PERMEABILITY PROPERTIES OF FINE RECYCLED AGGREGATE CONCRETE

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Abstract

It is generally accepted nowadays that concrete production has to become a more environmentally efficient industry, if concrete wants to keep its lead as the most used construction material in the world. To achieve that, researchers throughout the world have been trying to replace natural aggregates recycled aggregates from construction and demolition waste (CDW).

Much work has been done to promote recycled aggregates (RA) as valid materials in concrete production, with partial good results. If, on the one hand, the use of coarse recycled aggregates (CRA) in concrete production is generally accepted, even if at low replacement ratios or low-demanding applications, on the other hand, the use of fine recycled aggregates (FRA) is generally barred from concrete production.

The reasons for these strict restrictions are known and have been widely advertised in the past: FRA have high deleterious effects on the concrete performance, making it useless for most applications. And even if at the mechanical level the performance of these concretes could still be considered acceptable, the results regarding durability were quite disappointing during the earlier researches. In recent years research seems to contradict these results and FRA may become a viable source some specific care is taken during the design and production of the mixes.

In this paper, the permeability properties of fine recycled aggregate concrete are presented. The FRA used come from demolished concrete of known properties. Mixes with 10%, 30%, 50% and 100% by volume replacement of fine natural aggregates (FNA) with FRA were produced and tested for water absorption by immersion, capillary absorption, carbonation, chloride penetration and electrical resistivity.

The results that have been achieved seem to follow the most recent trend regarding the use of FRA in concrete production. It is possible to use FRA in concrete production and still produce a material with durability properties that comply with the minimum requisites for structural applications.

Keywords: concrete, fine recycled aggregates, permeability, chloride penetration, carbonation, electrical resistivity

1 Introduction

Regardless of the world crisis that has struck the vast majority of the industrialized countries, the construction industry is still growing worldwide and it is expected to continue so until 2030 (IHS, 2013). For that purpose, concrete has had a major role in the last century, since it is a material that requires easy to gather materials, is easy to manufacture and use, can have complex shapes, and has low production costs. For these reasons, it easy to understand why concrete is the most used material in the world with an estimate of 10 billion cubic meters produced every year [1]. To produce concrete it is required the use of large quantities of aggregates that lead increase the environmental pressure over the surrounding ecosystems [2]. In worldwide terms, the requirement for aggregates in construction industry (including concrete production) reached 48.3 billion tons in 2015 [3], showing that this environmental pressure is ever increasing. Regarding the extraction of fine aggregates, it can be achieved by dredging (from river and sea beds) and mining (from beaches and pits). In all cases there are severe environmental impacts of such activities in the local biosphere [4–6], as well as irreversible geomorphologic changes in the affected areas with unpredictable results [7–9].

One way of reducing this environmental impact for concrete production is by using by-products from industrial activities, particularly from construction. That is usually achieved by using recycled aggregates from construction and demolition waste (CDW) as replacements for natural aggregates. The viability of this replacement has been extensively studied throughout the last decades. The research has included mechanical properties [10–12], durability (Amorim et al., 2012; Kou and Poon, 2013; Pedro et al., 2014; Bravo et al., 2015), rheology [17,18], structural elements behaviour [19,20] and, more recently, with the analysis of the application of standard design rules for the case of recycled aggregate concrete [21].

Even though the use of coarse recycled aggregates (CRA) is currently accepted to some extent in a good number of civilized countries [22], the finer fraction is still strongly restricted or even banned. The reasons for such restrictions arise from earlier research, that classified fine recycled aggregates (FRA) has being highly heterogeneous, having high water absorption rates and levels of contaminants, that lead to unacceptable performance losses [23]. However, recent researches seem to contradict that FRA cannot be used in concrete production. Investigations conducted by Khatib [24], Solyman [25], Evangelista and de Brito [26–28], Pereira et al. [29,30], Cartuxo et al. [31,32], among others have shown that FRA can be used for concrete production if some specific care is taken, both in the design as well as in the production stage of these concretes. Regardless of these encouraging results, it is consensual that FRA concrete performs better in mechanical than in durability terms. In terms of water absorption by immersion, results have shown increases ranging from 15% [33] to 46% [26]. These results seem to be worse for water absorption by capillarity, with relative increases to the reference concrete ranging from 46 to 95%, depending on the water/cement ratio [32]. In all these cases, authors seem to point out that FRAC has higher porosity, which is responsible for the registered performance losses. Fumoto e Yamada [34] calculated the pore volume between 0.05 e 10 nm and concluded that this is 30% higher for concretes made solely with FRA. These conclusions were corroborated by Sagawa *et al.* [35] and Hwang *et al.* [36] that verified that not only the pore volume increases for FRAC, but also the average pore diameter increases.

