Evaluation of the performance of shotcrete in structural rehabilitation

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Abstract: Shotcrete is a continuous method of projecting concrete at high velocity, without the help of any formwork. This technique is being used, with great success, in the rehabilitation of reinforced concrete structures. The main advantages of using shotcrete, when compared with the use of regular concrete, are the flexibility, the compaction, the ability of adhesion to various materials and the remission of the formwork. The objective of this study is to characterize shotcrete in some of its most important parameters, named its mechanical and durability properties, which was achieved by running laboratory tests: compression tests, *pull-off* tests (bond strength), permeable porosity tests, accelerated carbonation tests and chloride ion penetration tests. Test panels with 1.90 x 1.90 m^2 were projected with two different dry mixtures of shotcrete, one with 350 kg/m^3 of cement and another with 450 kg/m^3. The panels were placed vertically and horizontally, to allow their projection in the horizontal and in the vertical (upwards direction), respectively. The rehabilitation works of a water reservoir slab where shotcrete was applied are also described.

KEYWORDS: shotcrete, dry-mix, compression resistance, carbonation, ion chloride penetration, bond strength.

1. INTRODUCTION

Shotcrete can be applied in almost all the cases in which conventional concrete is used. The choice of its use depends on the balance of many factors such as convenience, cost and the type of work. It is quite common to use this technique in new structures construction such as vaults, tunnels, canals, reservoirs and sewers. Another major area of application of shotcrete is the repair and strengthening of structures such as bridges, sewer systems, dams, walls, swimming pools, among others.

The sprayed concrete can be reinforced with fibers and is applied for conventional or refractory purposes. The fibers can be of steel or synthetic, like glass fibers and polypropylene, and its addition in concrete increases its resistance to bending, shear and impact.

Water reducers are commonly used in the wet-mix in order to improve workability without increasing the ratio a/c. Retarding admixtures are also used in the wet method and enable the extension of time working for the same mixture. Chemical-set accelerators may be implemented in both the dry-mix and the wet-mix processes (ACI 506R-05, 2005; Ryan, 1973). These increase the initial stiffness, which increases the productivity of the process by reducing the number of layers and may even increase the early strength of concrete. The disadvantage of using this type of additives is that some of them decrease the ultimate strength of concrete, so the dosage rates should be kept to a minimum.

Pozzolanic admixtures, like silica fume and fly ash, can be used in shotcrete. These materials provide a better workability to concrete, making it easier to pump in case of wet-mix process. In addition to that, they may provide more resistant to penetration of sulfates and to alkali-silica reactivity.

Shotcrete can achieve results quite competitive when compared with conventional concrete, in terms of cost, since it dispenses the assembly of formwork; in terms of mobility and accessibility, since the associated equipment is portable, it allows reaching inaccessible areas, and in terms of compatibility, since shotcrete has the ability to adhere to various materials such as concrete, steel and wood (Ryan, 1973). The main disadvantage comes from the rebound of coarse aggregates in shotcrete, which is affected by various factors like the speed of projection, the caudal projection, the distance and angle of impact, the thickness to be applied and, especially in dry-mix process, the operator's technical abilities (Ryan, 1973).

Shotcrete can be applied using two different methods: the dry-mix process and the wet-mix process. The main difference between these methods is that, in dry-mix process, the water is only added to the mixture in the nozzle, immediately prior to the application of shotcrete, while in the wet-mix method water is mixed with the other components in the beginning.
In terms of mechanical properties of shotcrete, specifically the bond strength and the compressive strength, it can be noticed that this material should develop a minimum value of 0.7 MPa for the tensile bond strength and for the compressive strength values between 40 to 50 MPa for the dry-mix process, and values between 30 to 50 MPa for the wet-mix (ACI 506R-05, 2005).
In the case of bond strength the substrate treatment is the determining factor in adherent ability between itself and the shotcrete, while the compressive strength depends mainly on the aggregates/cement (ag/cm) and water/cement (w/cm) ratios. The smaller the a/c ratio is, the more compact the concrete will be and, consequently, the greater its strength will be. In the case of dry-mix shotcrete, several authors indicate that it´s possible to achieve very low values for the a/c ratio, such as 0:35 to 0:50 (Cánovàs, 1984) or 0:30 to 0:40 (ACI 506R-05, 2005), while in the wet-mix process, the a/c ratio must be higher to give the necessary plasticity to concrete for their pumping. The volume of permeable voids is an important factor in the durability of shotcrete, making it more or less susceptible to phenomena like carbonation and chloride diffusion. Values between 14 and 17% are acceptable for permeable shotcrete void volume (ACI 506R-05, 2005).

