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Research Article

# Recycled aggregate concrete: Effect of homogeneity of origin concrete

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***Abstract***

*In the context of sustainable development, recycling and usage of demolished concrete consists an alternative for natural resources, as well for the construction debris landfill. This waste concrete could be used as aggregate and thus a concrete made with such recycled aggregates is a material friendly to the environment. This paper examines the effect of homogeneity of origin concrete on the splitting and compressive strength in recycled aggregate concretes up to the age of six months. The same concretes are also testing concerning their resistance to chlorides, when the ions penetrate either through their bottom side or after 28 days wetting-drying cycles. Concretes made with 100% recycled aggregates as well others made with only the coarse aggregate recycled. The recycled aggregates produced from concretes either of uniform quality and age or others taken from tested conventional cubic specimen of different ages and strengths. The way in which the tested properties are affected varies, related to the homogeneity of the original concrete.*

***Keywords:*** *Recycled Aggregate Concrete, Chlorides penetration, Wetting-drying cycles, Compressive strength.*

## 1. Introduction

Our relationship with the environment, its protection, the preservation of the rapidly declining natural resources and the need to acknowledge our responsibilities to the future generations consist the meaning and the essence of sustainable development.

In this context, an alternative option for the natural resources as well for landfills about the disposal of the construction debris is the usage of concrete that comes from construction and demolition work [B. Topcu *et al,* 1995, R. Gilpin *et al*, 2004, N. Oikonomou, 2005, M. Khalaf *et al,* 2004). This waste concrete can be used as aggregate and therefore the concrete with such recycled aggregate is a material friendly to the environment. Nowadays, the masses of concrete that must be withdrawn are continuously growing, causing severe environmental problems (S. Chandra, 2005). Many constructions are demolished, as a result of exceeding their limits of use, of new necessities and requirements, of natural disasters, etc. Moreover the concrete industries produce debris (precast elements, specimen after testing, returns because of delays, non – acceptance or miscalculation of the quantity).

Recycled aggregates (RA) that come from demolition usually aren't clean as they contain salts, bricks and tiles, dust, timber, plastics etc [S. Nagataki *et al*, 2004) Furthermore, if they are received from a recycling centre, they have been collected from several buildings and as a result, they exhibit lack of homogeneity and unstable, with a lot of differentiations, properties. This makes their use for the production of a new concrete hard (C. Hansen *et al*, 1983). On the other hand, RA that come from concrete (RCA) industries are relative clean, with only the cement paste adhered to them and since they originate from the same kind of concrete they have less differentiated and more stable properties.

Recycled aggregate concretes (RAC) have been used mainly for sub-bas constructions (pavement, road construction etc), and more rarely for other projects (B. Topcu *et al*, 1995, J. Collins, 1996, M. Tavakoli *et al*, 1996). In the past, sufficient experimental research was performed for their mix design, physical and mechanical properties (C. Hansen, 1992, ACI Committee 555, 2002, J. Xiao *et al,* 2005), but their durability has not been studied at that point. Water absorption and permeability, carbonation, dry shrinkage as well as freezing and thawing resistance (C. Lima *et al,* 2013, H. Dilbas *et al* 2014, R.V Silva *et al*, 2014) have been studied mostly. It has been established that the material properties depend on the strength of original concrete, W/C ratio, RCA moisture condition and the replacement ratio (A. Ajdukiewicz *et al*, 2002, A. Katz, 2003, A. Rao *et al*, 2007).

Moreover, due to the wide variation in the properties of the available resources, properties using local materials need to be investigated. This work examines concretes made with recycled concrete

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aggregate, originated from a ready mixed concrete industry and the effect of both homogeneity and strength of origin-initial-concrete are studied.

## 2. Experimental procedure

Two series of mixtures were prepared with 330 kg/m³ of cement CEM II42.5N (blended cement), complying to EN197 and w = water/cement ratio = 0,6.

