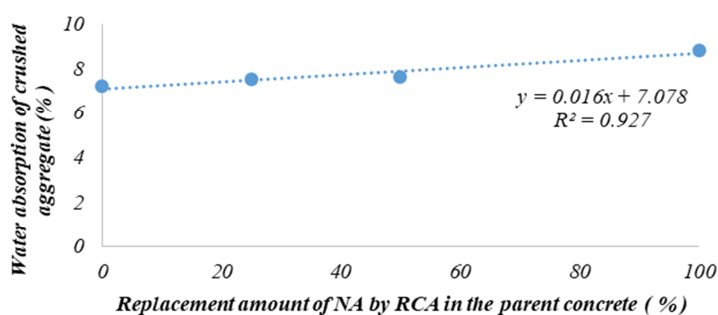


Fig. 6. Relationship between the water absorption of crushed aggregate and the replacement amount of NA by RCA in its parent concrete

Despite the lack of relationships between the Los Angeles indices of the crushed aggregates and the mechanical properties of their parent concrete; a strong regression relationship was observed between the crushed aggregates and their parent concretes. A linear relationship could predict the water absorption capacity of either the concrete or its crushed aggregate if one of them is known ($R^2 = 0.95$). Dealing with water absorption capacity was clearer in SCHSC than in normal-strength concrete, where the water absorption capacity was highly connected with concrete strength. In nearly all cases of SCHSC, the water absorptions were close and low despite the potential scattering of strength. *Fig. 7* shows the relationship between the water absorption capacity of the crushed aggregate and the water absorption capacity of its parent concrete.

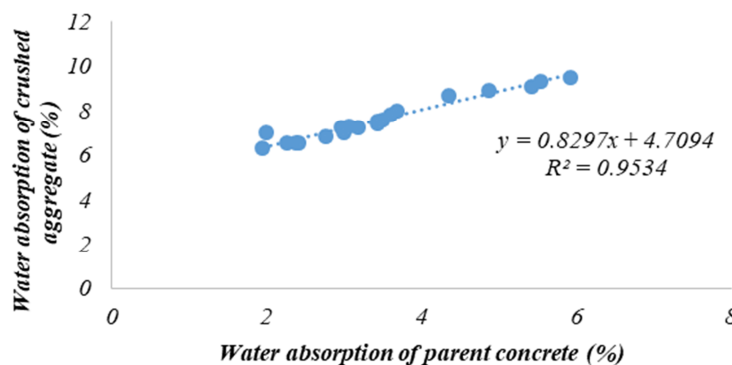


Fig. 7. Relationship between the water absorption of crushed aggregate and its parent concrete

4. Conclusion

Using crushed aggregate is hampered by the lack of technical confidence in its practical use due to its different behaviors like high porosity, high water absorption capacity and low density, which negatively affected the performance of the recycled aggregate concrete if it is compared with the natural aggregate concrete. However, the present study is an attempt for promoting the use of crushed aggregate, which they were resulted by crushing twenty-two different types of self-compacting high-performance concrete incorporated coarse recycled concrete aggregate. The main findings of the present study were:

1. By using the crushed aggregate (multiple recycled concrete aggregate) the aggregate could be changed from a nonrenewable resource to the partially renewable resource, it is recorded satisfying results, which is comparable to the coarse recycled concrete aggregate;
2. Incorporating any of waste fly ash, waste cellular concrete powder or waste perlite powder in self-compacting high-performance concrete enhances the Los

Angeles value of its crushed aggregate, however, there is no general relationship between the Los Angeles indices of crushed aggregate and the mechanical properties of their parent concrete;

5. The Los Angeles indices and water absorption capacity of multiple recycled concrete aggregate affected clearly by the dosage of coarse recycled concrete aggregate in its parent concrete, where the water absorption capacity increases by a linear relationship. While the Los Angeles index increases by polynomial relationship with maximum value at MRCA50;
 - where MRCA50 means a multiple recycled concrete aggregate produced from the first generation recycled aggregate concrete, which was originally prepared with 50% replacement of coarse natural aggregate by coarse recycled concrete aggregate
3. A strong relationship has been found between the water absorption capacity of crushed aggregate and the water absorption capacity of its parent concrete.

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