2. EXPERIMENTAL CAMPAIGN

2.1. Composition of shotcrete mixtures

In the composition of shotcrete it was used Portland cement type CEM I 42.5 R, washed sand with two different dimensions and a gravel with 6.35 mm for maximum dimension. Applying the Faury method, two compositions of shotcrete were calculated. The results for each one of them appear below, in Table 1.

Table 1 – Shotcrete composition for the test panels.

	Units	Composition 350	Composition 450
Cement	kg/m^3	350	450
Sand 02	kg/m^3	632	614
Sand 04	kg/m^3	300	269
Gravel	kg/m^3	678	642
Water	l/m^3	123	158
a/cm	-	0.35	0.35
ag/cm	-	4.60	3.39

2.2. Execution of the test panels

Before the shotcrete application, test panels, with 1.90 x 1.90 m^2, were built. First, these panels were reinforced with an electro-welded steel frame and were filled with a concrete class C30/37 until they reach a thickness of about 8 cm, obtaining thus the concrete substrate. Besides that, it was also placed a geotextile over the surface of the panels, which was regularly wet, to hydrate the concrete.
Of the five panels produced, two were placed horizontally (Figure 2a), so that the projection was made from the upwards direction and the remaining panels were placed vertically (Figure 1b).

(a) *(b)*

Figure 1 – Painel direction: *(a)* horizontal and *(b)* vertical.

72 days after the substrate concrete application, two types of substrate treatment were performed: water washing (hydromilling) and chipping with jackhammers, as it's shown in Table 2. After that, all panels were filled with shotcrete layers until a thickness of 7 cm was reached. Finally the concrete hydration was done with the help of a geotextile cloth which was periodically wet with water. It should be noted that this activity was performed following the parameters listed in NP EN 14487-2.

Table 2 – Test panels identification.

Substrate treatment	Panel directon	Cement composition (kg/m^3)
Hydromilling	H	350
	V	350
		450
Chipping	H	450
	V	450

During the projection works, it was observed that the concrete was not being applied with the correct pressure. Only after the work was complete it was found that due to a clog in the oil filter, the machine did not create enough pressure in the chamber. The problem was resolved by changing the filter; however the test panels were already finished at the time.

2.3. Shotcrete characterization testing methods

2.3.1. Pull-off test

The pull-off test aims to assess the ability of adhesion between the coating layer, whether it is a mortar or a concrete, and the substrate. This test consists in the application of a tensile force perpendicular to the surface (Figure 2) and is regulated by the NP EN 14488-4. With a drill a circular part is cut up to the base material, in order to define exactly the measuring surface. Then a metallic disc is glued to the lining of reinforcement with a resin glue. (Austin, *et al*., 1995; ASTM D7234, 2005).

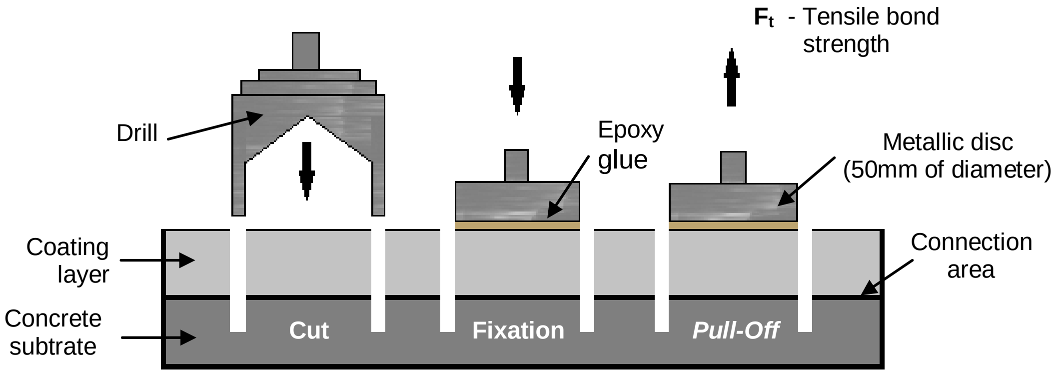


Figure 2 – Schematic representation of the of pull-off test phases.

