

# Production of greener recycled aggregate concretes using local supplementary cementing materials

## Abstract

In the study, supplementary cementing materials (SCMs) have been added in an attempt to improve the performance of recycled aggregate concrete. The use of such eco-friendly materials could also promote a further greening practice in the concrete industry. The concrete performance was evaluated in terms of mechanical properties and concrete permeability. Mechanical properties investigated include compressive strength and modulus of elasticity of concrete. Water permeability, chloride penetrability have particularly been studied to evaluate the permeability properties. The results revealed that the use of SCMs could improve produce greater compressive and modulus of elasticity than those of the recycled aggregate concrete alone. Further, the results showed that permeability properties of recycled aggregate concrete have significantly been improved with addition of these SCMs. Basaltic aggregates were used for comparison and SEM analysis was employed as well.

**Keywords:** recycled concrete aggregates, permeability, green concrete, scms, durability

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## Introduction

Many of towns have totally or partially been destroyed after five years of conflict in Syria. According to a report released by UN Economic and Social Council for Western Asia (ESCWA) in 2013, more than 1.2 million homes have been damaged or destroyed.<sup>1</sup> Among cities that suffered from building destruction due to the ongoing events, Aleppo was ranked the first with more than a half million of totally or partially destroyed buildings, followed by Damascus countryside which half of its houses were also destroyed. However, the current real figure of the destroyed buildings could be significantly over that reported by ESCWA.<sup>1</sup>

The resulting rubble could produce tremendous discarded concrete. Hence, the recycled concrete aggregates (RCA) are expected to be inevitable building materials during the post-war rebuilding in the country. Compared to natural aggregate, RCA, however, has a higher tendency of water absorption due to the attached old cement mortar, resulting in a decline of strength and durability of recycled aggregate concrete (RAC) and limits its wider application. To overcome the weakness of RCA, much work has been carried out on improvement of RCA quality.<sup>2</sup> This paper attempts to investigate the influence of adding SCMs on compressive strength and modulus of elasticity of RAC. Permeability properties of RAC such as water permeability and chloride penetrability have also been investigated. Some petrographic, chemical and physical properties have been reported, as well.

The importance of the study can be summarized in the following points:

- I. Begin preparations for the huge rebuilding work in Syria after the war comes to its end.
- II. Recycling concrete wastes is considered an inevitable approach in the country.
- III. The replacement of Portland cement by SCMs could significantly minimize the quantity of CO<sub>2</sub> released and the

energy consumed.<sup>3,4</sup> Furthermore, the addition of SCMs has been found to improve the properties of RAC.<sup>5-10</sup>

- IV. The study is not limited to the country, but it can also be applied to all areas containing similar SCMs.

## Materials and methods

### Materials

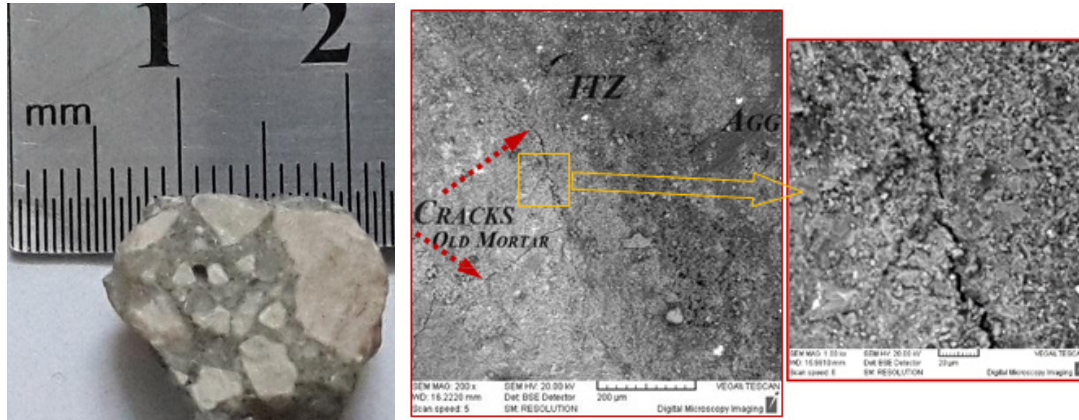
Obtaining concrete wastes from the completely or partially demolished homes has always been a logistic problem in the country. Therefore, coarse RCAs have been produced by crushing old concrete cubes (C25/30) used for compressive strength test. Fine recycled concrete aggregate was not considered for recycled aggregate concrete production because its application in structural concrete is generally not recommended.<sup>11,12</sup> Figure 1 shows a macrograph of a coarse RCA particle produced from crushing old concrete cubes, accompanied by a SEM analysis.

