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Valorization of Recycled Aggregate in Concrete and Mortar

Part B: Using recycled fine aggregate as a replacement for natural aggregates in mortar and as a replacement of cement

Hossam A. Elaqra[1,*]

[1]College of Applied Engineering and Urban Planning, University of Palestine, Gaza Strip, State of Palestine

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Abstract
In this study, the influences of partial replacements of sand by fine recycled aggregate (RA), and replacement of cement by very fine RA, on the mechanical behaviour and the microstructure changes of mortar were investigated. An experimental program was carried out for producing mortar incorporated with large volumes of RA of various particle sizes.
Using the two-step method, five mixtures were made for each part of study (part 1: only aggregate less than 630µm, and part 2: 360µm were replaced by natural aggregate NA), starting by a mix with 100 % of RA, and then 75%, 50%, 25% and 0%. Prism samples were molded in (4*4*16 cm) for mechanical testing (flexure and compression).
The results obtained showed that it is possible to use the fine RA to give mixes with compressive strength and flexure strength close to the control mix. Moreover, the use of super-plasticizer leads to a significant increase for both strengths. In the case of the replacement of cement with the very fine RA and in order to obtain green cement, both compressive and flexure strengths are closer to the control mix, which is consistent with microstructure investigations.

Keywords Recycled aggregate, Fine recycled aggregate, Very fine recycled aggregate, Mechanical behavior, Interfacial transition zone, Super-plasticizer.

تحسين جودة واستخدام الحصمة المعاد تدويرها

الجزء ب: استخدام الحبيبات الصغيرة المعاد تدويرها كبديل عن الحصمة الطبيعية في خلطة المونة وكبديل عن الإسمنت

ملخص:
يهدف هذا البحث لدراسة استبدال الحصمة الطبيعية بالمعاد تدويرها في خلطات المونة وكذلك الاستبدال الجزئي للإسمنت بواسطة الحبيبات الدقيقة (البودرة) من الحصمة المعاد تدويرها، ومن طرف آخر يدرس تأثير هذا الاستبدال على البنية التركيبية للخلطة. أظهرت النتائج أنه وفي كلا الحالتين (المونة والإسمنت) فإن قوة الخلطات الجديدة وبالنسب المعطاة هي ضمن القوة المسموحة لاستخدام المونة. وقد ساعدتنا الملاحظات بالمايكروسكوب الالكتروني المسحي على ربط هذه التغيرات في القوة مع التركيب البنيوي لها.

*Corresponding author e-mail address: helaqra@gmail.com

كلمات مفتاحية: الحصمة المعاد تدويرها، الحبيبات صغيرة الحجم المعاد تدويرها، الحبيبات الاكثر نعومة، التصرف الميكانيكي، المنطقة الانتقالية البينية، مقلل لكمية الماء في الخلطة، الملاحضات المايكروسكوبية.

1. Introduction:

Waste management has become vitally important since the demand for natural resources and the amount of construction and demolition waste have greatly increased, exerting huge pressure on the environment [1, 2]. Recent technology has greatly improved the recycling process for waste concrete [3].

In recent years, coarse recycled concrete aggregates have been widely studied, however only few data has been reported on the use of fine recycled aggregates. Moreover, a lack of long-term properties of RA concrete has to be pointed out [4].

It is considered that using crushed recycled concrete as aggregate for concrete or mortar production is a viable alternative to dumping and would help to conserve a biotic resource. This use has fundamentally been based on the coarse fraction because the fine fraction is likely to degrade the performance of the resulting concrete or mortar [5].

Fine recycled aggregates are seen as the last choice in recycling for concrete production. Many references quote their detrimental influence on the most important characteristics of mixes: compressive and tensile strength; modulus of elasticity; water absorption; shrinkage; carbonation; and chloride penetration [5-7].

Therefore, it is argued that the mechanical performance of mixes made with fine recycled concrete aggregates can be as good as that of conventional mixes, if super-plasticizers are used to reduce the water–cement ratio of the former mixes [5] or another type like flay ash or silica fume with limited amount.

It is known that 50% of recycled aggregate is fine aggregate; however its use is still limited [7, 8].

The reuse of structural concrete elements to produce new concrete aggregates is accepted as an alternative to dumping it and is favourable to the sustainability of natural reserves. Even though the construction sector is familiar with the use of coarse recycled concrete aggregates, the recycled fine concrete are classified as less noble resources.