Three types of scenarios may occur while executing a pull-off test and they are described in detail in Table 3.

Tabel 3 – Classification and description of the pull-off scenarios.

Typology	Failure mode	Description
A	Adhesive	Rupture through the interface between the shotcrete and support
B	Cohesive in the reinforcement concrete	Rupture in the shotcrete
C	Cohesive in the substrate concrete	Rupture in the subtstrate concrete

2.3.2. Compressive strength test

The compressive strength test consists of a gradual application of load at a constant speed, on the whole contact surface of the specimen, until the ultimate load is achieved. All tests were performed according to NP EN 12390-3. To determine the compressive strength of shotcrete two types of study were performed in parallel: one on cores extracted from test panels, according to NP EN 12504-1, and another on cubes whose filling was carried out by spraying or pouring.
Due to the replacement of the display of the compression machine used in the core tests (mortars compression machine), and the ignorance of the fact that the machine hadn't been calibrated after this repair, tests performed at 28 days may have been influenced by this mishap.
The tensile strength of cylindrical specimens for compression, f_c, was calculated according to Equation (1).

$$f_c = \frac{F}{\frac{d^2}{4}\pi} \; (MPa) \qquad (1)$$

With:
- F – ultimate compressive load (N);
- d – average diameter (mm).

To determine the compliance of the cores compressive strength it was used the NP EN 14487-1 parameters, which states that to assess the compliance of the concrete on the compressive strength at 28 days, for a number of results between 3 and 14, one has to verify two criteria:

1st Criterion: $f_{cm} \geq f_{ck,is} + 4$ (2)
2nd Criterion: $f_{ci} \geq f_{ck,is} - 4$ (3)

With:
- $f_{ck,is}$ – minimal characteristic compression resistance *in situ*;
- f_{ci} – individual result of tensile strength for each test ;

f_{cm} – average tensile strength of "n" results.
The cube tests were conducted in a compression testing machine for cubes, with a loading speed between 0.2 to 1.0 Mpa/s (Coutinho, *et al.*, 1994). The cubes compression tensile strength, fc, was calculated according to Equation (4).

$$f_c = \frac{F}{A}\ (MPa) \quad (4)$$

Com:
F – ultimate compressive load (N);
A – load aplication area (mm^2).

To define the compliance of the compressive strength of the cubes the NP EN 206-1 parameters were observed, which states that to assess the compliance of the concrete on the compressive strength at 28 days, for a number of results n = 3, one has to verify two criteria:

1st Criterion: $f_{cm} \geq f_{ck} + 4$ (5)

2nd Criterion: $f_{ci} \geq f_{ck} - 4$ (6)

2.3.3. Accelerated carbonation resistance test

Shotcrete accelerated carbonation resistance was determined by the method presented in the specification LNEC E391. This method consists on measuring the depth of the carbonation front of samples introduced into a chamber with a high concentration of CO_2 and with controlled atmospheric conditions. For this test five cores, with 100 mm of diameter, were extracted from each test panel, at 35 days of age. To protect the flat faces of cylindrical specimens a metacrylic varnish was applied, so that the carbonation progress was made mainly in the radial direction. Subsequently, the specimens were introduced in the accelerated carbonation chamber, with the following exposure conditions: temperature at 26°C, 60% of relative humidity and CO_2 content of 5 ± 0.5%. It was measured the depth of carbonation front which is identified by the line that separates the non-carbonated concrete that, due to phenolphthalein, is rose-carmine, from the carbonated concrete.

2.3.4. Chloride penetration resistance test

To determine the chloride diffusion coefficient into concrete, it was followed the specification LNEC E 463, which is based on the application of an electrical potential to the top of the specimen to force chloride ions transportation through the concrete (migration).
The test specimens were obtained from a drilling 100 mm cores from the test panels as indicated in the standards, and were set-up in the test tank as is presented schematically in Figure 3.