The SCMs used are limestone which was quarried from Hama governance, about 200km north of Damascus, and volcanic scoria which was collected from Tel Shiha' quarry, about 70km southeast of Damascus. SEM and EDX analysis of the limestone powder and volcanic scoria are presented in Figure 2. The chemical analysis of limestone and volcanic scoria used in the study is summarized in Table 1. This analysis was carried out by means of wet chemical analysis specified in EN 196-2 (1989). The total organic carbon (TOC) and clay contents of limestone have been determined in accordance with EN 13639 and EN 933-9, respectively.

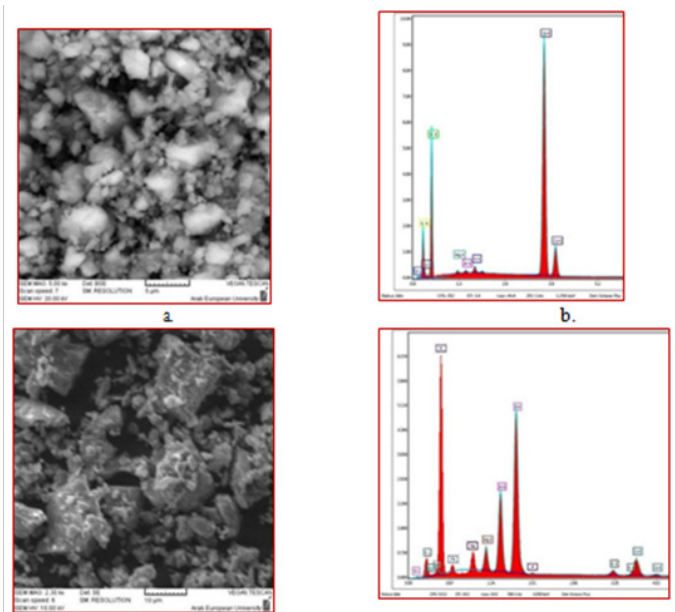
Crushed Basaltic aggregates extracted from As-Swaida'a region, about 100km southeast of Damascus, have also been used for comparison. The chemical analysis of the aggregates used in the study is listed in Table 1. This analysis has been carried out by means of X-Ray fluorescence. The cement used in the experiments was obtained from Adra Cement Plant, Damascus, Syria. Chemical analysis of cement is shown in Table 1. Limestone and volcanic scoria

have separately been ground to  $4200 \pm 100 \text{ cm}^2/\text{g}$  Blaine fineness, while the clinker and gypsum were underground into  $3600 \pm 50 \text{ cm}^2/\text{g}$ . Four binder samples were prepared; one plain Portland cement CEM I (control) (EN 197-1), two binary binders with one replacement levels

of 10% limestone filler or 25% volcanic scoria (EN 197-1) and one ternary binder containing both limestone filler and volcanic scoria with replacement levels of 10% and 25%, respectively. All replacements were made by mass of cement.



**Figure 1** a) Photograph of a coarse recycled aggregate particle; b) SEM of the particle: the old mortar and aggregate on both sides of the interfacial transition zone (ITZ) are shown.