Several countries have recommendations for the use of recycled coarse aggregate in structural concrete, whereas the use of the fine fraction is limited because it may produce significant changes in some properties of concrete. However, during the last decade the use of recycled fine aggregates (RFA) has achieved a great international interest. It is mainly because of economic implications related to the shortage of natural sands suitable for the production of concrete, besides to allow an integral use of this type of waste [9-11].

Chen et all. [12] showed that, keeping the recycled fine aggregate content and total water/cement ratio constant, with an increase in humidity in RFA from the oven-dried state, air-dried state to the saturated surface-dried state, in the same time it increases the cracking resistibility of recycled fine aggregate concrete (RFAC).

Evangelista and all showed that, it is reasonable to assume that the use of fine recycled concrete aggregates does not jeopardize the mechanical properties of concrete, for replacement ratios up to 30% [13].

Geng et al. [14] showed that the carbonation depth of RA increases with decreased minimum RA particle size and increased RA amount. At >40% RA amount, water significantly affects the carbonation. Fly ash addition favours the carbonation resistance of RA, especially at 20% cement replacement ratio. On the other hand, they show that the self-cementing ability of RA is proved by the microstructural analyses of RA. The poor microstructure of RA and the interfacial zone between the new cement paste and RA result in easier CO2 ingression for RA. Anastasiou et al. [15] showed that the use of fine construction and demolition waste aggregate increases the porosity in concrete and also reduces strength and durability.

Khatib [16] showed that the fine aggregate in concrete when replaced with 0%, 25%, 50% and 100% RA. Generally, there is strength reduction of 15–30% for mixes containing RA. However, mixes incorporating up to 50% RA exhibits similar long-term strength to that of the control. Even at 100% replacement of fine aggregate with RA, the reduction in strength is only 10%.

Jia et al. [17] showed that for mixes when prepared with 50% recycled fine aggregate (RFA) and 50% natural fine aggregates, that the moisture states of the RFA were controlled at oven-dried, air-dried and saturated surface-dried. A shrinkage–restrained ring device with clapboard was used to study the cracking resistibility of RFAC.

Pereiraa et al. [10] showed that the mixes with incorporation of recycled aggregates, were found to have poorer relative performance. The mechanical performance of concrete with recycled aggregates and super-plasticizers (like polycarboxylate) was generally superior to that of the reference concrete with no admixtures and of conventional mixes with lower performance super-plasticizer.

Piña et al. [18] used three types of cement, CEM II, CEM III/A and CEM V/A, the last two being sulphate-resistant cements containing blast furnace slag. Compressive, tensile and flexural strength properties decreased as the proportion of RA increased, compared with CEM II cements, the strength and permeability of the concretes made with sulphate-resistant cement decreased less as the amounts of mixed recycled aggregates (MRA) increased.

They also showed also that incorporation of gypsum contaminated fine recycled aggregates with SO_3 contents up to 2.9% by weight does not compromise the durability in mortars, regardless of the cement types, the consistency and the contaminant present.

Regarding the previous studies, using the maximum amount of recycled concrete and mortar is one of the goals of this study, without using any other supplementary elements which increase the cost of the final product, like super-plasticizers or silica fume. This way, the final product can be used in the under developed countries. On the other hand, the final product must have good mechanical properties especially in compression.

The objective of this paper is to present the second part of the results concerning the use of recycling fine aggregate as a replacement for the natural one. Compressive, flexure tests and microstructure observations were used to determine the best mixes and the amount of RA used.

2. Methodology:

The mechanical properties of recycled aggregate concrete (RAC) may be inferior to those of conventional concrete that contain natural aggregate, but they are nonetheless sufficient for some practical applications in terms of mix design, design specifications, etc.. The use of recycled aggregate serves to encourage the recycling of concrete waste in the construction industry as well as to preserve natural resources and the environment. To minimize the use of any other supplementary elements which increase the cost of the final product, like adding to the mix super- plasticizers or silica fume. Moreover, the final product must have good mechanical properties especially in compression. POON et al. [19-22], presented the two-stage method as a better solution for this problem.

3. Experimental procedures:

The experimental program was divided into two phases. In the first phase, the mortar mixes were cast in order to assess the mechanical properties (in compression and flexure test) in order to obtain the best mix. In the second phase mortar samples were prepared for scanning electron microscope observations in order to correlate the mechanical behaviour with the microstructure changes.

3.1. Materials and mix proportion

Mortar samples were prepared, in order to study the effect of the replacement of fine RA (part 1: only aggregate less than 630µm, and part 2: 360µm were replaced by NA) in compressive and flexure strength. Replacing the cement by very fine RA (less than 40µm) was also investigate. French made commercial cement called Vicat, cement CMI 52.5 N was used in mixing. The same cement was used in all mixes. Table 1 shows the composition of this French made.