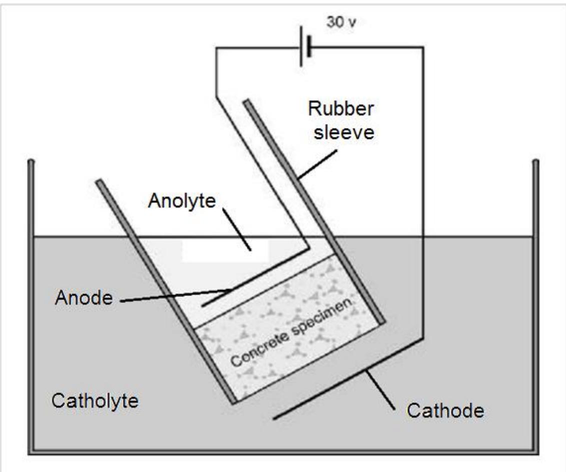


Figure 3 – Migration test set-up (Stanish, *et al.*, 1997).

Using the collected data from the chloride penetration test it was calculated the non-stationary-state migration coefficient from the simplified Equation (7):

$$D = \frac{0.0239(273+T)L}{(U-2)t}\left[x_d - 0.0238\sqrt{\frac{(273+T)Lx_d}{U-2}}\right] \tag{7}$$

With:

D – non-steady-state migration coefficient [x10^{-12} m^2/s];
U – absolute value of the applied voltage[V];
T – average value of the initial and final temperatures in the anolyte solution [ºC];
L – thickness of the specimen [mm];
x_d – average value of the penetration depths [mm];
t – test duration [h];

2.3.5. Porosity determination by water absorption

The determination of the water absorption by the hardened concrete at atmospheric pressure was made by following the LNEC E 394 specification, which proposed method is based on calculating the difference between the mass of hardened concrete specimen immersed in water and mass of the same specimen when dry.
Water absorption by immersion (A) is calculated in percentage by the following expression:

$$A_i = \frac{m_1 - m_3}{m_1 - m_2} \times 100 \tag{8}$$

With:

m_1 – mass of saturated specimen (g);
m_2 – hydrostatic mass of the saturated specimen (g);
m_3 – mass of the dry specimen (g).

3. Experimental campaign results

3.1. Adhesion of shotcrete to the substrate

The results for the pull-off test for the four cases in study are summarized in Table 4. Regarding the types of rupture tests, all of them were type B (Table 5), with the exception of some cases where the breach took place by the glue making them invalid tests. It was still possible to observe different aspects of the rupture surface, which are divided into two groups: those showing a good mix of the constituents of sprayed concrete and those who showed signs of insufficient connection between the aggregates. The test series 450 H and 350 H are example of the later, the rupture apparently occurred due to poor water mixing with the remaining elements of concrete or cement disability.

Table 4 – General characterization of the pull-off test results in MPa.

	Chipping		Hydromilling	
	450 H	450 V	450 V	350 H
Average	1,12	0,80	1,25	0,25
Standard deviation	-	0,06	-	-
Minimum value	0,20	0,76	1,22	0,10
Maximum value	2,04	0,87	1,27	0,41

Table 5 –Classification of the pull-off specimens rupture type.

Panel	Provetes	1	2	3
450 Horizontal Chipping	Rupture	B	Glue	B
	Surface Appearance	Insufficient mixing	-	Good mixing
	T (MPa)	0,20	(0,76)	2,04
450 Vertical Chipping	Rupture	B	B	B
	Surface Appearance	Good mixing	Good mixing	Good mixing
	T (MPa)	0,76	0,87	0,76
450 Vertical Hydromilling	Rupture	Glue	B	B
	Surface Appearance	-	Good mixing	Good mixing
	T (MPa)	(1,07)	1,27	1,22
350 Horizontal Hydromilling	Rupture	B	B	Glue
	Surface Appearance	Good mixing	Insufficient mixing	-
	T (MPa)	0,41	0,10	(0,46)

3.2. Compressive strength

Cores were extracted from test panels with a 45 mm drill and three series of tests were ran at 7, 15 and 28 days of age, each one with 10 cores. The cubes were executed in 15 x 15 cm^2 casts, and tested at 28 days after curing for 5 days at the construction site, then at a humid chamber at 20 ° C for 23 days

Due to the replacement of the display of the compression machine (mortars compression machine) and the ignorance that the machine hadn't been calibrated after the repair, the results from the cores tested at 28 days age may have been influenced by this mishap.