**Figure 2** SEM and EDX of the investigated SCMs. a) and b) limestone powder; c and d) volcanic scoria.

Five concrete mixes were prepared. The first mix was prepared using basaltic aggregate. The second mix was prepared using 100% coarse RCA and fine dolomite aggregate with CEM I added, whereas the third to the fifth mixes were prepared using 100% coarse RCA and fine dolomite aggregate with addition of 10% LF, 25% VS and 10% LF+25% VS as cement replacement, respectively. The grading of aggregate mixtures was kept nearly close to fuller's curve ( $D_{\max}=25\text{mm}$ ) for all concrete mixes. Some physical properties and grading of the aggregates are illustrated in Table 2 & Figure 3, respectively. Their quantities in  $1\text{m}^3$  concrete mix based on oven-dry condition are summarized in Table 3. All concrete mixes were designed to have a water-binder ratio of 0.6 which is a customary value in the local concrete plants. All concretes were designated as shown in Table 3. Nine concrete cubes ( $150\text{mm}$ ) and three concrete prisms ( $150 \times 150 \times 450\text{mm}$ ) were cast for each of mixture type and curing age for the determination of compressive strength and modulus of elasticity, respectively. Further, three concrete cubes ( $150\text{mm}$ ) were cast for each of mixture type and curing age for the determination of water permeability. Three concrete cylinders ( $100\text{mm} \times 200\text{mm}$ ) for each of mixture type and curing age were cast for evaluating the concrete penetrability of chloride ions. One slice of  $100\text{mm}$  in diameter and  $50\text{mm}$  in thickness was cut from the middle portion of each concrete cylinder specimens for using in the chloride penetrability test.

**Table 1** Chemical composition of the materials used in the concrete mixes

Chemical composition (by mass, %)	Materials				
	Recycled concrete aggregate	Basalt aggregate	Volcanic scoria	Limestone filler	Cement
$\text{SiO}_2$	1.13	45.76	44.91	1.57	20.13
$\text{Al}_2\text{O}_3$	0.63	16.87	16.98	0.69	5.14
$\text{Fe}_2\text{O}_3$	0.24	14.39	8.64	0.33	3.2
$\text{CaO}$	33.05	8.93	9.39	54.37	62.65
$\text{MgO}$	19.81	6.61	8.87	0.43	2.33
$\text{Na}_2\text{O}$	0.1	2.64	2.76	0.02	0.71
$\text{K}_2\text{O}$	0.2	1.05	1.75	0.01	0.24

Table Continued....

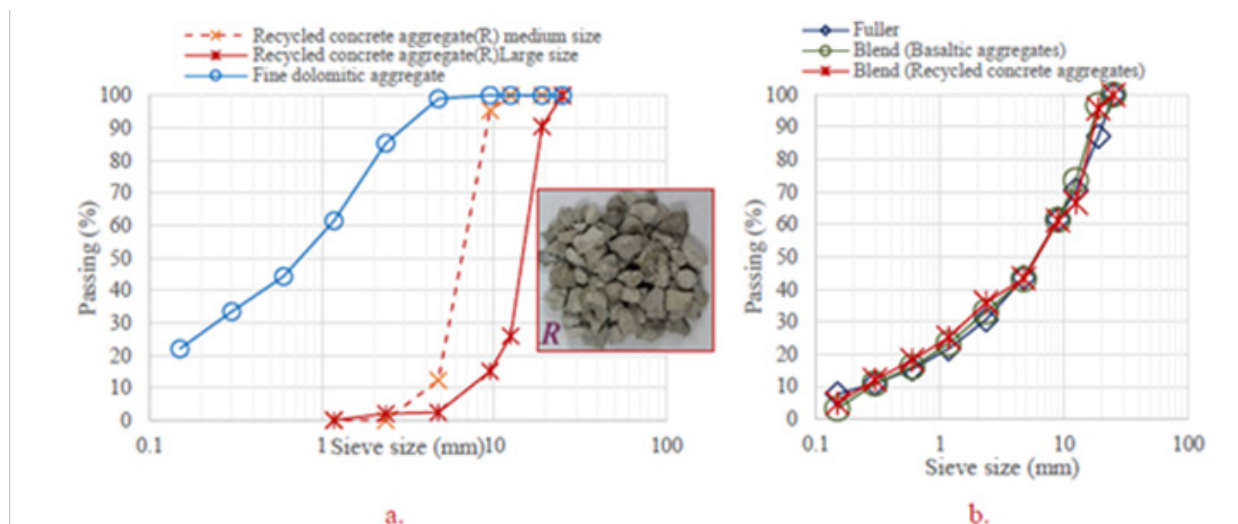
Chemical composition (by mass, %)	Materials				
	Recycled concrete aggregate	Basalt aggregate	Volcanic scoria	Limestone filler	Cement
TiO <sub>2</sub>	0.1	2.53	0.9	0.07	0.15
Cl-	0.02	0.01		0.01	0.05
SO <sub>3</sub>	0.02	-	0.01	0.01	2.35
Loss on ignition	44.59	1.1	0.36	42.22	2.39
Insoluble residue	0.1		5.01	-	0.69