Mixtures of the first series were made with aggregates that had been originated from concrete standard cubic specimen of 28-days characteristic cubic strength $f_{ck}$ =15 MPa (C12/15), $f_{ck}$ =20 MPa (C16/20) and $f_{ck}$=25 MPa (C20/25), where $f_{ck}$= $f_{0,05}$. Specimen had been crushed, during approximately one year, for controlling the production quality of a ready mixed concrete industry. This means that recycled aggregate (RCA) was of different ages and different standard compressive strength, such as that which could be taken from a recycling centre (inhomogeneous origin).

**Figure 1** Concrete specimen (left) and concrete blocks (right) used for the production of aggregates inhomogeneous and homogeneous origin, respectively.

For the second series, big block of C12/15, C16/20 and C20/25 concrete, about six months old, were crushed and used as RCA (Fig 1). This means that RCA were of the same age and as they originated from the same pan mixer they have the same compressive strength (homogeneous origin). For both series, six mixtures of recycled aggregate concrete (RAC) were prepared as well as one mixture with virgin aggregate, as reference normal concrete. Three of the six mixtures of each series, one for every compressive strength class of original concrete, were made with all their aggregates recycled (100% RAC) whereas the three remaining were made with virgin siliceous sand και recycled coarse aggregates (50% RAC).

Physical properties of all aggregates are given in Table 1, and mix proportions are shown in Table2. The low apparent density of RCA is due to the lower density of the old cement paste that is still adhered to them. It is noticed that RCA, produced from tested specimen, had surface moisture, instead of the usual water absorption because the day they were crushed and carried to the laboratory it was raining heavily. Homogeneous RCA, as their water absorption was high, before mixing, were immersed in water and left in the pan mixer for about 20 min, in order to get saturated.

**Table 1** Physical properties of aggregate

| Type of aggregate | Grading | | | | | |
|---|---|---|---|---|---|---|
| | 0-4 | 4-16 | 8-32 | 0-4 | 4-16 | 8-32 |
| | (mm) | | | | | |
| | Homogeneous origin | | | | | |
| | Apparent density (kg/m³) | | | Water absorption (%) | | |
| C12/15 | 1,78 | 1,78 | 1,79 | 5,38 | 5,38 | 5,38 |
| C16/20 | 1,78 | 1,78 | 1,78 | 6,38 | 6,38 | 6,38 |
| C20/25 | 1,78 | 1,78 | 1,78 | 7,38 | 7,38 | 7,38 |
| Normal | 2,64 | 2,65 | 2,65 | 2,55 | 1,90 | 1,70 |
| Type of aggregate | Inhomogeneous origin | | | | | |
| | Apparent density (kg/m³) | | | Surface moisture (%) | | |
| C12/15 | 2,20 | 2,38 | 2,44 | 1,06 | 1,03 | 1,01 |
| C16/20 | 2,20 | 2,43 | 2,44 | 1,06 | 1,02 | 1,02 |
| C20/25 | 2,20 | 2,42 | 2,47 | 1,07 | 1,03 | 1,02 |
| Normal | 2,63 | 2,64 | 2,65 | 1,03 | 1,01 | 1,00 |

**Table 2** Proportions of mixtures

| RAC (%) | $f_{ck}$, of RAC's origin concrete | C | W | Normal aggregates (% w/w) | | | Recycled aggregates (% w/w) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | (kg /m3) | | 0-4 | 4-16 | 8-32 | 0-4 | 4-16 | 8-32 |
| Homogeneous origin | | | | | | | | | |
| 100 | 15 | 330 | 198 | | | | 54 | 8 | 38 |
| | 20 | | | | | | 54 | 8 | 38 |
| | 25 | | | | | | 54 | 8 | 38 |
| 50 | 15 | | | 54 | | | | 8 | 38 |
| | 20 | | | 54 | | | | 8 | 38 |
| | 25 | | | 54 | | | | 8 | 38 |
| 0 | Normal | | | 54 | 8 | 38 | | | |
| Inhomogeneous origin | | | | | | | | | |
| 100 | 15 | 330 | 198 | | | | 50 | 9 | 41 |
| | 20 | | | | | | 50 | 9 | 41 |
| | 25 | | | | | | 50 | 9 | 41 |
| 50 | 15 | | | 50 | | | | 9 | 41 |
| | 20 | | | 50 | | | | 9 | 41 |
| | 25 | | | 50 | | | | 9 | 41 |
| 0 | Normal | | | 50 | 9 | 41 | | | |

In order to estimate the 28-days characteristic strength, 6 cubic specimen (15 cm) of each mixture were made, whereas for the development of compressive and splitting strength, cubic (10 cm) και cylinder (15×30 cm) specimen were prepared respectively. All specimen were stored in an air-conditioned room at 20±2 °C and >95% relative humidity, up to 28 days. Compressive strength at 7, 28, 90 and 180 days, as well as splitting strength at 28 and 180 days were estimated.

