TÉCNICO LISBOA

Durability performance of shotcrete produced with coarse recycled concrete aggregates

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Extended Abstract

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1. Introduction

According to the United Nations (2017), it is expected that the world population will continue to grow, reaching 8.6 billion people by 2030. This increase causes an alarming consumption of natural resources and production of waste. The construction sector alone is responsible for roughly one quarter of all the waste generated in the European Union (EU) (EEA, 2018). The application of recycled aggregates (RA) in concrete has been proved to be an efficient way to reduce this environmental impact. However, it represents only 8% of the total amount of aggregates used in the EU (UEPG, 2018), indicating that it is still necessary to raise awareness about the viability of concrete produced with RA.

The aim of this work was to study the durability of dry-mix shotcrete produced with coarse recycled concrete aggregate (CRCA).

A literature review on the properties of CRCA and its influence on concrete and shotcrete was conducted. The major conclusion was that CRCA has high porosity, due to the mortar adhered to the original natural aggregates (NA) present in this kind of RA. This property leads to high values of water absorption and low mechanical strength (Soares *et al.,* 2015).

The experimental study analyzed concrete with substitution ratios of 0%, 20%, 50% and 100%. To obtain the necessary specimens, two 1.50x1.10m panels were produced for each mix and cores extracted and tested for: water absorption by immersion, water absorption by capillarity, carbonation resistance, chloride ion penetration resistance and shrinkage. Along with this campaign, Duarte (2018) conducted a study concerning the mechanical performance of shotcrete produced with CRCA.

The results of this experimental campaign validate, in terms of durability, the viability of this solution.

In the next sections, the experimental procedure is presented in more detail as well as the results of the study and the underlying conclusions to be drawn.

2. Experimental procedure

2.1. Materials

Before starting the experimental work, it was necessary produce and obtain the following materials:

- CRCA: produced in laboratory, by crushing cast-in-place concrete beams;
- Natural aggregates: fine and coarse sand, fine and medium-size gravel;
- Cement: CEM I 42.5R.

All the coarse aggregates were sieved by using a sieve shaker, separated by fractions between 4 and 12.5 mm and stored in separated sealed containers. The fine aggregates were dried and stored in separated sealed containers.

2.2. Concrete's composition

The four concrete mixes studied were RC, C20, C50 and C100, corresponding to percentages of substitution of coarse natural aggregates (CNA) with CRCA of 0%, 20%, 50% and 100%. The composition of the four mixes can be found in Table 2.1.

Table 2.1 - Composition of the concrete mixes produced.

Material	Size fraction [mm]	Mixes composition [kg/m^3]			
		RC	C20	C50	C100
CNA [mm]	12.5-10	243.53	193.99	120.71	-
	10-8	232.90	185.52	115.44	-
	8-6.3	242.81	193.42	120.35	-
	6.3-4	164.56	131.07	81.56	-
CRCA [mm]	12.5-11	-	47.86	119.13	213.26
	10-8	-	45.77	113.93	203.95
	8-6.3	-	47.72	118.77	212.63
	6.3-4	-	32.34	80.49	144.09
Coarse sand	-	710.12	708.66	706.44	705.24
Fine sand	-	214.43	213.18	210.02	205.85
Cement	-	350.00			

2.3. Dry-mix shotcrete procedure

The process to produce each shotcrete panel was as follows:

- Production of wood formwork;
- Casting and curing of the substrate concrete for each panel;
- Lifting of the panels to a vertical position;
- Mixing the aggregates and cement, using a concrete mixer;
- Introduction of the dry mix in the upper chamber of the projection machine;
- Opening of the lower chamber;
- Projection of the dry mix through the nozzle, with the help of a compressor;
- Adjustment of the amount of water, by the nozzleman;
- Projection of the adjusted concrete on the vertical panels;
- Placement of the panels in a horizontal position;
- Curing of the shotcrete for about 5 days;
- Extraction of the specimens.

3. Experimental results and discussion

3.1. Aggregates properties

The aggregates' properties are presented in Table 3.1.

Table 3.1 - Aggregates' properties.