Considering this morphological changes in the concrete micro structure, it is expected that carbonation, as well as chloride penetration also increase with the usage of FRA. Carbonation wise, the results seem to be highly scattered. Solyman [37] observed an increase of just 17% in the carbonation depth for concrete with 100% FRA, while other authors [32,38] observed increases of 333 and about 900%, respectively. In terms of chloride penetration, the results seem to contradict themselves even further. Fraaij et al. [39] tested the chloride penetration of concretes made with 100% CRA and increasing rates of FRA and concluded that the later do not affect the concrete's performance regarding this property. These results are even better in the research conducted by Kou e Poon [40] that concluded that the presence of FRA in self compacting concrete has a beneficial effects due to the presence of filler. On the other hand, Levy e Heléne [41] observed losses in the electrical resistivity of FRAC, leading the authors to conclude that concretes mate with 100% FRA have high probabilities of reinforcement corrosion. These results are validated by other authors [26,32], which found chloride penetrations for FRAC to be 33 and 43 to 56% higher than those determined for the respective reference concretes.

From the results previously presented, it is clear that durability performance of FRAC is worse than that of the reference concrete of similar composition. The extent of this performance loss is not, however, clear as the results dispersion is significant. This has to do with the different research approaches used by each author, in terms of fixed parameters, mix design procedures, water/cement ratio assumptions, among others.

Considering all this, in this paper the permeability results (water absorption by immersion, capillary water absorption, carbonation, chloride penetration and electrical resistivity) of concretes made with increasing rates of FRA are presented and compared with those from a reference concrete made exclusively with natural aggregates.

2 Experimental program

The experimental program described here can be split in two different stages. During the first stage, a source concrete was produced and subsequently crushed and stored. This allowed to control its composition and original properties, in order to better correlate the subsequent results. The slump was 125 mm, and its average compressive strength at 28 days of open air curing was 28.7 MPa. It was then crushed with one single stage of crushing, using a jaw crusher. The aggregates were then sieved into fine and coarse fractions.

In order to maintain the cement paste similar in void content, it was decided to separate FRA in the various sizes that correspond to the basic series' sieves. This happened because the grading curves for FNA and FRA were different which, thus minimizing the effect of the scatter in aggregates size distribution in the various mixes, with different replacement rations of fine natural aggregates (FNA) with FRA.

The FRA were analysed in physical, mineralogical and microscopical terms and the results showed that FRA have high mortar content are highly carbonatated and do not present unhydrated cement particles [42]. The main properties of FRA used are presented in Table 1 and compared with the natural sands used. It can be seen that the major difference between all fine aggregates is that FRA have water absorption rates about ten times higher than FNA, which has to be taken into account during mixing. Their density is also lower, as a consequence of the presence of adhered mortar. There is a high content of particles sized below 63 μm, leading to an increased water demand during mixing. This higher fines content is directly related to the more brittle nature of FRA that leads to particles fragmentation during use. Additionally, the water absorption curve through time of FRA was determined using a method developed for the purpose [43]. This was done so that the water lost to the FRA during mixing was compensated, thus keeping the effective water/cement ratio close to constant.