In order to examine $Cl^-$ resistance, cubic specimens (10 cm) were used. After 28 days of curing, specimens were separated into two groups.

The upper side of specimen of first group was covered with a resin layer and specimens were immersed in an aqueous solution of NaCl (3M). From then on and every 28 days they were put in and out of the solution, by turns (wetting-drying cycles). The adjoining sides of 2nd group specimen were covered with resins up to the height of 3 cm from the bottom, and specimens were put in a solution of the same concentration in NaCl (3M), so that chlorides to penetrate through the bottom side only. At the age of 6 months, all specimen were taken out of solutions and perforated at 2, 4, 6 και 8 cm from the bottom surface. For the determination of total and free $Cl^-$ in ppm, via turbidity method and titration with $AgNO_3$ solution respectively, samples were received from the central axis.

## 3. Experimental results and discussion

### *3.1 Splitting strength*

In Table 3 results of splitting strength are given, as an average of 3 measurements. It can be seen that mixtures with inhomogeneous origin RCA have higher splitting strength (up to 60%), even than that of normal concrete. This is probably caused by the fact that RCA of homogeneous origin had higher water absorption. Thus, they were led to keep more water during mixing and this possibly worked loose the bond between cement paste and aggregate in hardened concrete. As it is kwon transition interfacial zone affects more the splitting strength (S. Poon *et al*, 2004).

**Table 3** Splitting tensile strength of mixtures (MPa)

| days | Recycled aggregates (% w/w) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 100% | | | 50% | | | 0% |
| | $f_{ck,cube}$ of origin concrete | | | | | | - |
| | 15 | 20 | 25 | 15 | 20 | 25 | |
| Homogeneous origin | | | | | | | |
| 28 | 1,8 | 2,1 | 2,1 | 1,4 | 2,1 | 2,0 | 2,8 |
| 180 | 2,1 | 2,5 | 2,7 | 1,8 | 3,3 | 2,6 | 3,1 |
| Inhomogeneous origin | | | | | | | |
| 28 | 2,1 | 2,3 | 2,4 | 2,1 | 2,6 | 3,2 | 1,6 |
| 180 | 2,4 | 2,7 | 2,5 | 2,5 | 3,3 | 3,3 | 2,4 |

It is also seen that the trend is the higher the characteristic strength of origin concrete is, the higher the RAC splitting strength results, irrespective of the replacement proportion of recycled aggregates or the homogeneity of their origin.

With regard to the proportion of RCA, an increase of replacement percentage increases the splitting strength in concretes with homogeneous origin RCA, whereas it is on the decrease when RCA has inhomogeneous origin. In the first case, the lack of bond strength between cement paste and aggregate is counterbalanced by the increase of the amount of old cement (6 months old and thus probably anhydrated), which is adhered to the fine recycled aggregate. In this way, the total amount of cement in the mixture is increased. In the second case, where the transition zone was stronger, the increase of the recycled material appears to weaken it. This increase or reduction of splitting strength appears to be approximately similar at all ages.

### *3.2 Characteristic strength*

Characteristic cubic strength ($f_{ck}$=$f_{0.05}$) of all RAC (Table 4) is higher than the $f_{ck}$ of concretes from which they originate, irrespective of the homogeneity.

$f_{ck}$ of concretes, with homogeneous origin RCA, does not appear to be affected by original concrete's strength, whereas it seems to be affected by the rate of recycling. All 100% RAC had the same $f_{ck}$ value that is slightly lower than that of the normal concrete. All 50% RAC had the same $f_{ck}$ that is equal to that of normal concrete. Namely, it appears that $f_{ck}$ is more influenced by the quality (and probably also by the quantity) of new cement (II 42.5N), which is stronger compared to that of the old -origin- concrete (II 32.5N for low strength old concrete C12/15 and C16/20 and combination of II32.5N and II42.5N for old C20/25).

