Mechanical performance of shotcrete produced with recycled coarse aggregates from concrete

Gonçalo Filipe Marques Duarte

Extended Abstract

Master’s Degree in Civil Engineering

Supervisors

Professor Doctor Jorge Manuel Caliço Lopes de Brito

Professor Doctor Miguel Nuno Caneira Bravo

Jury:

President: Prof. Doctor José Joaquim Costa Branco Oliveira Pedro

Supervisor: Professor Doctor Jorge Manuel Caliço Lopes de Brito

Member: Prof. Doctor João Carlos De Oliveira Fernandes de Almeida

May 2018

1. Introduction

The construction sector is one of the main players in environmental impacts generation. The build-up of construction and demolition waste, CDW, is responsible for 31% of the waste generated in the European Union (EEA, 2009). The increase in the world population also resulted in the generalised consumption of natural resources. To reduce the exploitation of natural aggregates, solutions with recycled aggregates have been studied as a way of making the sector more sustainable.

This study intends to contribute to the sustainability of concrete, since there is a tremendous lack of information concerning the application of recycled aggregates in shotcrete. With this investigation, it was possible to determine the technical viability of a solution of shotcrete with the incorporation of recycled concrete coarse aggregate, RCCA. The mechanical performance study was made in parallel with a campaign concerning the durability of shotcrete with RCCA.

Other experimental campaigns in Instituto Superior Técnico have been made to study the influence of RCCA on the mechanical performance of regular concrete, such as Ferreira *et al.* (2011), Fonseca *et al.* (2011), Ceia *et al.* (2016) and Soares *et al.* (2015). The major finding is a reduction of the mechanical properties, as a consequence of the adhered mortar present in the recycled aggregates, resulting in higher porosity and water absorption capacity. In terms of shotcrete, Santos *et al.* (2011) performed an experimental campaign concerning the performance of shotcrete, but only with natural aggregates. Chan (1998) tested regular concrete and shotcrete with full substitution of natural aggregates with recycled ones.

Although with a reduction in mechanical properties, RCCA are considered to have better performance in comparison with other types of recycled aggregates, such as ceramic ones.

The first step of this study was a national and international literature survey, in order to compile the knowledge on the topic of recycled aggregates and their influence on concrete, and the present state-of-the-art on shotcrete. Afterwards, the experimental campaign was performed, with the definition of different compositions to be analysed with the following ratios of substitution: 0%, 20%, 50% and 100%; the production of RCCA, the preparation of the panels, and finally, the concretization of the dry-mix process. After curing, specimens were extracted and the corresponding hardening properties determined. Finally, an analysis of the results was performed, comparing them with the literature.

2. Experimental procedure

2.1. Materials

The first step towards the experimental work consisted in the definition of the different materials required to produce all compositions. The materials used were the following:

- Natural aggregates: Fine and coarse sand, fine and medium-size gravel, since the maximum size of the aggregate was 12.5 mm;
- Recycled aggregate: coarse recycled aggregate from concrete produced in laboratory;
- Cement: CEM I 42.5R;
- Tap water.

2.2. Production of coarse recycled aggregates from concrete

In order to obtain the required coarse recycled aggregates, the following procedure was adopted:

- Assemblage of a form to receive the cast “in situ” concrete;
- Casting and vibration of concrete;
- Concrete curing for 28 days;
- Form removal;
- Crushing of concrete using a jaw crusher;
- Sieving of the resulting aggregates to 4-12.5 mm, using an aggregate sieve machine.

2.3. Concrete’s composition

Four concrete compositions were produced, each corresponding to a different percentage of substitution of NCA with RCCA. The replacement ratios were 0%, representing the reference concrete, 20%, 50% and 100%. The substitution used was by volume, resulting in less mass as the substitution of NA with RCCA increased. Table 1 presents the composition of the different mixes tested.

Table 1. Composition of the concrete mixes produced.