**Table 2** Some characteristics of the different aggregates used in the experiments

Pozzolan activity index (%) (ASTM C618)		79 (at 7 days)		90 (at 28 days)		
Characteristic	Fine dolomite aggregate	Recycled concrete aggregates		Basaltic aggregates		
		Medium size	Large size	Fine	Medium size	Large size
Specific gravity	2.7	2.39	2.43	2.73	2.78	2.79
Absorption (%)	1.5	4.79	5.14	1.54	1.34	1.34
Sand equivalent (%) (ASTM D 2419)	76			87		
Los Angeles (%) (ASTM C33)			33.9			17.3
Na <sub>2</sub> SO <sub>4</sub> soundness (%) (ASTM C 88)			1.9			0.41

**Table 3** Ingredients of the prepared concrete mixes

Concrete mix	Fine aggregates	Medium-Size aggregates	Large Size aggregates	PC (kg)	LF (kg)	VS (kg)	Water (kg)	Total weight
BBC	718	220	879	350	0	0	210	2377
Plain RAC	676	284	705	350	0	0	210	2225
RAC-LF	674	282	702	315	35	0	210	2218
RAC-VS	673	282	701	262.5	0	87.5	210	2216
RAC-LF-VS	671	281	699	227.5	35	87.5	210	2211

**Figure 3** particle size distributions of the investigated RCA (left) and fuller curve with the blends (right)

## Methods

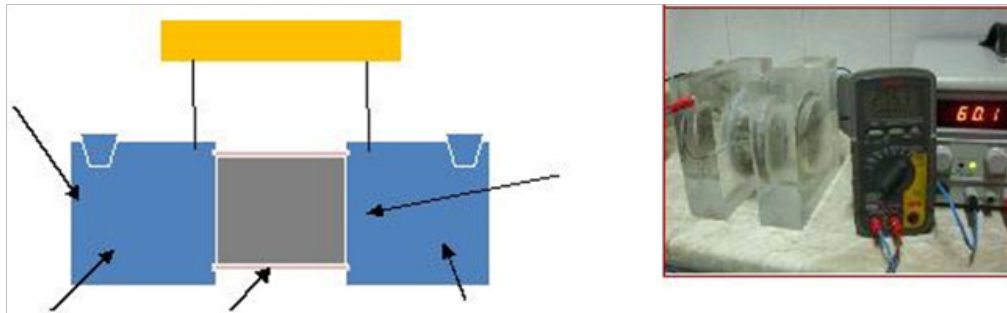
The compressive strength development has been determined on 150mm cubic concrete specimens at ages of 2, 7, 28, 90 days, in accordance with ISO 4012. The static modulus of elasticity of concrete

was determined in accordance with ASTM C 469. The specimen was instrumented with three strain gauges. The test was carried out on the concrete specimens at the ages of 7, 28 and 90 days. Concrete permeability measured in terms of depth of water penetration<sup>13</sup> has been carried out as per the standard EN 12390-8 after 7, 28 and 90



days curing. The rapid chloride penetrability test (RCPT) has been conducted in accordance with ASTM C 1202. The set-up of RCPT is illustrated in Figure 4. The total charge passed through the sample, in

coulombs, is determined by calculating the area under the current–time plot during the 6-h test period. Three cylinder specimens of each concrete mix were tested after 7, 28 and 90 days curing.