$f_{ck}$ of most concretes with inhomogeneous RCA is the same with that of normal concrete. However there are deviations, with measurements much lower or much higher than these of normal concrete. The cause of these deviations is not clear and the characteristic strength probably is affected by the old, adhering to aggregate, anhydrated cement percentage.

**Table 4** Characteristic strength of mixtures

| Percentage of recycled aggregate (w/w) | | | | | | |
|---|---|---|---|---|---|---|
| 100% | | | 50% | | | 0% |
| $f_{ck,cube}$ of origin concrete ($f_{0,05}$) | | | | | | - |
| 15 | 20 | 25 | 15 | 20 | 25 | |
| $f_{ck,cube}$ of RCA with homogeneous origin RCA | | | | | | |
| 25 | 25 | 25 | 30 | 30 | 30 | 30 |
| $f_{ck,cube}$ of RCA with inhomogeneous origin RCA | | | | | | |
| 30 | 25 | 30 | 20 | 37 | 30 | 30 |

### *3.3 Compressive strength*

In Table 5, compressive strength of mixtures is given as an average of 3 (10X10 cm cubs) measurements.

Compressive strength in most mixtures with homogeneous RCA, after 28 days, is higher (up to 52%) than that in mixtures with inhomogeneous ones, mainly when RCA percentage is 50%. However, at early ages (up to 28 days), inhomogeneous origin mixtures are stronger than homogeneous ones. Homogeneous RCA are 6 months old and therefore, they have higher levels of old non-hydrated cement. The additional hydration of that anhydrated cement probably increases the strength at later ages. On the contrary, inhomogeneous RCA are of different ages (young as well as up to one year old), thus, the old cement that is adhered to them is more hydrated. Therefore, inhomogeneous RAC have higher strength at an early stage, but at later ages, the cementing potential is diminished or seems to depend on the amount of anhydrated adhering old cement. Decrease of RCA, from 100% to 50%, raises compressive strength (up to 36%) in most mixtures, except for those of inhomogeneous and high strength origin, where the decrease of RCA percentage results to reduction of strength down to 19%.

**Table 5** Compressive strength of mixtures (MPa)

| days | Recycled aggregates (% w/w) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 100% | | | 50% | | | 0% |
| | $f_{ck,cube}$ of origin concrete | | | | | | - |
| | 15 | 20 | 25 | 15 | 20 | 25 | |
| Homogeneous origin | | | | | | | |
| 7 | 18,7 | 23,1 | 19,7 | 22,0 | 21,0 | 25,4 | 20,4 |
| 28 | 31,8 | 29,3 | 21,8 | 26,2 | 26,3 | 29,6 | 23,1 |
| | 34,8 | 34 | 27,4 | 38,7 | 38,8 | 34,4 | 34,6 |
| 180 | 35,9 | 36,6 | 30 | 42,1 | 42,7 | 37,4 | 34,8 |
| Inhomogeneous origin | | | | | | | |
| 7 | 25,7 | 22,4 | 20,2 | 26,4 | 32,8 | 16,7 | 22,9 |
| 28 | 29,1 | 26,8 | 24,8 | 30,6 | 35,2 | 20,2 | 27,2 |
| | 30,3 | 34,3 | 30,4 | 34,8 | 37,7 | 28,6 | 35,0 |
| 180 | 30,9 | 35,2 | 32,1 | 34,9 | 38,9 | 30,6 | 38,4 |

In comparison with normal concrete, when RCA's origin is homogeneous, compressive strength in all mixtures is higher (1 to 38%), with the exception of 100% recycled C20/25 mixture, which exhibits lower strength (3-21%) compared to normal. When RCA's origin is non-homogeneous and recycling rate is 100%, all mixtures exhibit lower strength (1-20%) than that of normal concrete. Decrease of non-homogeneous RCA percentage, from 100% to 50%, favours mixture produced from old C12/15 and C16/20. These mixtures exhibit higher strength compared to normal concrete, beyond 90 days the first one (up to 15%) and at all ages the second one (up to 43%). On the contrary, the decrease of non-homogeneous RCA range leads to a higher reduction of strength in the C20/25 mixture (20-27%).