		Mixes composition [kg/m^3]			
		RC	C20	C50	C100
Coarse natural aggregates [mm]	12.5-10	243.53	193.99	120.71	-
	10-8	232.9	185.52	115.44	-
	8-6.3	242.81	193.42	120.35	-
	6.3-4	164.56	131.07	81.56	-
Coarse recycled aggregates [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			

2.4. Dry-mix shotcrete procedure

The process that precedes the dry-mix process was the following:

- Production of two panels per composition, each with 1.10m x 1.50m;
- Substrate concrete casting;
- Curing of the substrate concrete;
- Lifting the panels to a position close to vertical;

The dry-mix shotcrete procedure was as described:

- Mixing of cement with aggregates, using a concrete mixer;
- Placing of the mix in the first chamber of the projection machine;
- Opening of the second chamber;
- Air coming from compressor conducts the mix through the hose;

- Mixing with water at the tip of the hose and projection;
- Placing of the panels in the horizontal direction;
- Curing for five days and beginning of specimens' extraction.

2.5. Tests

The tests performed in aggregates were:

- Size grading: standard NP EN 933-1 (2000), NP EN 933-2 (1999);
- Density and water absorption: standard NP EN 1097-6 (2003);
- Bulk density: standard NP EN 1097-3 (2002);
- Los Angeles wear: standard LNEC E 237 (1970);
- Humidity content: standard NP EN 1097-5 (2011);
- Shape index: standard NP EN 933-4 (2002).

Table 2 shows the tests executed, in order to evaluate the hardened properties, in each shotcrete composition.

Table 2. Hardened properties of shotcrete.

	Age [days]	Number of specimens	Standard
Pull-off strength	40	3-5	NP EN 14484-4 (2005)
Compression strength	7	3	NP EN 12390-3 (2009)
	28	5	
	56	3	
Splitting tensile strength	28	3	NP EN 12390-6 (2003)
Ultra-sound pulse velocity	28	5	NP EN 12504-4 (2007)
Modulus of elasticity	28	3	Eurocode 2
Abrasion resistance	91	3	DIN 52108 (2002)

3. Experimental results and discussion

3.1. Aggregates properties

Aggregates represent most of the weight of concrete. They have an important function in its fresh and hardened properties. The incorporation of recycled aggregates in the mix is associated with a reduction in the mechanical properties and durability.

Table 3 represents the results obtained in the physical characterization of the different types of aggregates, used as part of the produced shotcrete.

As seen in Table 3, the density of RCCA is lower than that of fine and medium-size gravel, as a consequence of the adhered mortar in this type of aggregate, which also results in the increase of water absorption. The old mortar present in RCCA is also responsible for the increase of Los Angeles wear, since the resistance to fragmentation is negatively affected. The thinner and longer shapes of RCCA are the reason for higher shape index. In summary, it is possible to say that the RCCA have lower quality than the NCA.

Table 3. Properties of the aggregates.

	Fine sand	Coarse sand	Fine gravel	Medium-size gravel	RCCA 4-12.5
ρ_a [kg/m^3]	2587	2623	2708	2724	2658
ρ_{rd} [kg/m^3]	2548	2574	2634	2624	2370
ρ_{sss} [kg/m^3]	2564	2594	2661	2648	2478
WA_{24} [%]	0.59	0.71	1.02	1.65	4,55
ρ_b [kg/m^3]	1557	1544	1409	1406	1287
% voids	40.0	40.0	46.6	46.1	45,7
Shape index [%]	-	-	22.3	26.7	45
Los Angeles wear [%]	-	-	25		36

3.2. Fresh shotcrete characterization

Since a dry mix process was used in the production of concrete, it was not possible to control the water/cement ratio in the different compositions. However, it was feasible to determine to quantity of water used in each composition. In this way, the water/cement ratio was determined.

At this stage, the loss of material by rebound was also determined. This indicator is an indirect approach to the quality of the shotcrete, since rebound is associated with loss of coarse aggregates, and worsening of mechanical performance. Table 4 shows the results obtained from the shotcrete production.

Table 4. Shotcrete production results.

	w/c ratio	Rebound loss [%]	Δ_{BR} [%]
BR	0.46	27.27	-
B20	0.47	21.09	22.66
B50	0.50	26.14	4.14
B100	0.50	19.11	29.92

It is possible to observe that compositions with higher RCCA content also present higher w / c ratio, which was expected. In terms of rebound, a maximum reduction of approximately 30% was possible with the incorporation of RCCA in the mix, which is a positive result. This can be explained by the physical characteristics of these aggregates, such as the roughness, the lower density, and the increased capacity of water absorption, which tend to have a cohesive behaviour.