There are presented in Table 6 the tests results for the compressive strength at ages 7, 15 and 28 days. The results were rounded to 0.5 MPa as the NP EN 12504 standard dictates.

Table 6 – Compressive strength results of the cores MPa.

Panel	Age (days)	Specimens number	Final average	Standard deviation (δ)	Minimum value	Maximum value
			(rounded to 0,5 MPa)			
350 V	7	9	23,5	3,0	20,52	28,70
	15	9	24,0	3,0	19,68	26,92
	28	10	23,5	3,0	19,08	27,78
350 H	7	7	21,0	2,0	18,33	23,21
	15	8	26,0	5,0	20,46	33,03
	28	10	26,5	2,5	23,26	30,16
450 V	7	7	23,5	6,0	16,98	32,25
	15	10	26,5	3,0	23,13	30,05
	28	9	25,0	4,0	18,09	30,89
450 H	7	10	26,0	5,0	19,84	32,98
	15	10	29,0	4,0	24,24	34,50
	28	9	30,0	3,0	25,26	34,51

To get an idea of the values that would possibly be achieved at 28 days (if the incident with the machine displays hadn't occurred), it was established the trend of increasing resistance of the tests performed at 7 and 15 days with a logarithmic regression (Figure 4). The choice of the regression type was based on the fact that in previous studies it was the one which better described the resistance increase over time.