	Fine sand	Coarse sand	Fine gravel	Medium-size gravel	CRCA	Standard
ρ_a [kg/m^3]	2587	2623	2708	2724	2658	EN 1097-6 (2013)
ρ_{rd} [kg/m^3]	2548	2574	2634	2624	2370	
ρ_{sss} [kg/m^3]	2564	2594	2661	2648	2478	
WA24 [%]	0.59	0.71	1.02	1.65	4.55	
ρ_b [kg/m^3]	1557	1544	1409	1406	1287	EN 1097-3 (1998)
% voids	40.0	40.0	46.6	46.1	45.7	
Shape index [%]	-	-	22.3	26.7	45	EN 933-4 (2008)
Δ LA [%]	-	-	25	25	36	EN 1097-2 (2010)
w [%]	-	-	-	-	2	EN 1097-5 (2008).

Table 3.1 shows that CRCA has higher values of water absorption and lower density than CNA, and the Los Angeles coefficient is higher. All these effects were due to the high porosity and low mechanical strength of the mortar adhered to the original NA present in the CRCA. These aggregates also displayed a higher shape index, as a result of the thinner and longer shapes of CRCA. The water content of CRCA was 2.0%. The particles size distribution was determined, following the EN 933-1 (2012) and EN 933-2 (1995) standards. CRCA had a more extensive particles size distribution. However, this situation was not a problem in this study since all the aggregates were sieved and separated by fractions.

3.2. Fresh shotcrete characterization

In dry-mix shotcrete the amount of water is controlled by the nozzleman, which means the w/c ratio cannot be directly controlled. However, it was possible to measure the amount of water used in each projection and calculate the w/c ratio using that information. The rebound effect was also measured. The results for both rebound and w/c ratio are displayed in Table 3.2. As expected, the w/c ratio increased as the CRCA substitution ratio increased, except for C100 that maintained a similar level to C50.

Table 3.2 - Fresh shotcrete characterization.

	w/c ratio	Rebound loss [%]	Δ_{RC} [%]
RC	0.46	27.27	-
C20	0.47	21.09	22.66
C50	0.50	26.14	4.14
C100	0.50	19.11	29.92

In terms of the rebound effect, there was a reduction of about 30%, for C100. The rebound effect is one of the main disadvantages of shotcrete, so this is an important result. The reduction of the rebound effect can be explained by the geometrical properties of CRCA, its low density and roughness, and the increased water absorption of the shotcrete with incorporation of CRCA.

3.3. Hardened shotcrete durability performance

3.3.1. Water absorption by immersion

The water absorption by immersion test was conducted at 28 days. The values observed can be consulted in Table 3.3.

Table 3.3 - Water absorption by immersion.

	Water absorption by immersion [%]	ΔRC (%)
RC	13.4	0.0
C20	14.4	7.7
C50	14.6	8.6
C100	15.4	14.7

The incorporation of CRCA in the shotcrete resulted in an increase of absorption, with a maximum of 15.4% for C100. However, with the exception of RC, all concrete mixes respected the values proposed by ACI Committee 506 (2016) for good quality shotcrete, i.e. between 14% and 17%. The increase of absorption resulted from the increase of w/c ratio, which is necessary to maintain the workability across all mixes and from the high porosity of the mortar adhered to the NA present in the CRCA. There was also a good linear correlation between the water absorption and the CRCA ratio, with a correlation co-efficient of about 0.88.

3.3.2. Water absorption by capillarity

The water absorption by capillarity tests were conducted at 28 days and lasted for 72 hours. The evolution of water absorption along with the CRCA ratio and with time is presented in Figure 3.1 and Figure 3.2, respectively.

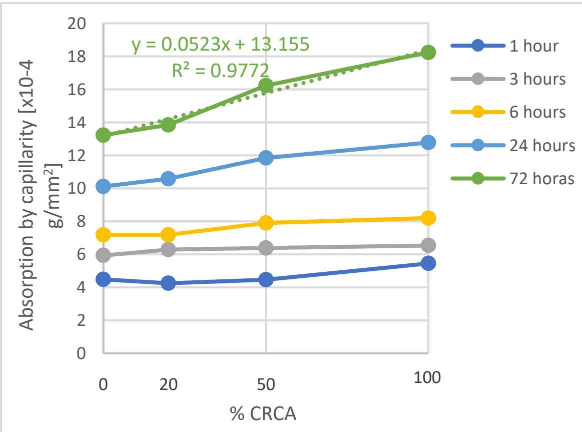

Figure 3.1 - Evolution of water absorption by capillarity with %CRCA.