Table 1 *Chemical composition of cement used in study*	
Constitution	% by mass
$3CaOSiO_2$ (C_3S)	66
$2CaOSiO_2$ (C_2S)	14
$3CaOAl_2O_3$ (C_3A)	12
$4CaO\ Al_2O_3Fe_2O_3$ (C_4AF)	8

Using the two-step method, five mixtures were made for each part of study (only aggregate less than 630µm and 360µm were replaced by NA), starting by a mix with 100 % of RA, and then 75%, 50%, 25% and 0%. Prism samples were molded in (4*4*16 cm) to be tested then for mechanical properties (flexure and compression).

Tables 2, 3, and 5 show the composition of the mix, water to cement ratio (w/c) decreases with the increase in the amount of NA. Table 4 shows the mix's composition (the same like table 3), but with the addition of super-plasticizers (2% by weight of cement) to evaluate the effect of super-plasticizers on the mechanical behavior of the mixes.

Molds were greased before used with oil, to facilitate the demoulding. Mixes were compacted by a vibrating table. Finally, molds were covered with a plastic film to prevent fast water evaporation. Then molds were stored in 100 % relative humidity for 48h after casting, the samples were demoulded and kept in water for 28 days in preparation for the testing, to assure a rate of 100 % relative humidity and facilitate the process of the hydration.

Table 2 *Mixes composition of part 1 for 630µm replacement*

Mix (%)	Water (gm)	Cement (gm)	Recycled (gm)	Natural (gm)	Aggregate (gm)	w/c
100	300	333	1000	0	1000	0.90
75	275	333	831	169	1000	0.83
50	273	333	663	337	1000	0.82
25	254	333	495	506	1000	0.76
0	244	333	326	674	1000	0.72

Table 3 *Mixes composition for part 2 for 360µm replacement*

Mix (%)	Water (gm)	Cement (gm)	Recycled (gm)	Natural (gm)	Aggregate (gm)	w/c
100	300	333	1000	0	1000	0.90
75	275	333	887	113	1000	0.86
50	273	333	755	225	1000	0.82
25	254	333	662	338	1000	0.78
0	244	333	550	450	1000	0.72

Table 4 *Mixes composition 360µm avec 3% de Super-Plasticizer*

Mix (%)	Water (gm)	Cement (gm)	Recycled (gm)	Natural (gm)	Aggregate (gm)	w/c
100	233	333	1000	0	1000	0.70
75	220	333	887	113	1000	0.66
50	213	333	755	225	1000	0.64
25	203	333	662	338	1000	0.61
0	187	333	550	450	1000	0.56

Table 5 *Mixes composition 40µm*

Mix (%)	Water (gm)	Cement (gm)	Recycled (gm)	Aggregate (gm)	w/(c+RA)
0	187	333	1000	1000	0.56
5	187	316	17	1000	0.56
10	190	299	34	1000	0.57
15	190	282	51	1000	0.57
20	193	265	68	1000	0.58

3.2. Microstructure observations:

This part of the study was carried out in French (LGM in ENTPE) and Switzerland (LMC in EPFL) universities. Mortar slices were cut, then hydration was stopped using Isopropyl alcohol, 99.9 %, samples were then stored in desiccators for two weeks using a vacuum pump (less than 10 mbar).

Samples were taken from the desiccators and were polished for SEM observations. Samples were impregnated under vacuum in epoxy resin, once resin becomes hard enough it was then polished. In the first step, samples were polished to remove the excess of resin, but a very thin slit of resin was left in the sample to be polished by diamond powder with decreasing gradually from 9µm to 3µm and at the end 1µm. Samples were covered by a 20nm carbon coating to create a conduction layer which does not interfere with X-ray microanalysis. The polished samples were studied in backscattered electron (BSE) mod using FEI quanta 200 SEM, 15 kV were used in order to maximize contrast.

4. Results and discussion

4.1. Mechanical properties:

This part discusses the effect of the replacement of fine RA size 0-630µm by a natural one. Figure 1 shows the results of compressive strength (σ in MPa) for mixes prepared by the replacement of RA by NA less than 630µm. More than three samples were tested and the average was reported on the graph.

The compressive strength (σ in MPa) of mixes decreases smoothly with the increasing of the amount of RA in mixes. This decrease is related to the increasing of water to cement ratio (w/c).The compressive strength of the mix prepared with 100% of fine RA showed the lower value, this mix has the higher value of w/c, however it stills near 30MPa for all mixes.