3.3. Hardened shotcrete mechanical performance

3.3.1. Pull-off strength

To secure the viability of the mechanical performance in any shotcrete, it is essential that the adhesion to the substrate is assured. Adhesion is one the most important properties in the process of evaluation of shotcrete. The values obtained in each composition are presented in Table 5.

There is no evident trend in these results, i.e. the incorporation of RCCA in shotcrete does not result in a clear tendency in the adhesion to substrate. Comparing with other studies, Santos *et al.* (2012) obtained values between 0.25 MPa and 1.12 MPa in a dry-mix process, and Seymour *et al.* (2011) obtained, after 91 days of curing, an average value of 1.58 MPa. It is stressed that this property was only studied by other authors using natural aggregates. The values obtained are higher than the minimum recommended value by ACI 506-05 (2005), which is 1.0 MPa.

Table 5. Pull-off strength.

% RCCA	F_t [kN]	σ_t [MPa]
0	2.18	1.11
20	2.11	1.08
50	2.17	1.11
100	2.23	1.14

3.3.2. Compressive strength

The compressive strength was determined after 7, 28 and 56 days of curing. The results in each composition are shown in Table 6. As expected, the incorporation of RCCA resulted in a reduction of this property between 20% and 30%. The lower strength of RCCA, related with its adhered mortar and easier propagation of micro-cracks, is the main responsible for the result. Figure 1 shows a clear correlation between these properties at the analysed ages.

Table 6. Compressive strength at 7, 28 and 56 days.

%AGRB	$f_{cm,7}$ [MPa]	S_d	D_{BR} [%]	$f_{cm,28}$ [MPa]	S_d	D_{BR} [%]	$f_{cm,56}$ [MPa]	S_d	D_{BR} [%]
0	18.27	1.50	-	37.18	2.43	-	43.24	1.52	-
20	17.72	1.54	-3%	33.83	2.97	-9%	36.58	2.00	-15%
50	15.99	3.69	-12%	30.35	3.30	-18%	35.77	3.43	-17%
100	14.09	0.43	-23%	27.25	4.71	-27%	31.91	3.26	-26%

Chan (1998) obtained a reduction of 56% in a dry-mix total substitution of fine and coarse aggregates. Comparing with concrete studies, Ferreira *et al.* (2011) obtained reductions around 17% for total substitution of RCCA, while Soares *et al.* (2015) achieved 28%.

Figure 2 shows the evolution of compressive strength with time for each composition. A major growth between 28 and 56 days in B50 and B100 is observed, showing a slower rate of hardening of cement, which may result in more time to stabilize the strength.

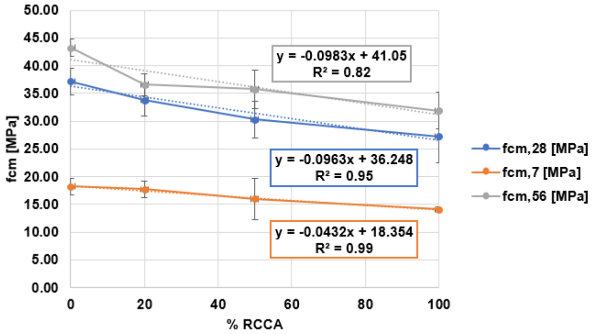

Figure 1. Compressive strength *versus* substitution ratio of NA with RCCA.

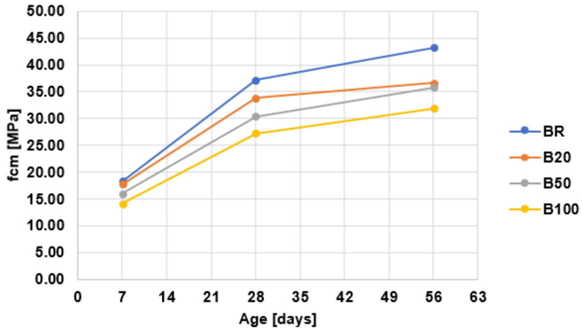

Figure 2. Evolution of compressive strength with age.