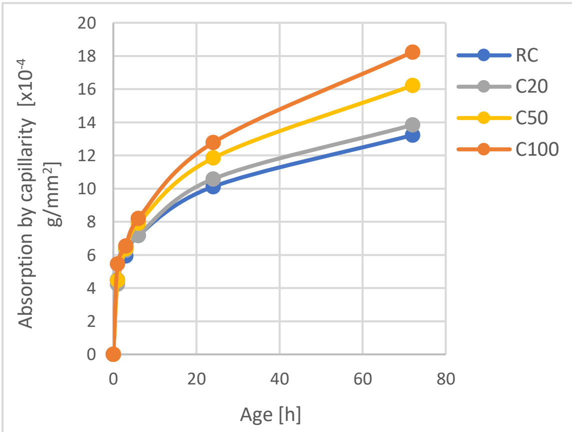

Figure 3.2 - Evolution of water absorption by capillarity with age.

The incorporation of CRCA in the shotcrete led to an increase of absorption by capillarity (Figure 3.1). This increase is a consequence of the higher w/c ratio, which is necessary to maintain the workability across all the mixes, and of the high porosity of the mortar adhered to the NA present in the CRCA. Figure 3.1 also reveals that the absorption by capillarity follows a linear relation with the CRCA ratio.

Figure 3.2 shows that the water absorption by capillarity developed mostly in the first hours after the concrete was in contact with water. There was a C20 increase of only about 5%. In this study, the absorption coefficient proposed by Browne (1991) was also calculated and all the mixes recorded high-quality classifications.

3.3.3. Chloride ion penetration resistance

The value of the chloride diffusion coefficient of the RC was similar to the one found by Santos (2011), i.e. around 13.1x10^{-12} m^2/s. Figure 3.3 shows that the chloride ion coefficient increased as the substitution ratio of CNA with CRCA increased. There is a linear relationship between these two variables that is demonstrated by the high correlation coefficient (0.99). This result can be explained by the high porosity of the mortar adhered to the NA present in the CRCA. The result may have also been influenced by the higher w/c ratio of the shotcrete with higher CRCA content. In Figure 3.3, it can be observed that at 91 days the diffusion coefficient was lower, meaning that there was higher resistance to chloride penetration with the increase of curing time. This effect is due to the higher volume of hydration products.

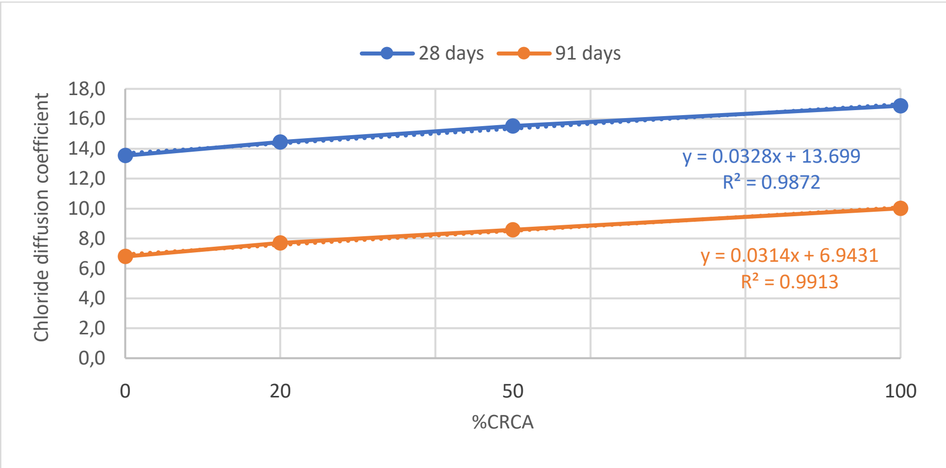

Figure 3.3 - Evolution of chloride diffusion coefficient with CRCA.

The classification suggested by Gjørv (2009) was used to evaluate the chloride penetration resistance. Using the results recorded for the chloride diffusion coefficient, at 28 days, only C100 obtained a low penetration resistance, while the remaining compositions presented moderate resistance. At 91 days, all the mixes presented high resistance. The shotcrete studied in this campaign had higher values of penetration resistance than those determined for cast concrete with RA (Soares *et al.,* 2015; Bravo, 2016). This may mean that shotcrete is less susceptible to chloride penetration. It was also determined that the chloride diffusion coefficient increased linearly as the water absorption by capillarity increased. This last relationship was also observed by Ferreira (2000) for cast concrete with RA.