From previous studies (part A), it was showed that the increase of water to cement ratio w/c makes the interfacial transition zone between RA and the new cement paste weaker and produce sources of cracks in mix until failure. This is the case of the mixes of 100% of RA.

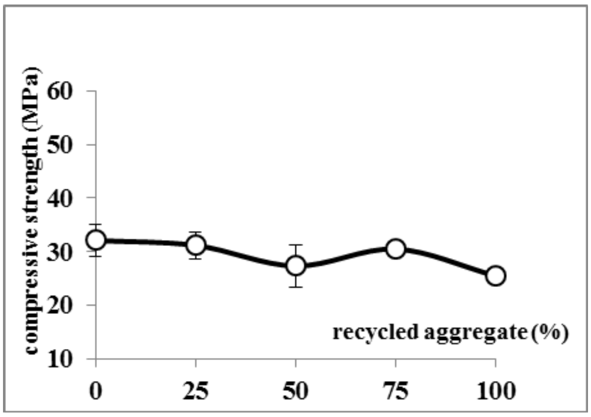


Figure 1 *Compressive strength of samples prepared by replacing aggregate less than 630µm*

Figure 2 shows the result of flexure test in prismatic samples. The results show that using up to75% of RA will not change the strength, where the flexion strength (σ in MPa) still has the value around 6.5MPa. On the other hand, compression tests show the same results (until 75% of replacement the strength remains unchanged, see figure 1), where the compressive strength still has a value more than 30MPa.

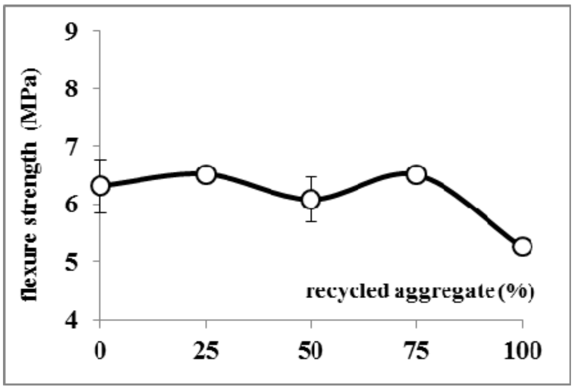


Figure 2 *Flexure strength of samples prepared by replacing aggregate less than 630µm*

In the analyses on the effect of the fine RA on the mechanical behavior of mortar, it is necessary to test the replacement of RA smaller than 600µm.

The results of the compressive strength as a function of the replacement of fine RA less than 360µm (mixes are given in table 2). The results (Figure 3) show that there is no significant change in the compressive strength of mixes; it has a value of more than 30MPa. This result shows that RA size between 600µm and 360µm has more negative effect on strength of mixes than RA smaller than 360µm.

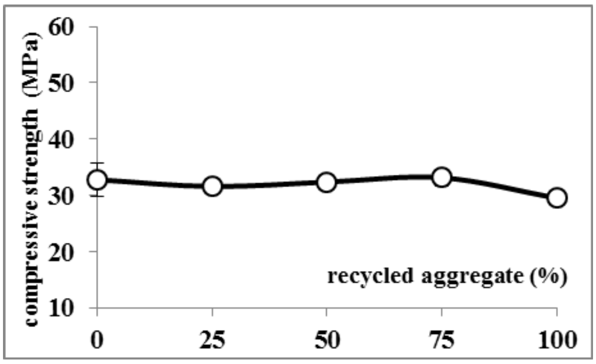


Figure 3 *Compressive strength of samples prepared by replacing aggregate less than 360µm*

The results of mixes on flexure test is presented in figure 4, it shows a smooth change of behavior of flexure strength until 50% of the replacement, where the strength has a value near 6MPa. Then the strength decrease as the replacement increase, for 100% of replacement the strength has a value of 5MPa.

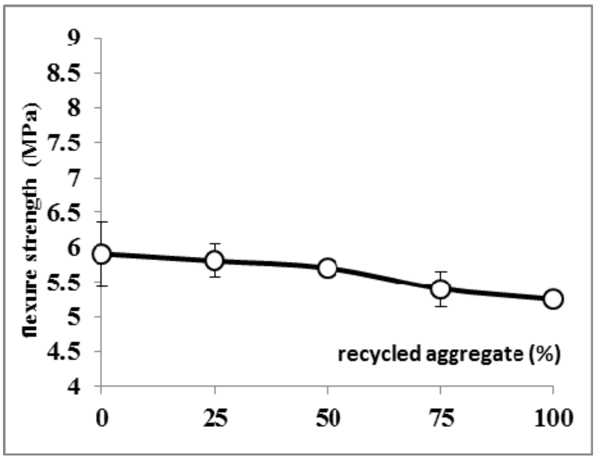


Figure 4 *Flexure strength of samples prepared by replacing aggregate less than 360µm*

When adding super-plasticizer to mixes the mechanical response of mixes changes and gives a higher value on compressive and flexure strength.