Table 1 – Main properties of fine aggregates

	Density (g/cm^3)				Water absorption (%)	Sand equivalent (SE)
	Dry	Saturated surface dry	Aparent	Bulk		
FRA	2.00	2.21	2.53	1.33	10.43	69
FNA1	2.55	2.58	2.62	1.48	1.07	87
FNA2	2.55	2.58	2.62	1.56	0.96	95

The mixes with FRA were designed according to the Faury's method [44], with volumetric replacement ratios of FNA with FRA of 10%, 30%, 50% and 100%. The FRA were added by sieve size, so that each fraction corresponded to the exact percentage of the combined natural sands. All mixtures had a fixed slump of 80±10 mm, in order to reduce the performance affecting parameters to minimum. In addition to the FRA, two natural sands, two limestone gravels, type I 42.5R cement and tap water were used. Table 2 presents a summary of the mixes analysed, including the estimated effective water/cement ratios. As it can be seen, there is a slight increase of the effective water/cement ratio with the increase of FRA. That is directly related to the increased amount of fine content in the mixes, that will require higher quantities of water, as well as to the higher specific surface of the FRA, with a direct effect on the water demands.

Table 2 – Mix compositions

	RC	C10R	C30R	C50R	C100R
Replacement ratio (%)	0	10	30	50	100
Cement (kg/m^3)	360	360	360	360	360
Water (l/m^3)	191	194	194	198	202
Ratio $(w/c)_{ef}$	0.53	0.54	0.54	0.55	0.56
Fine sand (kg/m^3)	381	343	265	188	0
Coarse sand (kg/m^3)	347	312	241	171	0
FRA (kg/m^3)	0	57	171	284	568
Gravel 1 (kg/m^3)	351	351	349	348	348
Gravel 2 (kg/m^3)	681	681	677	673	673

In addition to the tests under discussion is this paper, several other tests were conducted, including mechanical properties. Among these, the compressive strength, the splitting tensile strength and the modulus of elasticity were tested at 28 days of age, and the results are presented in Table 3. As it can be seen, there is a loss of mechanical performance within these concretes, which is gradually worsened by the increase of FRA. Compressive strength has a decrease of about 8.6% for the mixture with 100% of FRA. A similar effect happens for the other two properties, with a decrease of about 17 and 12%, for tensile and modulus of elasticity, respectively. These results are a consequence of the inclusion of FRA, which are more porous and fragile, but also to the increase in the water/cement ratio, that will lower the overall performance of the mixtures.

The water absorption test by immersion was performed at 28 and 120 days, on three 0.10m cubic specimens, using the procedures established in national standard LNEC E-394 [45]. In this test, the specimens are placed under water until constant mass is achieved. After that, the hydrostatic mass for each specimen is determined and then the dry mass is achieved by placing them in a 105ºC oven.

Capillary water absorption was measured in three cylindrical specimens with 0.15m of diameter and 0.10m of height. After being in a 40ºC chamber for 14 days, the specimens were placed in a 5mm layer of water and the changes in mass were measured at 3, 6, 24 e 72 hours, in accordance to national standard LNEC E-393 [46].

Carbonation resistance was measured in cylindrical specimens of 0.1m of diameter and 0.05m of height that were kept in a climatic chamber (20ºC, 5% of CO2) throughout the test, in agreement with national standard LNEC E-391 [47]. The circular surfaces of the specimens were coated with an epoxy based paint so that CO2 penetration happened exclusively through the revolution surface. Tests were performed at 7, 14, 21, 28, 56, 91 and 182 days of age at which the specimens were split and sprayed with a 1% concentration phenolphthalein solution was applied to fracture surface.

Table 3 – Mechanical properties of FRAC at 28 days of age

	RC	C10R	C30R	C50R	C100R
Compressive strength, $f_{cm,cyl}$ (MPa)	33.6	32.1	32.7	32.8	30.7
Tensile strength, f_{ctm} (MPa)	3.42	3.07	3.16	3.20	2.84
Modulus of elasticity, E_{cm} (GPa)	37.2	36.6	37.0	34.3	32.9

Chloride penetration tests were conducted in a non-steady state regime, in accordance to national standard LNEC E463 [48], derived from the Nordtest standard NT Build 492 [49]. Three cylindrical specimens of 0.1m of diameter and 0.05m of height were tested at 28 and 120 days of age, after being saturated under vacuum with a calcium hydroxide solution.