3.3.4. Carbonation resistance

The results of this study for the RC at 91 days are quite lower than the values recorded by Santos (2011), which ranged from 8.20 mm to 18.50 mm, indicating a higher resistance to carbonation. This large discrepancy in results may be explained by a higher effective w/c ratio in the study conducted by Santos (2011).

It could also result from the difficulties experienced during the experimental campaign conducted by Santos (2011), such as the existence of gaps in various specimens and the inefficacy of the protective product used on the tops of the specimens.

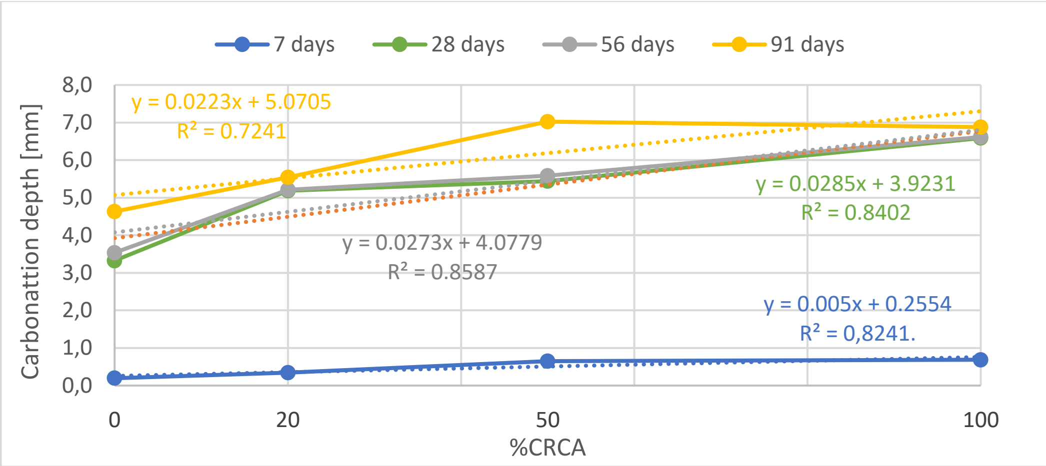

Figure 3.4 - Evolution of carbonation depth with %CRCA.

Figure 3.4 indicates that the depth of carbonation increased as the percentage of substitution of CNA with CRCA increased. This can be explained by the higher w/c ratio of the mixes with higher substitution ratio of CNA with CRCA, which is necessary to maintain the workability in all mixes. The higher water absorption by the CRCA compared to the CNA also leads to higher carbonation depths.

Figure 3.4 shows that the carbonation depth has a linear relation with the increase in the CRCA substitution ratio, which is confirmed by the value of R^2 that varies between 0.72 and 0.86. This relation is in line with the conclusions of Silva *et al.* (2015). Moreover, between 7 and 28 days there was a large variation in the depth of carbonation, which was no longer observed in the following time intervals, especially between 28 and 56 days, when the depth remained more constant. This happened because most of the hydration reactions had already occurred after 28 days. In fact, this is one of the advantages of shotcrete, i.e. although it does not achieve strength as high as analogous cast concrete, it has the ability to achieve higher strength in less time. It is noted that this trend has also been observed in compressive strength.

3.3.5. Shrinkage

The values obtained in the shrinkage test are presented in Table 3.4. Except for C20, shrinkage increased as the substitution ratio of CNA with CRCA increased. The results of the linear regression and the determination coefficient (0.86) suggest that the two properties have a linear relation.

The increase in shrinkage is justified by the increasing w/c ratio and by the lower modulus of elasticity of the CRCA, which reduces the capacity of concrete to restrict shrinkage (Whiting *et al.* 2012).

The higher value of RC when compared to C20 can be explained by the higher rebound effect observed in RC (around 27%), which led to a higher cement concentration as previously found by Armengaud *et al.* (2017). The studied specimens may have also been extracted from a zone of the panel in which the concrete had a higher effective w/c ratio. It is recalled that in the dry-mix process, the nozzleman can regulate the amount of water during the projection to maintain the workability. Figure 3.5 shows that the shrinkage followed a logarithmic function with time which proves that the shrinkage occurred mainly at young ages, after which the values tend to remain unchanged. This trend was also observed in most of research about cast concrete (Bravo, 2016; Cartuxo *et al.,* 2014; Whiting *et al.,* 2012).