**Figure 4** a) & b) Schematic representation (left) and view of experimental setup of rapid chloride penetration test (right).

## Results and discussion

### Properties of RCA and SCMs

As seen from Table 2, the water absorption (%), Los Angeles value (%) and Na<sub>2</sub>SO<sub>4</sub> soundness (%) of coarse RCA were 5%, 33.9% and 1.9%, respectively. These expected results for coarse RCA can mainly be attributed to the residue of mortar adhering to the original aggregate.<sup>14</sup> The coarse RCA are less hard and resistant to freezing than natural aggregates (i.e. basaltic aggregates), but values of Los-Angeles (33.9% on average) and soundness (1.9% on average) remain acceptable with regards to the allowable 45% & 12% limits usually required, respectively (ASTM C33).

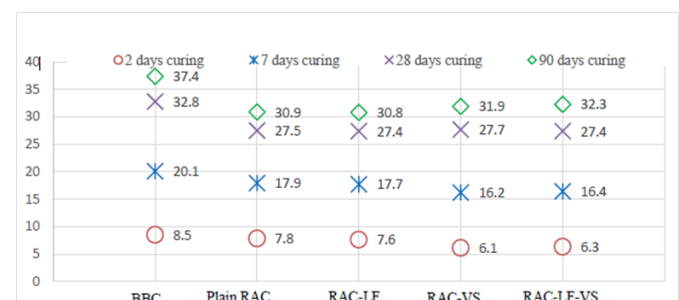
On the other hand, the chemical composition of limestone powder has been found to be 55% CaO (CaCO<sub>3</sub> ratio is about 97%) with a loss on ignition value of 43%. The total organic content (TOC) and clay content of the studied limestone has been determined as 0.36% & 0.56%, respectively. According to EN 197-1 standard, the CaCO<sub>3</sub> ratio of limestone employed in the production of blended cement should be at least 75%, and the clay content of limestone should not exceed 1.2%. Based on the analysis results, the studied limestone can be used as ingredient in cement production. In addition, volcanic scoria satisfied the standards requirements for such a material by having a combined SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub> of more than 70%, a SO<sub>3</sub> content of less than 4% and a loss on ignition of less than 10% (ASTM C618:2001). SiO<sub>2</sub> reactive content is more than 25%, as well (EN 197-1) Furthermore, volcanic scoria has a strength activity index with Portland cement (PC) higher than the values specified in ASTM C618 (2001).

### Compressive and splitting strength of concretes

The development of the compressive strength with age of basaltic-based concrete (BBC) and recycled aggregate concrete (RAC) with and without SCMs is illustrated in Figure 5. As expected, the compressive strengths of concrete increased with curing time, but with a different rate of strength gain. In general, there is a 16% decrease in 28 days-compressive strength of plain RAC as compared to BBC. This observation is similar to that reported in the literature<sup>15–18</sup> and departs from that of other researchers<sup>19–21</sup> who observed that the decrease in strength ranged from 25 to 45%. The insignificant decrease could be attributed to the use of crushed concrete cubes free from impurities or unwanted substances.

The relatively lower compressive strengths of plain RAC, as illustrated in Figure 5, could be explained by the heterogeneity

and porosity of recycled concrete aggregates. These properties have a negative influence on RAC quality due to the following: (i) the increased concrete porosity which could mainly be attributed to the residue of mortar adhering to the original aggregate (ii) the weak aggregate-matrix interfacial bond<sup>22–24</sup> and (iii) the fissures which might be formed in recycled aggregates during processing thereby rendering the recycled aggregate having weaker structure.<sup>25</sup> This explanation has been confirmed by SEM analysis of the recycled aggregate used in the experiments, as shown in Figure 1.