The electrical resistivity of FRAC was also conducted on three cylindrical test specimens, with similar curing and preparation as in the chloride penetration tests. A 60V DC current was applied to the specimens, sustaining a 2kg preload, in accordance to the procedures proposed by RILEM TC 154-EMC (2000). The passing current was then measured using a standard multimeter.

3 Results and discussion

3.1 Water absorption by immersion

The results for the water absorption test by immersion can be seen in Figure 1. The absolute values at 28 days change from 14.21%, for the reference concrete and 16.85%, for the concrete with 100% FRA. Looking at the variation between these two values, it can be seen that it seems to change linearly with the replacement ratio. At 120 days of age, the same trend is visible, with absolute values that are similar to those registered at 28 days. Water absorption for the reference concrete was 14.16%, corresponding to an improvement of just 0.35%, compared to the values at 28 days.

Analyzing the effect of including FRA in the concrete mixes, it can be notice that there is an increase of about 20% in the water absorption by immersion for the C100R mix, compared to the reference concrete. This is directly related to the higher porosity of FRA. This has also been recorded by other authors with the same conclusions [26,32,51]. On the other hand, the need for an increased in the water/cement ratio (even if at slight terms), causes, on its own, greater porosity to the cement paste, and therefore increases the ability to absorb water [37,52].

Additionally, it can be seen that there is no change in performance after 28 days of age, even though there were unhydrated fly ash present in the matrix. This is probably related to the fact that this property is less sensitive to any microstructural change that may occur beyond that age [53,54].

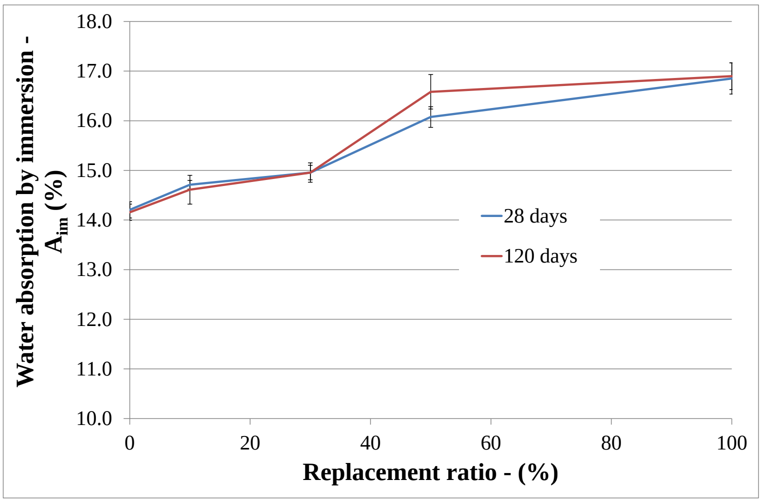

Figure 1 – Water absorption by immersion

3.2 Capillary water absorption

The capillary water absorption results at 28 and 120 days can be seen at Figures 2 and 3, respectively. In absolute terms, the capillary water absorption at 72h, for 28 days of age, changed from 1.86 and 6.26 g/mm^2, with a linear variation between these values as a function of the replacement ratio. This trend also occurs for earlier test ages. For 120 days of age, capillary absorption changed from 1.86 e 4.24 g/mm2, at 72 h of testing. As it happened with the tests carried out at 28 days of age, there is a linear trend for the variation of capillary water absorption with the replacement ratio, regardless of the test time.

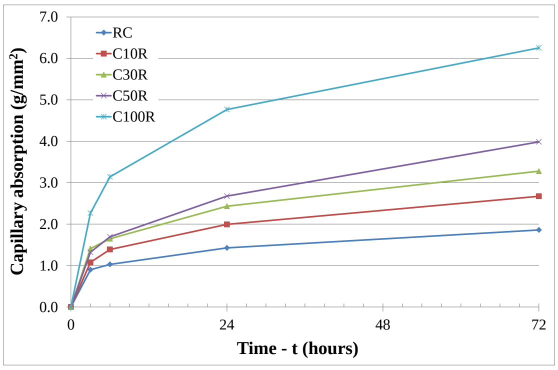

Figure 2 – Capillary absorption at 28 days.