Figure 5 shows the change of compressive strength as a function of the replacement of fine RA. The compressive strength of mixes was increased with 27% in comparison with mixes prepared without super-plasticizer. Only the mix with 100% of RA gives the lowest compressive strength compared to the other mixes, it is more than the value of 30MPa.

This results show the importance of using of a smaller amount of water in mixes, which is adequate with the role of the super-plasticizer to reduce the amount of water, thus increasing the strength.

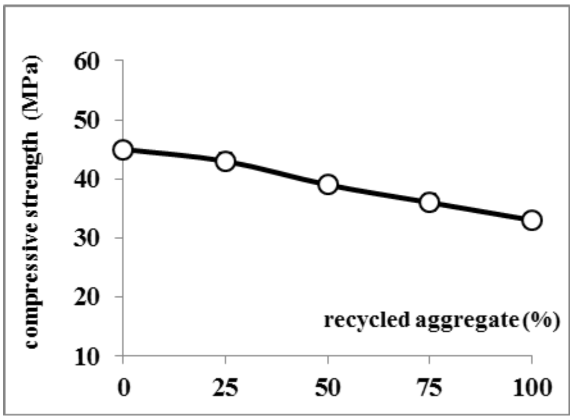


Figure 5 *Compressive strength of samples prepared by replacing aggregate less than 360µmavec Super-plasticizer*

Also the flexure strength of mixes prepared with super-plasticizer is increased. Figure 6 shows the flexure strength as a function of the replacement of fine RA. The results show a decrease of the strength of mixes with a high amount of RA (75% and 100%). All values of flexure strength are increased by 10%.

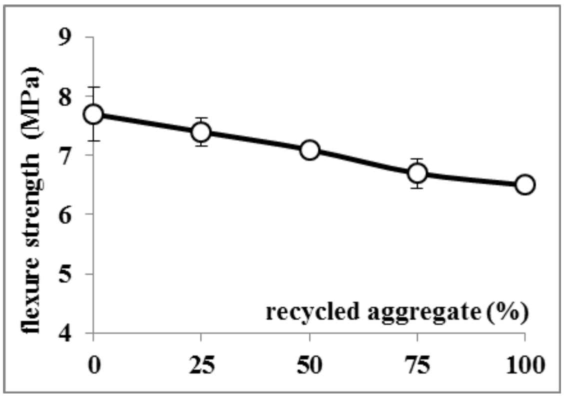


Figure 6 *Flexure strength of samples prepared by replacing aggregate less than 360µm avec Super-plasticizer*

This part of the study discusses the effect of using the very fine RA as a replacement of cement in mortar mixes with 100% of NA (see table 5).

The result of compressive strength as a function of replacement of very fine RA is presented in figure 7. The curve shows two behavior, the first one between 0 and 5% where the compressive strength stays stable around 50MPa. The second shows a decrease with the increasing of the replacement, up to 20% of replacement where the compressive strength is around 40MPa.

The results show that the use of 20% of replacement still in the range of use of mortar, which is higher than the French standard (35MPa).

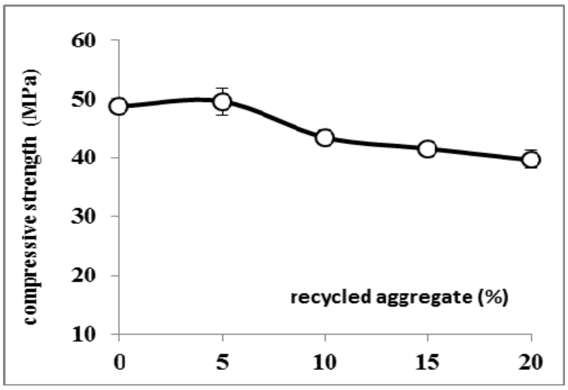


Figure 7 *Compressive strength of samples prepared by replacing cement by very fine RA*

Figure 8 shows the result of flexure strength of mixes, the graph shows that up to 10% of replacement the strength value does not change significantly (around 8MPa). Then it decreases for 15% and 20%of the replacement.