Table 3.4 - Shrinkage test results.

Age [days]	RC		C20		C50		C100	
	[m/m]	Δ_{RC} [%]	[m/m]	Δ_{RC} [%]	[m/m]	Δ_{RC} [%]	[m/m]	Δ_{RC} [%]
7	-4.16E-04	-	-1.89E-04	-55	-4.21E-04	1	-5.19E-04	25
28	-5.36E-04	-	-4.23E-04	-21	-5.99E-04	12	-8.07E-04	51
60	-5.96E-04	-	-4.92E-04	-17	-7.90E-04	33	-8.58E-04	44
91	-6.26E-04	-	-5.14E-04	-18	-8.18E-04	31	-8.65E-04	38

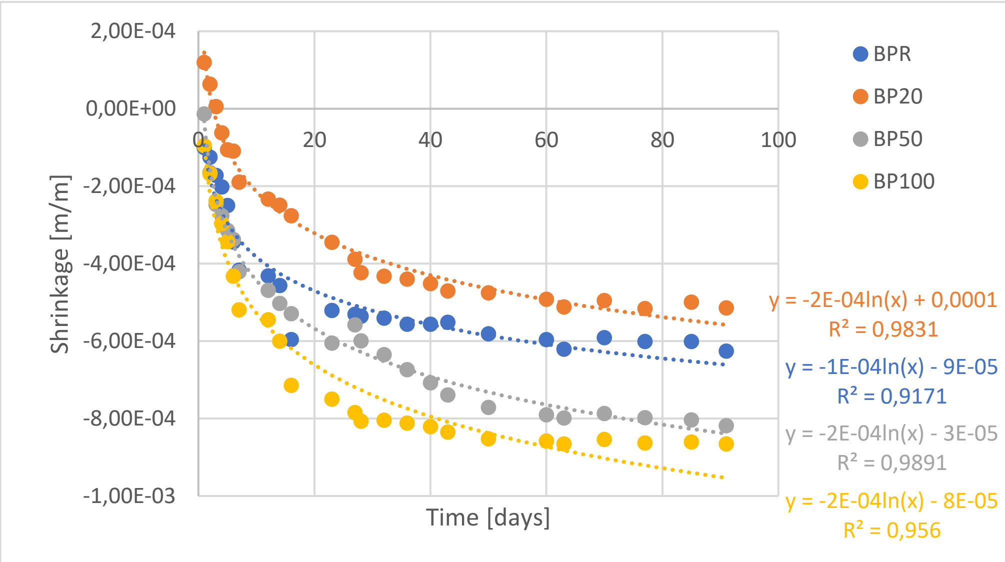

Figure 3.5 - Shrinkage evolution with time.

4. Conclusion

The aim of this experimental campaign was to study the durability of dry-mix shotcrete with incorporation of CRCA. The CRCA used in this study had lower values of density and coefficient of Los Angeles and higher water absorption, due to the mortar adhered to the original NA that were present in the CRCA.

As result of the higher water absorption of CRCA, it was necessary to increase the w/c ratio in the shotcrete mixes with higher percentage of CRCA, in order to maintain the workability.

It was possible to measure the rebound effect and there was a decrease in the amount of material lost as the percentage of CRCA increased.

Due to the greater w/c ratio, which is necessary to maintain the workability in the compositions with higher amounts of CRCA, and to the greater absorption of the CRCA, the absorption by immersion and capillarity of the shotcrete increased as the CRCA ratio increased.

The chloride penetration resistance and the carbonation resistance decreased for the same reasons, but the values remained at acceptable levels as evidenced by the comparison with the results of Gjørv (2009) and Santos (2011).

As expected, the most affected property was shrinkage, which presented relatively higher values than those obtained for analogous cast concrete. This effect resulted from the rebound effect, which led to an effective composition with a higher percentage of cement. The variation relative to RC observed in this study was similar to the variation recorded in previous research about cast concrete. This experimental campaign showed that the use of CRCA in shotcrete is feasible at the technical level but also at the economic level due to the reduction of the rebound effect. These findings are relevant and prove that it is possible to use CRCA in shotcrete. The use of this kind of aggregates may contribute to solve natural resources' shortages and waste management.

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