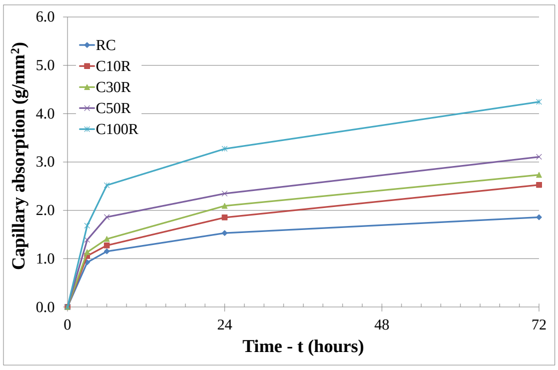

Figure 3 – Capillary absorption at 120 days.

The main justification for the increase in capillary absorption is naturally related to the higher porosity presented by the FRA, that lead to longer capillaries [26,55,56]. Comparing the results at 28 and 120 days, it is noticed that there is a consistent reduction of capillary absorption with age. That is even more noticeable for higher replacement ratios. These phenomena may be caused by the presence of fly ash in the FRA. Other authors [57,58] have tested that the secondary hydration reactions between calcium hydroxide and the fly ash fill out the capillaries.

3.3 Carbonation

The carbonation depth measured throughout the entire test can be seen in Figure 4. In absolute terms, the carbonation depth is higher for FRAC that for RC. At 182 days of age, the carbonation depth ranged from about 14 mm, for the reference concrete and about 20.4 mm, for concrete C100R. For the remaining mixes the results are usually between the previous two values, although some dispersion is registered.

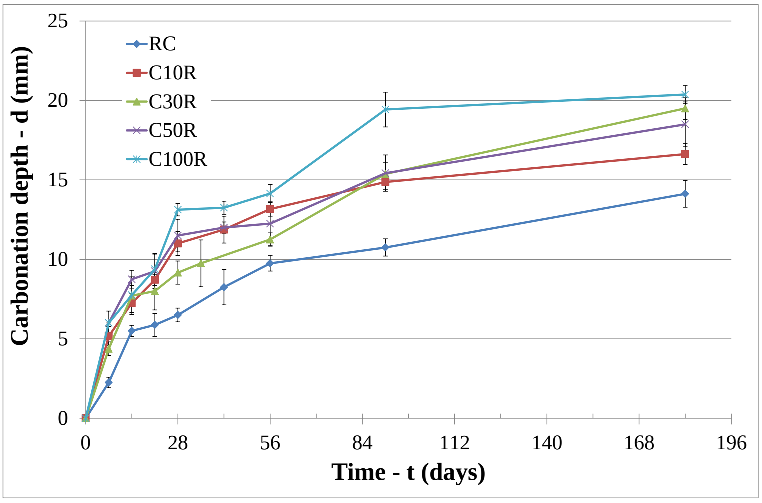

Figure 4 – Carbonation evolution with time

Carbonation depth (d) can be estimated for a given time interval (t) using Fick´s first law, according to equation (1), in which K_c is the carbonation coefficient.

$$d = K_c . t^{0,5} \tag{1}$$

Considering the results presented it was possible to establish the carbonation coefficients for the tested families using non-linear regression models. The results for these regressions can be seen in Table 4, along with the determination coefficient (R^2) and the relative changes to the reference concrete's carbonation coefficient. The carbonation coefficient increases almost linearly (if C10R is ignored) and has a maximum increase of 60% compared to the RC.