Generally, concretes made with low strength recycled aggregates exhibit nearly similar behaviour, regardless of homogeneity and participation rate of RCA in mixtures. On the other hand, mixtures containing RCA of higher strength appear to be the most unfavorable. Given the fact that all RAC were prepared with the same amount (and type) of cement and water, the difference probably is due to the type and quantity of, adhered to aggregate, old cement.

*3.4 Resistance to Cl- penetration*

In Table 6 and 7 total chlorides after 6 months curing in NaCl solution is given. Corrosion initiates when chlorides concentration is higher than 0.2% by weight of cement. This concentration was converted into ppm on the basis of mixing proportions and it is given in the same Tables 6 and 7.

In wetting – drying cycles curing (Table 6), normal concrete exhibits higher total $Cl^-$ concentrations in all depths, thus, RAC are more resistant to ion penetration, regardless of proportion, homogeneity or concrete cover. In any case, a decrease of RCA percentage depresses total $Cl^-$ concentration, which means that it improves durability.

When strength of origin concrete is low, no significant difference was found between the homogeneous and inhomogeneous origin mixtures. However, the more the strength of origin concrete increases, the greater differentiations come across among mixtures and inhomogeneous origin mixtures have higher concentration. Anyway, regardless of homogeneity and recycling proportion, bound to total $Cl^-$ ratios in all RAC (Table 6 and 7) range at very high levels (0,95-1) and they are much higher than these in the normal concrete (0,91-0,99).

Concerning the critical threshold level, total $Cl^-$ concentration in normal concrete is found much more above it, in all depths, whereas concentrations in most RAC, made with either 100% homogeneous or 50% inhomogeneous RCA, are found under or slightly above the level, in cover depth ≥4 cm. As to 100% RAC, made with inhomogeneous RCA, although their total $Cl^-$ concentration is above the threshold level in all depths, it is lower than that of normal concrete.

In case that $Cl^-$ penetrates through the one (bottom) side of specimen (Table 7), 100% RAC are considered to be the most undesirable in every concrete cover. Among the others mixtures, when RCA is of homogeneous origin, 50% RAC have the lowest total $Cl^-$ concentration and when RCA is of inhomogeneous origin, normal concrete is the best mixture.

Homogeneous RAC commonly give better results, mainly when recycling proportion is 50%. Bound to total $Cl^-$ ratios, of all RAC, range at high levels 0,83-1 against 0,44-1 of normal concrete (Table 6 and 7).

As for the critical threshold level, almost all 100% RAC give measurements under threshold level in cover depths > 4 cm, whereas when RCA is reduced to 50% or 0%, mixtures' values seem to be under the limit in concrete cover > 2 cm.

Regarding the manner of curing, for 100% RAC, bottom side $Cl^-$ penetration seems to be the most undesirable as opposed to 50% RAC and to normal concrete, for which wetting-drying cycles curing (tides etc) is the most unfavourable one.

## Conclusion

### Splitting tensile strength

√ Inhomogeneous origin RAC have higher splitting strength even higher than this of normal concrete.

**Table 6** Free $Cl^-$ (ppm), bounded to total $Cl^-$ ratios and critical threshold level of mixtures. Wetting – drying cycles