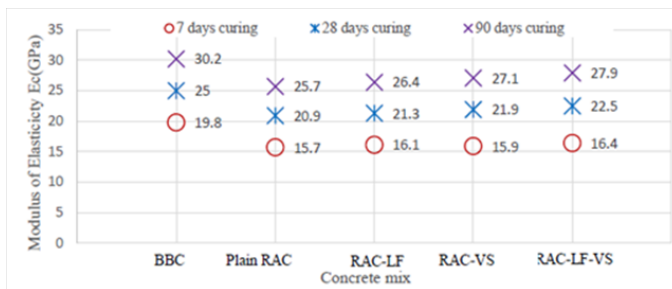


**Figure 5** Compressive strength development of the investigated concrete mixes.

By contrast, the addition of SCMs enhanced the compressive strengths to reach values equal or even bigger than those of RAC. This could be explained by the more compacted interfacial transition zone (ITZ) when using fine additives; thereby the bond between the hydrated blended cement and aggregate becomes stronger. Contrary to expectation, the positive influence of adding volcanic scoria might be clearly observed only after 7 days curing, as shown in Figure 5. This could be attributed to the relatively high fineness of natural pozzolans (i.e. 4200cm<sup>2</sup>/g) which increases their surface area, resulting in higher activity.<sup>26</sup>

### Modulus of elasticity

Figure 6 shows the secant modulus of elasticity at three different curing times (x-axis) for the concretes tested. The development of static modulus of elasticity of RAC without and with SCMs has almost the same trend as in case of compressive strength as shown in Figure 6. The highest modulus of elasticity was found for control mix which was 25.0GPa after 28 days curing and it was higher than that of RAC by about 19%. The decrease in modulus of elasticity of RAC could mainly be due to the significant quantity of cement mortar attached to RA which makes the concrete more porous and less stiff.<sup>27–29</sup> Such a reduction was also reported by other researchers.<sup>29–31</sup>

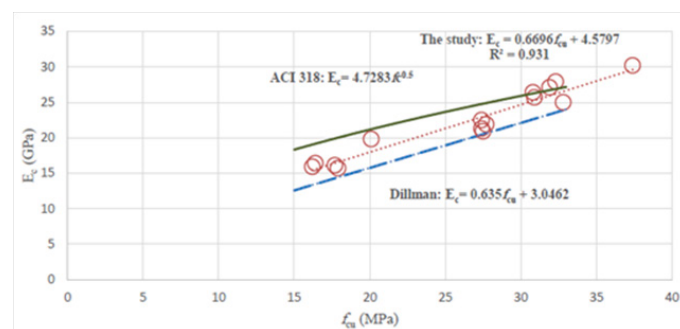


**Figure 6** Modulus of elasticity of the investigated concretes with curing age.

The addition of SCMs increased the modulus of elasticity of concrete. The corresponding increase of the 7 days-cured concrete was 10%, 15% and 20% for the concrete mixes prepared with LF, VS and LF+VS, respectively. This could be attributed to the more compacted concretes when adding fine and pozzolanic additives.<sup>3,4</sup> The relationship between the compressive strength and the modulus of elasticity was established. The equations suggested by ACI 318 and Dillman<sup>32</sup> for the modulus of elasticity in terms of compressive strength are also shown. It is clear that the ACI equation slightly overestimates while the Dillman equation<sup>32</sup> underestimates the modulus of elasticity of concrete prepared with recycled aggregates.