Table 4 – Carbonation coefficients for the tested concretes

	K_c (mm/year^{0,5})	R^2	$\Delta K_{c,RC}$ (%)
RC	21.98	0.96	-
C10R	29.49	0.82	34.1
C30R	29.58	0.97	34.6
C50R	31.11	0.85	41.5
C100R	35.06	0.88	59.5

Generally speaking, FRAC present lower carbonation resistance than the comparable RC. This is again related to the higher porosity of FRA and particularly to the increase in the water/cement ratio. Fumoto and Yamada [34] studied the influence of the water/cement ratio on the carbonation of FRAC and concluded that the water/cement increase negatively affects the Co2 diffusion throughout the dement paste. This has been corroborated by Geng and Sun [38].

3.4 Chloride resistance

The chloride penetration results can be seen in Figure 5. In general, the chloride coefficient ranges from 16.3 to 23.0 $\times 10^{-12}$ m^2/s, at 28 days of age and from 15.8 to 24.0 $\times 10^{-12}$ m^2/s, at 120 days of age. As it can also be seen, there is a linear trend for the evolution of chloride penetration with the replacement ratio, which is directly related to the porosity of FRA, as well as to the water/cement ratio.

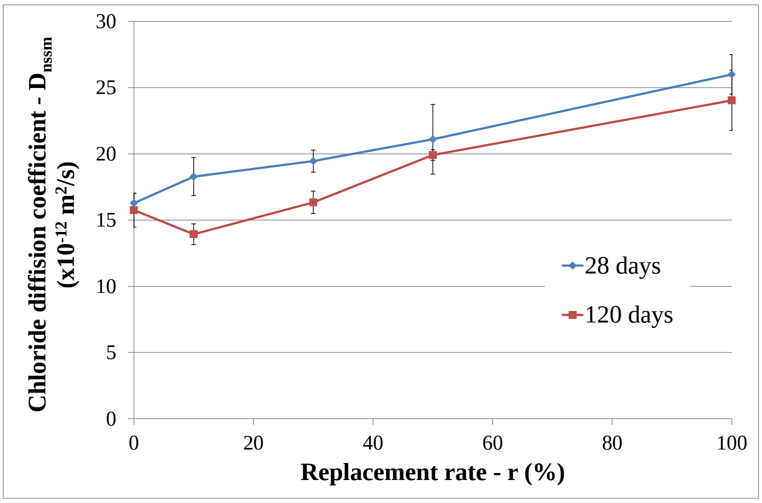

Figure 5 – Chloride penetration tesults

AS stated before, chloride penetration is directly related to the porosity of concrete. Several authors have established the correlations between these two properties using microscopic techniques [59–63]. Following this line of thought, an analysis of the relation between chloride penetration and capillary absorption has been conducted and it presented in Figure 6. As it is possible to conclude, there is an excellent linear correlation between both properties.

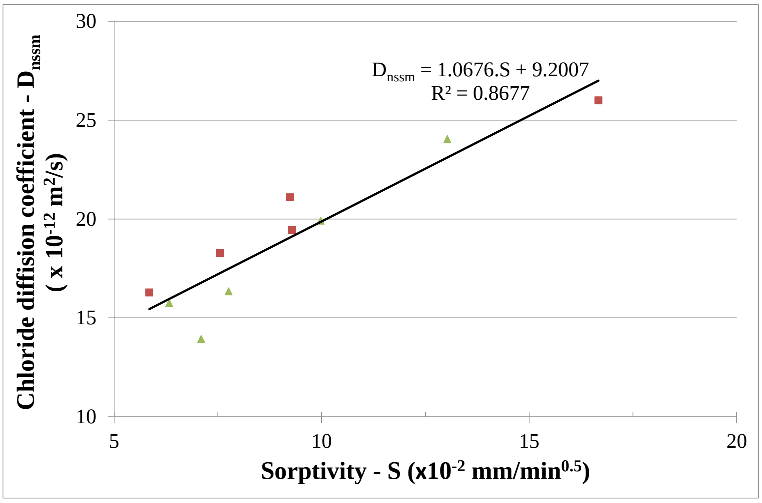

Figura 6 – Correlation between chloride penetration and capillary absorption

3.5 Electrical resistivity

The electrical resistivity results are presented in Figure 7. In absolute terms, the electrical resistivity ranges from 67.6 and 53.1 Ω.m, for 28 days of age, and 72.3 e 55.2 Ω.m, for 120 days. For both ages, this property shows a linear decrease withthe replacement ratio. The loss of electrical resistivity with the replacement ratio ranges from 21.5 and 23.7%, for 28 and 120 days, respectively. This loss is associated with the porosity of FRA that allow the na higher current transfer [64].