3.3.3. Splitting tensile strength

This property is referred to be less affected by the incorporation of RCCA than compressive strength, because it depends more on the bonding between different elements of concrete. In fact, the incorporation of RCCA may result in a better bond between the aggregate and the cement paste, since these aggregates are rougher and present more water absorption, leading to a more cohesive behaviour. The results obtained for this property are presented in Table 7.

Table 7. Splitting tensile strength.

%AGRB	f_{ctm} [MPa]	D_{BR} [%]
0	3.33	-
20	3.10	-7%
50	3.01	-10%
100	2.84	-15%

A maximum reduction of 15% is observed, which is clearly lower than that obtained in compressive strength, such as expected. These results are in conformity with those of authors that studied regular concrete, such as Pereira (2002) and Di Niro *et al.* (1998), with reductions between 20% and 30%, but lower in comparison with compressive strength. Some authors even obtained an increase in this property, such as Soares *et al.* (2015) and Fonseca *et al.* (2011). In terms of shotcrete, Chan (1998) obtained a reduction of 47%, which is lower than the corresponding reduction in compressive strength (56%). Figures 3 and 4 show the relation between splitting tensile strength and respectively the incorporation of RCCA, and the compressive strength.

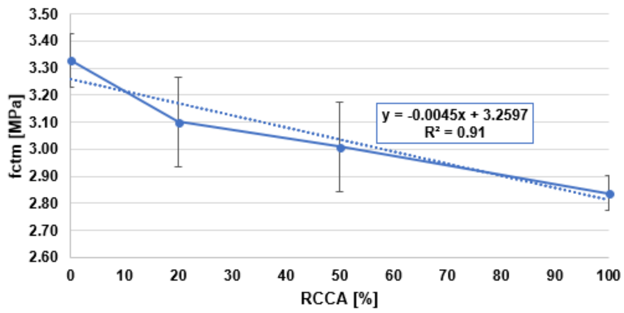

Figure 3. Splitting tensile strength *versus* substitution ratio of NCA with RCCA.

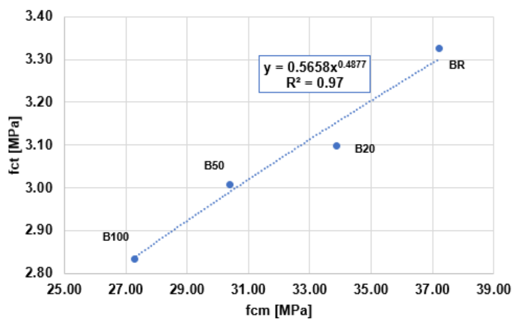

Figure 4. Splitting tensile strength *versus* compressive strength.

3.3.4. Ultra-sound pulse velocity

The ultra-sound pulse velocity represents an indirect measurement of the quality of concrete, since higher porosity is related with lower values of this property. This expectation was confirmed, since compositions with greater incorporation of RCCA resulted in lower ultra-sound pulse velocity, as shown in Table 8. The maximum reduction was around 7%, which agrees with other researches using regular concrete, such as Soares *et al.* (2015) and Santos *et al.* (2009), which obtained a maximum reduction of respectively 6% and 8%, respectively.

Table 8. Ultra-sound pulse velocity.

%AGRB	v_{us} [kms^{-1}]	D_{BR} [%]
0	4.82	-
20	4.79	-0.45
50	4.54	-5.66
100	4.48	-6.97

The relation between ultra-sound pulse velocity and incorporation ratio of RCCA is also clear, with a R^2 value above 0.85, showing a clear trend between these variables, as seen in Figure 5. The relation of this property with compressive strength was also analysed, as shown in Figure 6. In this study, there is an evident relationship between both them, with an R^2 value above 0.90, which is consistent with the fact that RCCA contributes also to the reduction of compressive strength. The lack of results of ultra-sound velocity test in shotcrete with recycled aggregates is stressed.