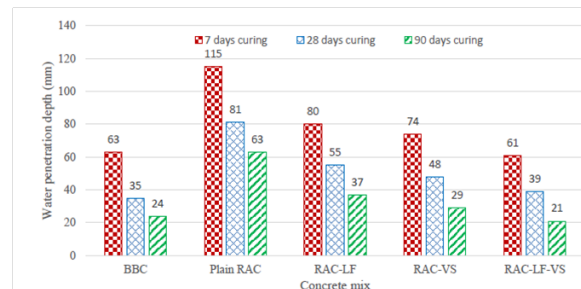
### Water permeability of concrete

Figure 8 shows the water penetration depth test results for BBC and RAC without and with SCMs. As expected, plain RAC was more permeable than BBC and RAC with additives. For instance, 28 days-cured RAC had a water penetration depth 81mm, showing an increase of about 130% compared to the BBC mix. Such an increase, as agreed by Limbachiya et al.<sup>33</sup> and Gholamreza et al. work<sup>34</sup> could be due to the presence of adhered mortar on RCA in the mixture. This adhered mortar which is characterized by its higher porosity and its higher water absorption served as potential conduit for water transport.<sup>35</sup> The higher permeability of RAC indicated a reduction in durability when it is used.



**Figure 7** Relationship between the cubic compressive strength and the modulus of elasticity of the studied concrete mixes.

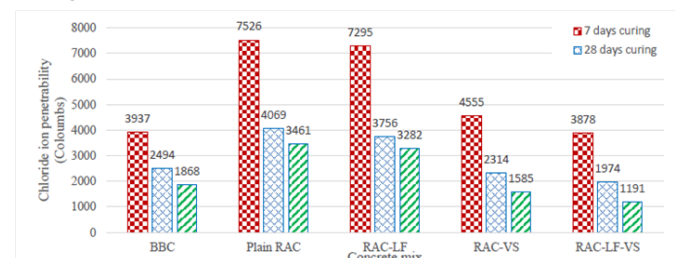
Plain RAC specimens were found to be permeable even after 90 days curing. However, as shown in Fig. 8, Adding SCMs has significantly reduced the penetration depths even after shorter curing times. The reason for the reduced permeability of RAC-VS and RAC-LF-VS is believed to be due to the following: i) the pozzolanic reaction which might occurred between  $\text{SiO}_2$  reactive from volcanic scoria and calcium hydroxide,  $\text{Ca(OH)}_2$  released during cement hydration. This reaction produces additional C-S-H gel which fills up the micro pores in ITZ, thus leading to higher resistance to water penetration; ii) the filling effect of the additives which might block the microspores and fissures especially at ITZs.



**Figure 8** Water penetration depths of the examined concretes with curing age.

### Rapid chloride penetrability test (RCPT)

Figure 9 the total charge passed for plain RAC, as illustrated in Figure 9, was always greater than those for BBC by about 91%, 63%, and 85% after 7, 28 and 90 curing days, respectively. The high level of charge passage ( $>4000$  coulombs) in RAC may be attributed to the porosity of recycled concrete aggregates. Unlike natural aggregate, the (RCA) itself imposes the higher porosity arising from the mortar debris on the surface of the (RCA) particles, which could substantially enhance the ionic mobility.<sup>9</sup> However, the concretes containing both limestone filler and volcanic scoria showed the best performance among all the specimens. The improvement in resistance to chloride penetration could be due to the relatively high compacted structure in these specimens especially in ITZs and their reduced electrical conductivity. This result is in good agreement with the findings in the literature.<sup>7,36,37</sup>