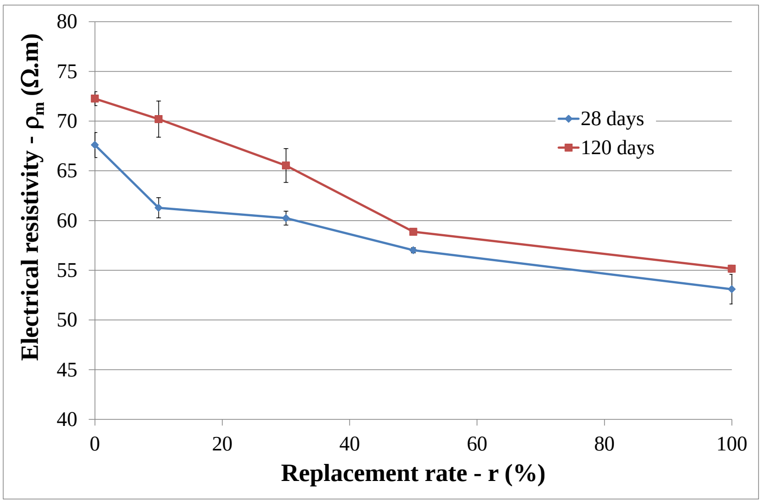

Figure 7 – Electrical resistivity of FRAC

The Duracrete work group established [65] that the electrical resistivity (ρ) and the chloride coefficient presented a non-linear correlation according to equation (2), being A and b regression constants and b being negative.

$$D = A.\rho^b \quad (2)$$

Based on this model, a non-linear regression was conducted that showed reliable results, with a correlation coefficient of R^2 = 0.94, as it can be seen in Figure 8.

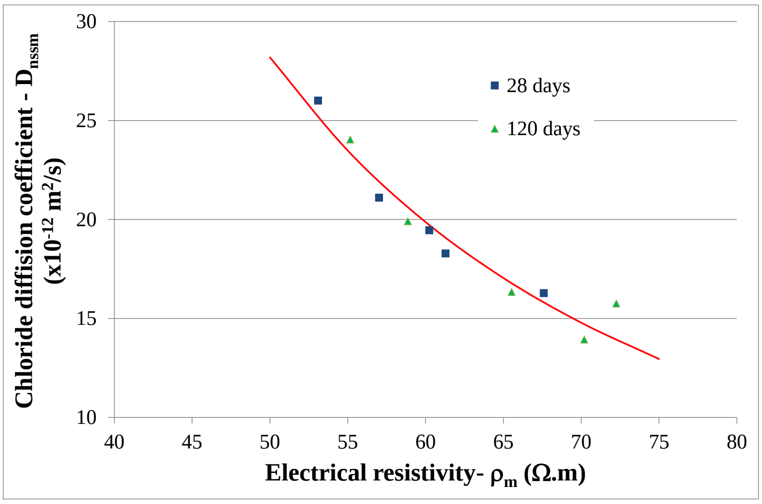

Figure 8 - Correlation between Chloride diffusion and electrical resistivity

4 Conclusions

The permeability properties for FRAC are clearly influenced by the presence and quantity of FRA. This is in direct relation with the inclusion of materials that are more porous and allow the transport of fluids through them. The following conclusions can be drawn:

- Water absorption by capillarity is influenced by the presence of FRA and by the water/cement ratio; the age does not seem to affect the performance beyond 28 days;

- Capillary absorption is follows the same trend, even though the age effects are noticeable;

- Carbonation resistance has a major decrease with the presence of FRA;

- Chloride penetration presents a good correlation with capillary absorption;

- Electrical resistivity can be established based on the chloride diffusion.

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