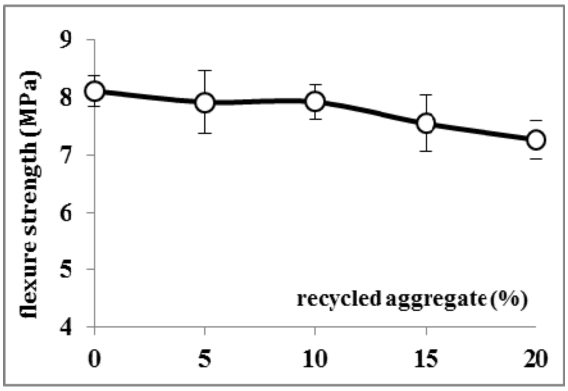


Figure 8 *Flexure strength of samples prepared by replacing cement by very fine RA*

4.2. X-Ray Diffraction:

The X-ray diffraction spectrum of very fine RA less than 40µm is shown in figure 9 the presence of the C_2S C_3S. It is known that the C_2S particle takes a long time before total hydration and this may be the responsible for the increase of the strength of cementitous composite after a long time.

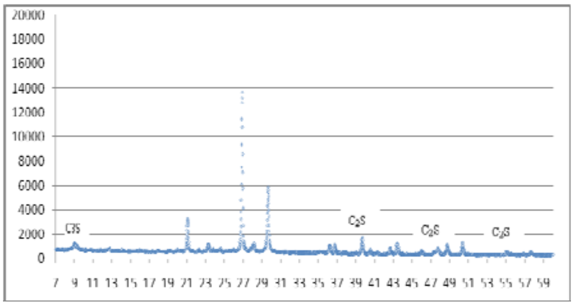


Figure 9 *X-ray diffraction of very fine RA*

4.3. Microscopic observations:

To understand the mechanical behavior of mixtures, microstructure observations by scanning electronic microscope (SEM) were carried out on the different RA and mixes.

Figure 10 shows the RA image by SEM, different shapes (angular and round aggregate) and sizes were observed (figures 10a and b). Figures 10c and d show the microstructure of the interfacial zone of the RA (hydrate products and the presence of very high porosity).

The chemical composition of very fine RA was determined by SEM X-ray diffraction; figure 11 shows this composition by the mapping method of the aggregates. The surface of aggregate presents a hydrate product of C-S-H and other aluminates hydrate product. The porosity present in these hydrate products can be filled by the new cement past. Thus it can produce a stronger cohesive bond with a new cement pastes which contribute to the strength of the mixes.

After mixing with new cement paste, this interfacial zone was filled with the very fine RA (the replacement of cement, see figure 12a and b).

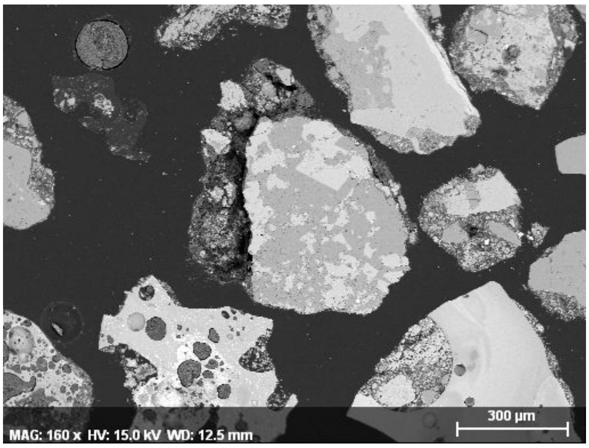
Figure 12a shows the role played by the very fine RA on the new structure, three mechanisms are suggested:

1- Filling the space in the porous region between NA, which come from a smaller size of very fine RA than the porosity size.

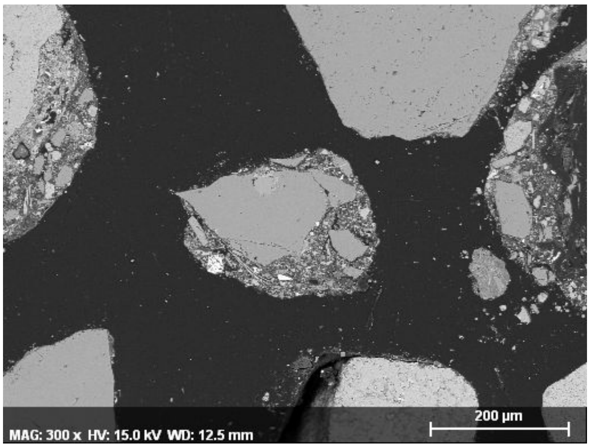
2- The second mechanism is the participation of very fine RA in the hydration process; the C3S was taking place in the hydration process and would lead to higher compressive strength in mixes.