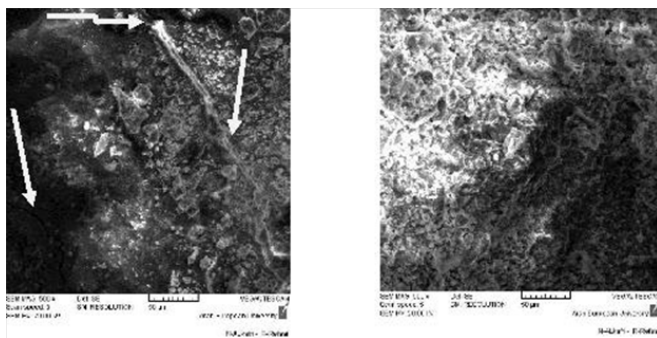


**Figure 9** Chloride ion penetrability of the tested concretes with curing age.

The addition of volcanic scoria alone also significantly decrease the chloride ion penetration. The formation of more hydration products as volcanic scoria hydrated might block the ingress path of chloride ions, thus enhancing the resistance to chloride penetration.<sup>3</sup> Furthermore, the results obtained clearly indicate that the water permeability data cannot effectively be used to predict the concrete resistance to the chloride-ion penetration and vice-versa, especially when limestone filler is used in concrete. Although the limestone filler basically acts as filler, its use in the plain RAC did not significantly decrease the concrete chloride ion permeability, as shown in Figure 9. This may be related to the higher level of  $\text{OH}^-$  ions present in the pore fluid of the concrete made with limestone powder.<sup>38</sup> These ions act as a supporting electrolyte because of its higher ionic conductivity than other ions present in pore fluid ( $\text{K}^+$ ,  $\text{Na}^+$  and  $\text{Ca}^{2+}$ ).<sup>38</sup>

Finally, it is worthwhile to mention that the results obtained were confirmed by SEM analysis as shown in Figure 10. It was clearly noted from Figure 10A, the presence of micro cracks and the lack of compactness in the plain RAC specimen. On the other hand, more compacted microstructures particularly at ITZs were observed in the RAC containing SCMs as clearly seen in Figure 10B. No apparent fissures were detected. Chloride ion penetrability (Coulombs) Figure 9. Chloride ion penetrability of the tested concretes with curing age

this compacted microstructure may be attributed to the following: i) the filler effect of additives. This effect is likely because both limestone filler and ground volcanic scoria were finer than the Portland cement, so they could fill the micro pores in the ITZs around aggregates; ii) despite that limestone filler has no pozzolanic property, its fine particles could contribute to form new hydration products, like carboaluminate phase, which might fill the micro cracks and thus reduce the pore ratio.<sup>39</sup> This carboaluminate phase might be of greater importance particularly in binders containing supplementary cementitious materials of significant contents of aluminates such as volcanic scoria similar to that used in the present investigation;<sup>40</sup> iii) the pozzolanic reaction between the glassy phase in natural pozzolans and the CH released during cement hydration. The continuation of this reaction and the formation of further cementitious products such as C-S-H and C-A-S-H<sup>3</sup> may block the fissures originally present in RCA contributing to make the concrete denser and less permeable to water and chloride ions.



**Figure 10** Scanning Electronic Micrographs of ITZ of plain RAC, and RLC-LF-VS after 7 days curing. a) SEM of plain RAC; b) SEM of RLC-LF-VS.

## Conclusion

- i. RAC has been shown to be weaker and less durable than similar concrete made of natural aggregates. The old cement paste present in recycled concrete aggregate which has higher porosity and might contain microcracks due to the crushing process of old concrete, could be responsible for the worse performance of RAC. However, the lower density of RCA could be an advantage when reduced structural dead load or increased fire resistance is desired.
- ii. The defects of using RAC can be offset by addition of SCMs which significantly improved the properties of RAC. Adding such SCMs, particularly with relatively high fineness, not only enhanced the durability properties of RAC but also maintained or even improved the mechanical strengths despite their high content. However, adding limestone powder alone could not be recommended in chloride-bearing environments.
- iii. The reuse of demolished concrete structures can potentially reduce coarse aggregate costs, resulting in reduced CO<sub>2</sub> emissions associated with aggregate transportation, and reduced construction debris placed in landfills. Further, use of binders containing SCMs can lead to an efficient use of natural resources, saving energy consumption and reduction in gaseous emissions. So, use of recycled concrete aggregates with SCMs could be considered an ecological and economic approach in the post-war reconstruction in the country.
- iv. Although the studied crushed old concrete cubes could be a potential option for making concrete, using recycled concrete

aggregate obtained from demolished homes needs to be further investigated in order to gain the required confidence in its performance. This need could be due to the wide variation in the properties of recycled concrete aggregates.

## Acknowledgements

None.

## Conflict of interest

The author declares no conflict of interest.

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