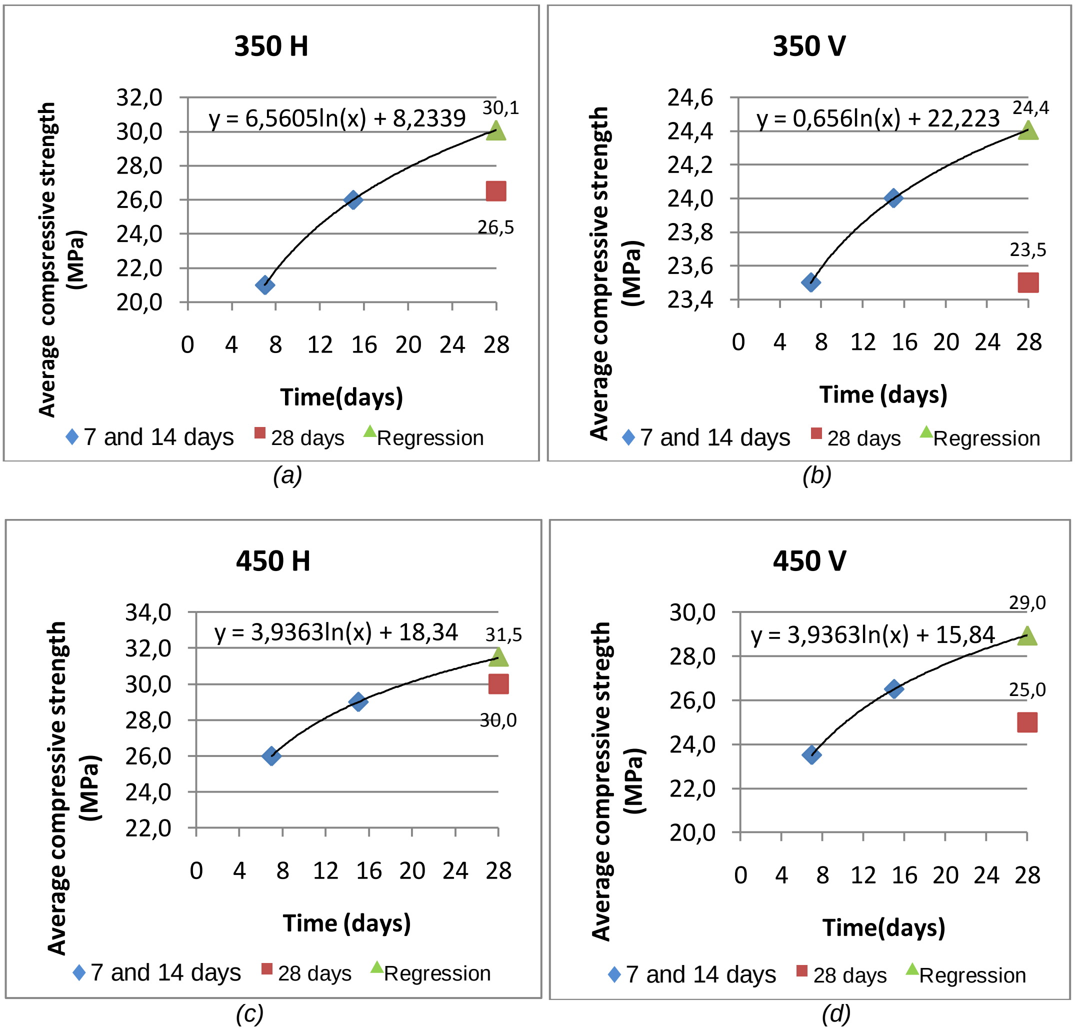


Figure 4 – Growth rate of the average compressive strength for each test panel.

The cores verification of compliance is presented in Table 7. In Table 8 shows the results for the average compressive strength on cubes with 450 kg/m^3 of cement and also their compliance analysis for class C30/37.

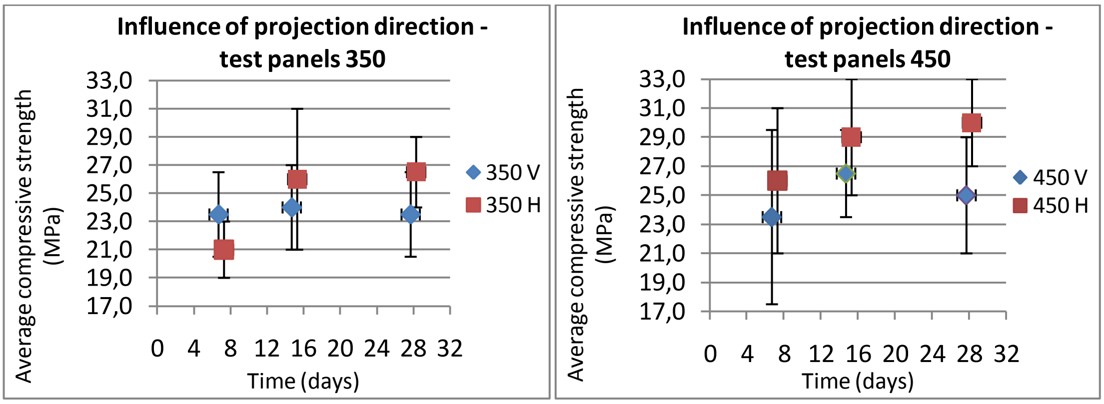
Table 7 – Verification of compliance for the tested cores.

Series	1st Criterion		2nd Criterion	
	$f_{cm} > f_{ck,is}+4$		$f_{min} > f_{ck,is}-4$	
350 V	23,5	35,0	19,08	27,0
350 H	26,5		23,26	
450 V	25,2		18,09	
450 H	30,0		25,26	

Table 8 – Average compression strength values for tested cubes (rounded to 0.5MPa) and its compliance analysis

Cubes	1º Criterion		2º Criterion	
	Average tension	$f_{ck}+4$	Minimum value	$f_{ck}-4$
450 projected	30,50	41	26,15	33
450 casted	44,50		43,40	

The analysis regarding the influence of projection direction in shotcrete compressive strength is done in Figure 5.



(a) (b)

Figure 5 – Influence of the projection direction in shotcrete compressive strength for shotcrete mixtures (a) 350 e (b) 450.

3.3. Accelerated carbonation resistance

Three sets of carbonation depth readings were performed after 36, 76 and 93 days of exposure in a carbonation chamber. In the first set five specimens of each type of sample were tested, the second time 3 samples were measured and, in the last measurement there were used 2 pieces of each sample were used. Figure 6 shows the linear variation of uniform carbonation thickness for each series according to the square root of exposure time on the carbonation chamber. It was also applied a linear regression for each series to determine the accelerated carbonation constant k.