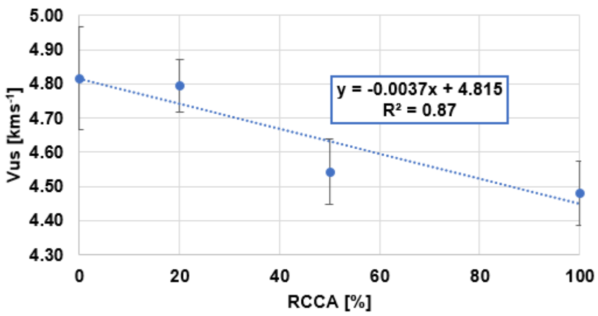

Figure 5. Ultra-sound pulse velocity *versus* substitution ratio of NCA with RCCA.

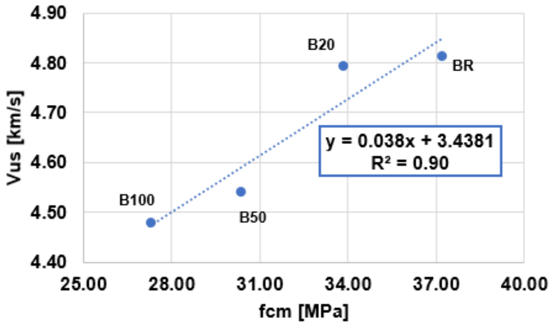

Figure 6. Ultra-sound pulse velocity *versus* compressive strength.

3.3.5. Modulus of elasticity

The modulus of elasticity is one the most affected properties since it is highly dependent on the composition of the aggregates present in the mix. RCCA are more deformable than NA, so it is expected that the resulting concrete also has greater deformability. The results of the modulus of elasticity are presented in Table 9. The incorporation of RCCA resulted in the decrease of the modulus of elasticity, such as expected. The maximum reduction observed was approximately 31%. Chan (1998) obtained a maximum reduction of 52%, using a dry-mix shotcrete process, which is consistent with the results obtained in the present study.

Table 9. Modulus of elasticity.

%AGRB	E_{cm} [GPa]	D_{BR} [%]
0	26.14	-
20	25.41	-2.79
50	24.34	-6.88
100	18.08	-30.84

A trend relating this property with the incorporation ratio of RCCA in concrete is observed in Figure 7, showing that the presence of adhered mortar in these aggregates results in the increase of the deformability of these aggregates, and consequentially that of the resulting concrete. The relation of this property with the compressive strength at 28 days was also analysed (Figure 8). A good correlation between these properties is observed.

3.3.6. Abrasion resistance

Table 10 shows the results in abrasion resistance in function to the substitution of NCA with RCCA. It is evident that the incorporation of RCCA resulted in less loss of thickness of concrete. This result can be explained with the properties of these aggregates. Although less resistant, their roughness is responsible for a better bonding with the cement paste, which is responsible for the positive results in this property. Similar observations were made by investigations concerning regular concrete, such as Ceia *et al.* (2016) and Soares *et al.* (2014) that also obtained better results with RCCA.

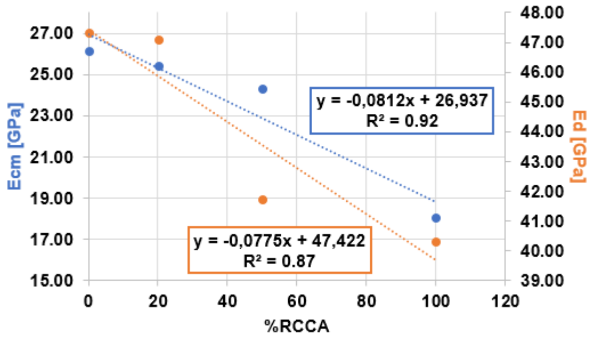

Figure 7. Modulus of elasticity *versus* substitution ratio of NCA with RCCA.