| Cover (cm) | Percentage of RCA (w/w) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 100% | | | 50% | | | 0% | 100% | | | 50% | | | 0% |
| | $f_{ck,cube}$ of origin concrete (MPa) | | | | | | | $f_{ck,cube}$ of origin concrete (MPa) | | | | | | |
| | 15 | 20 | 25 | 15 | 20 | 25 | | 15 | 20 | 25 | 15 | 20 | 25 | |
| | Homogeneous origin | | | | | | | Heterogeneous origin | | | | | | |
| | **Total $Cl^-$ (ppm)** | | | | | | | | | | | | | |
| 2 | 2676 | 2079 | 1029 | 1029 | 1348 | 923 | 3194 | 2983 | 3479 | 3411 | 2679 | 2229 | 2083 | 3495 |
| 4 | 675 | 334 | 433 | 433 | 225 | 307 | 862 | 523 | 875 | 864 | 316 | 422 | 855 | 884 |
| 6 | 490 | 202 | 424 | 424 | 143 | 220 | 978 | 473 | 595 | 647 | 350 | 418 | 179 | 759 |
| 8 | 1028 | 521 | 708 | 708 | 384 | 507 | 1093 | 825 | 955 | 965 | 587 | 881 | 922 | 991 |
| | **Threshold (ppm)** | | | | | | | | | | | | | |
| | **364** | **341** | **384** | **323** | **323** | **326** | **308** | **353** | **349** | **351** | **328** | **324** | **326** | **316** |
| | **Free $Cl^-$ (ppm)** | | | | | | | | | | | | | |
| 2 | 289,0 | 53,2 | 62,1 | 88,7 | 8,9 | 17,7 | 53,2 | 133,0 | 133,0 | 398,9 | 53,2 | 44,3 | 88,7 | 292,6 |
| 4 | 8,9 | 8,9 | 8,9 | 8,9 | 0,0 | 8,9 | 8,9 | 8,9 | 8,9 | 44,3 | 8,9 | 8,9 | 35,5 | 35,5 |
| 6 | 8,9 | 8,9 | 8,9 | 8,9 | 0,0 | 8,9 | 8,9 | 8,9 | 8,9 | 17,7 | 8,9 | 8,9 | 0,0 | 8,9 |
| 8 | 8,9 | 17,7 | 8,9 | 8,9 | 8,9 | 8,9 | 26,6 | 8,9 | 20,2 | 26,6 | 8,9 | 17,7 | 8,9 | 44,3 |
| | **Bound/Free $Cl^-$** | | | | | | | | | | | | | |
| 2 | 0,89 | 0,97 | 0,94 | 0,91 | 0,99 | 0,98 | 0,98 | 0,96 | 0,96 | 0,88 | 0,98 | 0,98 | 0,96 | 0,92 |
| 4 | 0,99 | 0,97 | 0,98 | 0,98 | 1,00 | 0,97 | 0,99 | 0,98 | 0,99 | 0,95 | 0,97 | 0,98 | 0,96 | 0,96 |
| 6 | 0,98 | 0,96 | 0,98 | 0,98 | 1,00 | 0,96 | 0,99 | 0,98 | 0,99 | 0,97 | 0,97 | 0,98 | 1,00 | 0,99 |
| 8 | 0,99 | 0,97 | 0,99 | 0,99 | 0,98 | 0,98 | 0,98 | 0,99 | 0,98 | 0,97 | 0,98 | 0,98 | 0,99 | 0,96 |

**Table 7** Free $Cl^-$ (ppm), bounded to total $Cl^-$ ratios and critical threshold level of mixtures. One side penetration