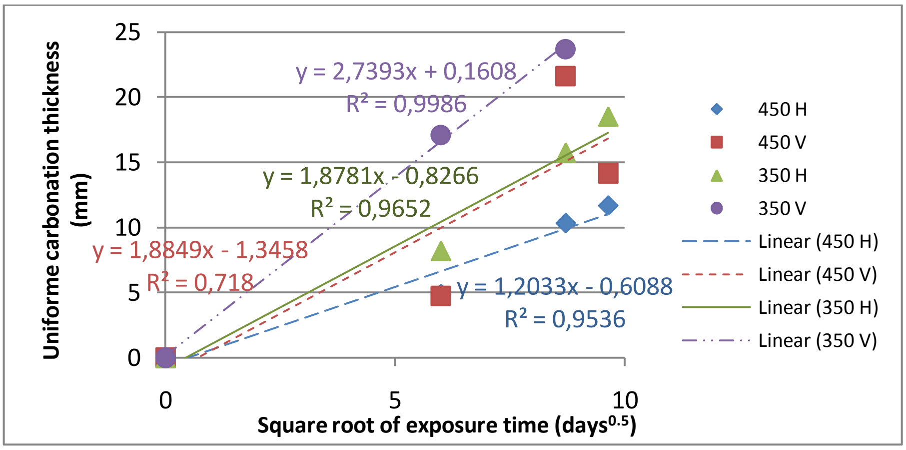


Figura 6 – Variation of the uniform carbonation thickness with de square root of exposure time.

3.4. Chloride penetration resistance

There were performed three specimens with 100 mm diameter and approximately 50 mm thickness for each mixture under study. The results obtained for the chloride diffusion coefficient of each sample is shown in Figure 7.

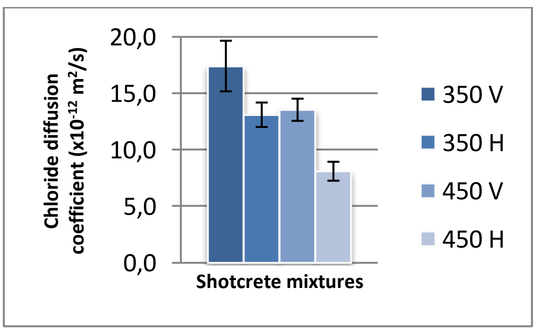


Figure 7 – Chloride diffusion coefficient.

3.5. Determination of porosity by water absorption

Only two specimens per shotcrete mixture, with 100 mm diameter, were tested, instead of the three recommended by the specification, because this test was not foreseen in the initial plans and so it was used the remaining specimens of other tests. The results for the percentage of water absorption of each sample are presented in Table 9.

Table 9 – Results for the percentage of water absorption of each shotcrete mixture.

ID		m_1 (g)	m_2 (g)	m_3 (g)	Absorption (%)	Average absorption (%)
350 H	1,1	988,4	553,7	934,2	12,5	12,8
	1,2	1101,7	612,5	1037,9	13,0	
350 V	2,1	689,4	390,3	650,1	13,1	12,9
	2,2	791,6	449,0	748,1	12,7	
450 H	3,1	1084,0	616,5	1025,2	12,6	12,9
	3,2	848,1	481,0	799,9	13,1	
450 V	4,1	778,8	447,1	738,9	12,0	12,8
	4,2	759,4	430,0	714,5	13,6	

4. CASE STUDY

4.1. Description

In parallel with the study presented earlier, it was possible to follow a rehabilitation work of a slab in which shotcrete was used. SAMS Oeiras and Amadora was the owner of the project: "Restoration of Brandoa Medium Reservoir" which was undertook by the company H Tecnic, Ltd. One of the tasks involved the reparation of the bottom side of the tank top slab, in which shotcrete was applied after its reinforcement with A 400NR, 12 mm diameter steel (Figure 8).

Figure 8 – Application of shotcrete on the bottom side of the top slab, which was previously reinforced.

Shotcrete was designed for resistance class C30/37 and exposure class XD1 with 350 kg/m^3 of cement. The batching of the shotcrete components by volume, cement/gravel/coarse sand/fine sand was 3:6:2:3 and was also added polypropylene fibers and silica fume with concentrations of 600 g/m^3 and 14 kg/m^3, respectively. For shotcrete quality control, two test trays were carried out according to NP EN 14488-1. The tests made with the extracted cores, were run at 20 and 28 days old. Cubes were also casted with two different compositions: one with polypropylene fibers and silica fume, and another with only the polypropylene fibers. The compression test for these specimens was run at 28 days old, according to NP EN 12390-3.