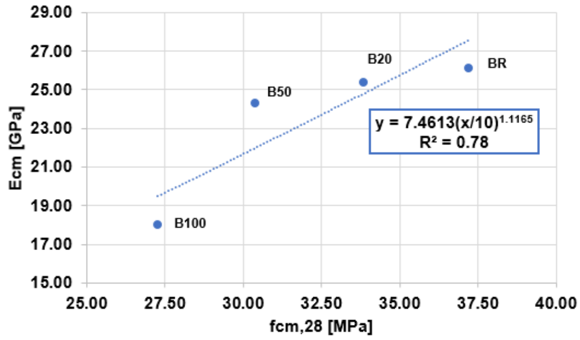

Figure 8. Modulus of elasticity *versus* compressive strength.

Table 10. Abrasion resistance.

	ΔL [mm]	ΔL [%]	D_{BR} [%]
0	**5.14**	**8.13%**	**0.00%**
20	**4.82**	**7.49%**	**-7.93%**
50	**5.01**	**7.73%**	**-4.94%**
100	**4.62**	**7.06%**	**-13.13%**

4. Application to tunnelling

With the results obtained in the experimental campaign, an application of the different compositions in structural substrates of tunnels was determined. The study case is a deep circular tunnel in rock massif, as described in Carranza-Torres (2000). In order to evaluate the interaction between the massif and the substrate, the converge-confinement method was used. The main components of this method are the ground reaction curve and the substrate characteristic curve.

Since the strength and the modulus of elasticity decrease with the incorporation of RCCA, it is expected that a solution with higher substitution of NCA with RCCA requires greater thickness of the tunnel walls. To study the increase of thickness needed to maintain the mechanical properties, two different types of solutions were analysed. The first one was based on a criterion of equal strength, $p_{s,máx}$ and the second one on an equal stiffness criterion, K_s.

Figure 9 shows the results obtained through both criteria. It is observed that a stiffness criterion results in a lower increase of thickness, of around 20%, which might be interesting from an economic point of view. It is important to refer that this example represents a circular tunnel subjected to an isotropic field stress. The consequence is that the tunnel walls are subjected to simple compression, resulting in a necessary increase of thickness close to the reduction ratio observed in the modulus of elasticity.

It is possible to conclude that the reduction of mechanical performance with the incorporation of RCCA can be compensated with a higher thickness, without compromising the deformability of the tunnel, proving its technical viability.

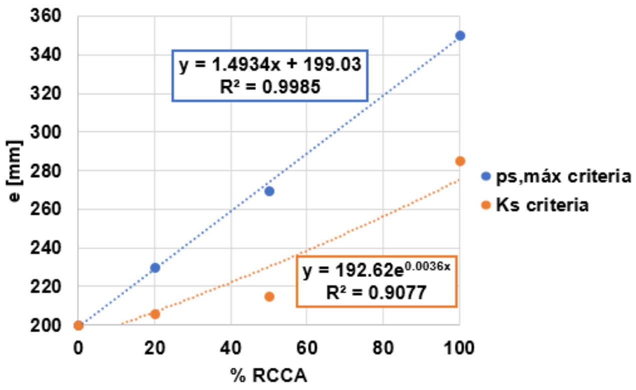

Figure 9. Variation of thickness with RCCA, required through both criteria.

5. Conclusion

This experimental campaign studied the influence of RCCA on dry-mix shotcrete. The main results are the following:

- Comparatively with natural coarse aggregates, RCCA have lower density, lower Los Angeles wear and higher water absorption because of the adhered mortar. The shape index was substantially higher in RCCA due to its longer and thinner shape;
- The pull-off strength test resulted in no evident relation between the pull-off strength and the incorporation ratio of RCCA;
- Compressive strength had maximum reductions between 20% and 30%, which were higher than those of splitting tensile strength, whose maximum reduction was 15%, and relates with a pattern of less influence of RCCA on the former property;
- Ultra-sound pulse velocity was reduced with the incorporation of RCCA, due to the higher porosity of these aggregates;
- Modulus of elasticity presented significant reductions, due to the higher deformability of RCCA, which is consistent with the literature;
- Abrasion resistance increased with the incorporation of RCCA, as a consequence of their roughness and shape that allows a better bond to the cement paste.

With these results, the technical viability of a dry-mix shotcrete solution with RCCA is proven, which is an important step towards its future application in work sites and a contribution to the sustainability of construction.

6. References

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