| Cover (cm) | Percentage of RCA (w/w) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 100% | | | 50% | | | 0% | 100% | | | 50% | | | 0% |
| | $f_{ck,cube}$ of origin concrete (MPa) | | | | | | | $f_{ck,cube}$ of origin concrete (MPa) | | | | | | |
| | 15 | 20 | 25 | 15 | 20 | 25 | | 15 | 20 | 25 | 15 | 20 | 25 | |
| | Homogeneous origin | | | | | | | Heterogeneous origin | | | | | | |
| | **Total $Cl^-$ (ppm)** | | | | | | | | | | | | | |
| 2 | 5088 | 4900 | 6231 | 1046 | 1014 | 531 | 1055 | 3621 | 3673 | 6326 | 2553 | 2178 | 2050 | 1070 |
| 4 | 1679 | 368 | 560 | 148 | 129 | 113 | 157 | 547 | 1090 | 909 | 240 | 394 | 203 | 180 |
| 6 | 316 | 148 | 246 | 138 | 101 | 89 | 142 | 232 | 585 | 268 | 174 | 368 | 171 | 134 |
| 8 | 82 | 135 | 83 | 75 | 71 | 75 | 80 | 210 | 375 | 210 | 172 | 289 | 144 | 129 |
| | **Threshold (ppm)** | | | | | | | | | | | | | |
| | **364** | **341** | **384** | **323** | **323** | **326** | **308** | **353** | **349** | **351** | **328** | **324** | **326** | **316** |
| | Free $Cl^-$ (ppm) | | | | | | | | | | | | | |
| 2 | 753,5 | 336,9 | 663,1 | 97,5 | 8,9 | 81,9 | 8,9 | 602,8 | 602,8 | 916,1 | 115,3 | 35,5 | 97,5 | 234 |
| 4 | 203,9 | 8,9 | 35,5 | 8,9 | 8,9 | 8,87 | 8,9 | 35,5 | 35,5 | 35,5 | 8,9 | 8,9 | 8,9 | 35,5 |
| 6 | 8,9 | 8,9 | 8,9 | 8,9 | 0,0 | 8,87 | 8,9 | 35,5 | 8,9 | 8,9 | 8,9 | 8,9 | 0,0 | 8,9 |
| 8 | 8,9 | 0,0 | 8,9 | 0,0 | 0,0 | 0 | 0,0 | 17,7 | 8,9 | 8,9 | 8,9 | 8,9 | 0,0 | 8,9 |
| | Bound/free Cl | | | | | | | | | | | | | |
| 2 | 0,85 | 0,93 | 0,89 | 0,91 | 0,99 | 0,85 | 0,99 | 0,83 | 0,84 | 0,86 | 0,95 | 0,98 | 0,95 | 0,78 |
| 4 | 0,88 | 0,98 | 0,94 | 0,94 | 0,93 | 0,92 | 0,94 | 0,94 | 0,97 | 0,96 | 0,96 | 0,98 | 0,96 | 0,80 |
| 6 | 0,97 | 0,94 | 0,96 | 0,94 | 1,00 | 0,90 | 0,94 | 0,85 | 0,98 | 0,97 | 0,95 | 0,98 | 1,00 | 0,93 |
| 8 | 0,89 | 1,00 | 0,89 | 1,00 | 1,00 | 1,00 | 1,00 | 0,92 | 0,98 | 0,96 | 0,95 | 0,97 | 1,00 | 0,93 |

√ The higher $f_{ck}$ of origin concrete is, the higher RAC splitting strength appears, regardless of replacement percentage or RCA homogeneity.

√ Increase of RCA percentage proportion improves splitting strength in homogeneous RAC, whereas reduces it in case of inhomogeneous RAC.

### Characteristic strength

√ $f_{ck}$ of all RAC is higher than $f_{ck}$ of origin concrete.

√ $f_{ck}$ of most inhomogeneous RAC is either equal or higher than that of normal concrete. $f_{ck}$ of 100% homogeneous RAC is slightly lower than that of normal concrete, whereas $f_{ck}$ of 50% homogeneous RAC is equal to $f_{ck}$ of normal concrete

### Compressive strength

√ Compressive strength in most homogeneous RAC, after 28 days, is higher than that in inhomogeneous RAC.

√ Decrease of RCA percentage, increases compressive strength in most mixtures.

√ In comparison with normal concrete, almost all homogeneous RAC have higher compressive strength whereas almost all inhomogeneous RAC, after 28 days, have lower strengths

## Chlorides

√ The most undesirable for 100% RAC is the bottom side penetration of $Cl^-$. For both 50% RAC and normal concrete, the most unfavourable curing is the one with wetting-drying cycles.
√ Decrease of RCA percentage improves chlorides penetration resistance.
√ In wetting-drying cycles, RAC exhibits the lowest total and free $Cl^-$ concentration, regardless of RCA proportion, or homogeneity, or concrete cover depth.
√ In one side $Cl^-$ penetration, the most unfavourable mixture is 100% RAC. The best mixture is 50% RAC which has the lowest total $Cl^-$concentration when RCA is homogeneous.
√ Bound to total $Cl^-$ ratios in all RAC, regardless of homogeneity and recycling percentage are much higher than the ones in normal concrete in drying cycles and at very high levels in one side penetration.

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