4.2. Results and discussion

The results for the cores compressive strength were obtained from 10 samples and are presented in Table 10. The compliance check for these specimens is performed on Table 11 while in Table 12 is presented the values for the cubes compressive strength and its compliance verification.

Table 10 - results for the cores compressive strength.

Age (days)	Average compressive strength	Standard deviation (δ)	Minimum value	Maximum value
	(rounded to 0,5 MPa)			
20	43,5	5,0	35,1	49,1
28	47,5	3,0	43,7	53,0

Table 11 – Compliance verification for the extracted cores.

Criteria of compliance					
1st Criterion			2nd Criterion		
$f_{ck,is} + 4 < f_{c,med}$			$f_{ck,is} - 4 < f_{c,min}$		
35,0	<	47,5	27,0	<	43,7

Table 12 - Values for the cubes compressive strength and its compliance verification.

Cubos	1st Criterion		2nd Criterion	
	$f_{c,med} \geq f_{ck}+4$		$f_{c,min} \geq f_{ck}-4$	
Fibers	41,0	41	40,4	33
Fibers + Sikafume®	44,0		39,1	

The average compressive strength for the cores specimens is conform to the required class (C30/37) and is superior to the result obtained for the cubes of the same age (28 days) and the same composition (fiber + Sikafume ®), which can be explained by the fact that the projection enhance the concrete compaction. Comparing the values obtained for the cubes compressive strength it is possible to conclude that for the same content in cement and fibers, cubes with silica fume have higher resistance, furthermore it was observed that with this component the projection process was more profitable because it reduces the rebound loss, hence less waste.

5. Conclusion

5.1. Mechanical properties: bond and compression strength

- The higher the value of bond strength is, the greater is the cement content on shotcrete. The bond strength is the highest in the panels that were projected from upwards direction. This occurrence might be explained by the fact that to achieve the same thickness of shotcrete in both projection directions, more layers were applied to the horizontal panels then the vertical ones, which may have enhanced the compaction of the concrete on these panels.
- In absolute terms, all the values for the bond strength were higher than the recommended theoretical minimum (0.7 MPa), with the exception of the 350 H-Hydromilling specimens series.
- The hydromilling substrate treatment is the process that leads to the highest bond strength.
- Shotcrete is the determinant component since all the valid ruptures occurred in this element, which makes the shotcrete traction strength responsible for the test panels' bond resistance. This means that, in any case, the substrate treatment was enough to bear no responsibility in the rupture.
- The reliability of the bond strength test results was a little poor since the 450 H-Chipping values are not statistically conclusive. This could be improved with the increase of the tests quantity.
- The compressive strength increases with the increment of cement content in shotcrete and has higher values for the cases when shotcrete was applied in upwards direction. In terms of absolute values, the extracted cores compression tests were all below the level defined by the strength class C30/37, i.e., they weren't conform. This fact maybe explained with the problems that occurred during the projection operation. To reinforce

this hypothesis, in the study case the projection was made after the gun was fixed resulting in compliant values of compressive strength with the strength class.

5.2. Durability: porosity, carbonation and chloride penetration

- To the same conditions and time of exposure the thickness of carbonation increases with the decreasing cement content and shows higher values for the vertical panels cases (horizontal projection). As for the speed of the carbonate propagation in the concrete it appears that the greater is this value, the lower is the cement content in the mixture and shows higher values for the horizontal projection direction (vertical panels).
- It was observed that the results for carbonation resistance have a linear behavior with the square root of time, as expected. The variability of results is quite low in all cases except for 450 V.
- The chloride diffusion coefficient increases with decreasing cement content and shows higher values for shotcrete projected horizontally.
- Comparing the porosity results with the expected value (14% to 17%), it appears that all of them are slightly below the minimum. With this fact it could be deduced that all the specimens had good compaction but the results for carbonation and chloride penetration indicate that, for the same composition, the vertical panels have lower durability, which shows that these shotcretes are more porous. In fact, as previously mentioned, the porosity test was executed with only two specimens of each composition, and the results were all very close between different compositions. Thus, we conclude that the porosity test leaves some doubts about the representativeness of reality, and the conclusions obtained from accelerated carbonation tests and chloride penetration are more reliable.

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