3- The third possible mechanism may be caused by the facility of hydrate product present on the surface of RA to make a stronger bond with a new cement paste.

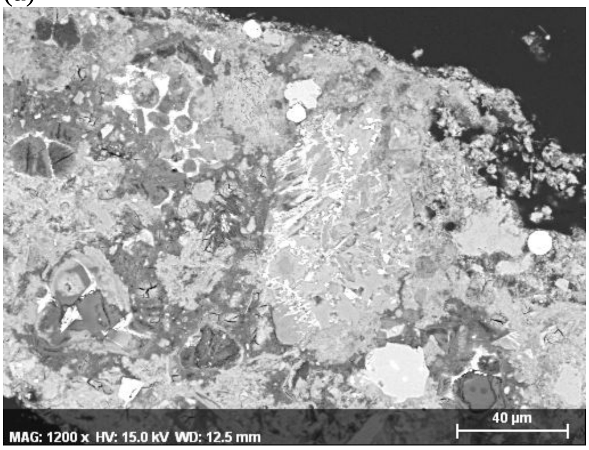
These possible mechanisms contribute to the increase of the strength of the mixes prepared with the replacement of very fine RA of cement.



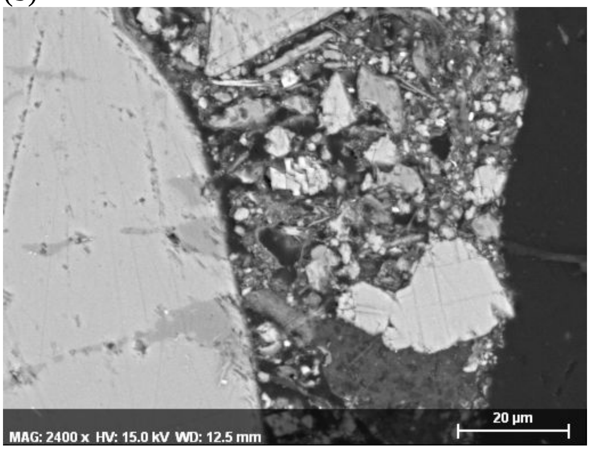
(a)



(b)

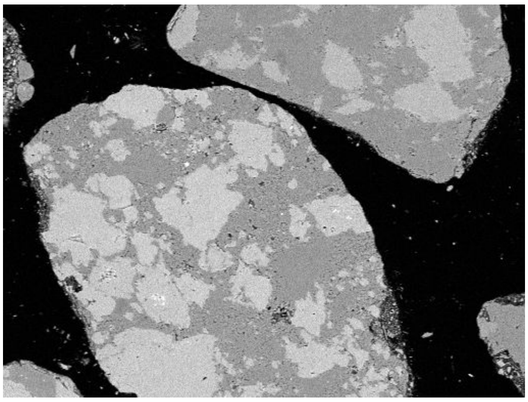


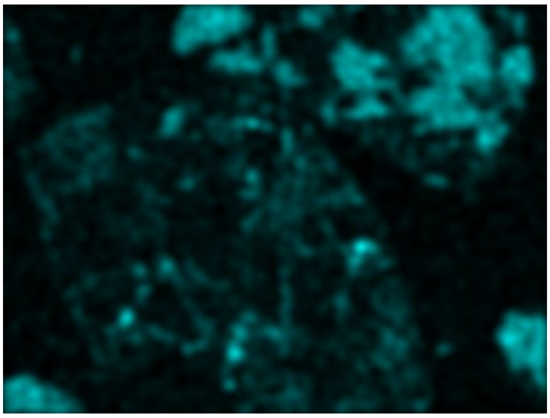
(c)

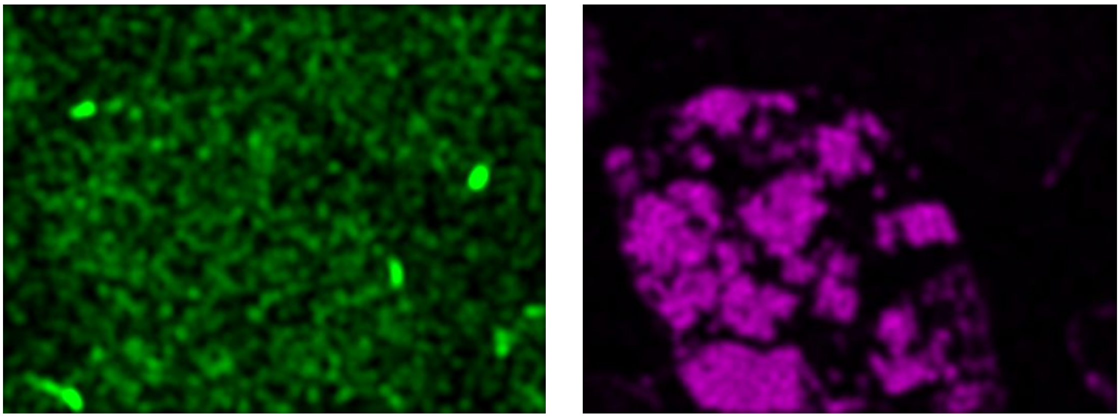


(d)

Figure 10 *Microstructure observations on RA*

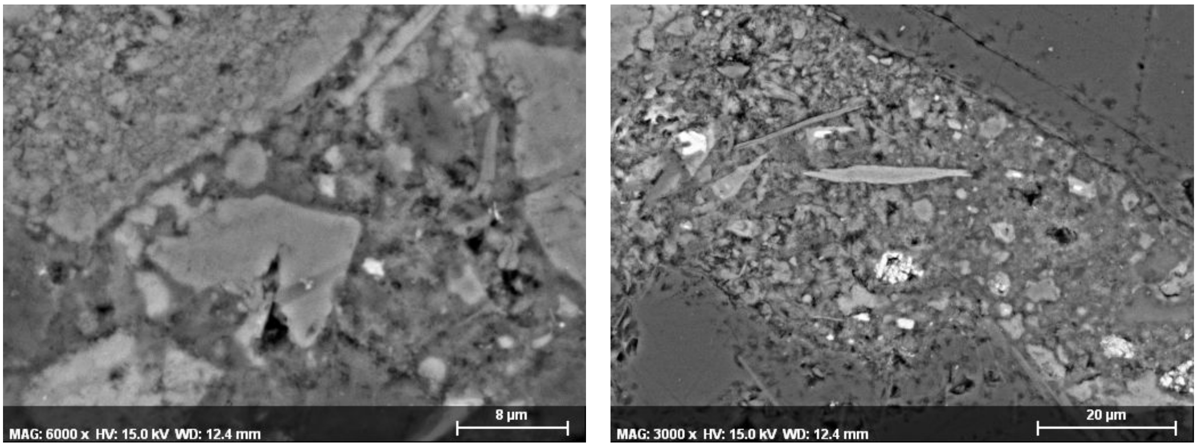

(a)


(b)Al



(c) S (d) Ca

Figure 11 *Mapping on very fine RA done by SEM*



(a) (b)

Figure 12 *Microstructure observation on mixes prepared with RA*

5. Conclusions:

The results of the replacement of RA size less than 600µm show that the compressive strength for all mixes are close to the 30MPa which is in the range of strength for the use of mortar, only mixes with a replacement of 100% have a signification decease in the strength (near 25MPa). The same results are obtained for flexure strength, where all mixes have a strength value near 6.5MPa and only mixes with a replacement of 100% have low strength (5.5MPa).

The mixes with a replacement of fine RA size (less than 360µm) showed a compressive strength near 30MPa and in flexure strength shows stable values for the replacement of up to 50% then it decreases with the increase of RA where the strength is around 5MPa. These results show that, the incorporation of a high amount of RA leads to the weakness of the structure and the facilitation of damage especially on the interface with the new cement paste. However, the replacement of both size less than 600µm and 360µm can be used in mortar. It is suggested that the RA size between 600µm and 360µm should be eliminated, because these aggregate sizes decrease the compressive strength of mixes.

On the other hand, the use of super-plasticizerson in the mixes by replacement of RA size less than 360µm gives higher strength for both compressive (more than

27%) and flexure (more than 10%). The lower amount of water to cement ratio and the densification of the transition interfacial zone between old and new cement paste are the factors responsible for the increase in the strength.

The replacement of cement with very small size of RA (less than 40μm) on mortar gives higher compressive (higher than 40MPa) and flexure strength (higher than 6MPa) values higher than standard mix. The microstructure observation was vnalrgiery useful to understand this increase, which allows us to observe the presence of hydrate product on the surface of aggregate (C-S-H) and aluminates hydrate products. Three possible mechanisms can explain the increase of strength in the case of the incorporation of very fine RA as a replacement of cement:

1- Its small size help the particles to fill the interfacial transition zone between natural aggregates and the cement paste,

2- The involvement of C_2S and C_3S present on the very fine RA lead to increasing the bond strength with the new cement paste and increase the hydrate product on the mixes,

3- Hydrate products on the surface of aggregate lead to higher bond between aggregate and new cement paste.

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