Use of wet-mix shotcrete in the repair of reinforced concrete structures

Case study of a rehabilitation work in a marine environment

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Wet spraying consists of the continuous application of ready-mixed concrete shot from a nozzle under compressed air onto a substrate, without the use of formwork. Setting time may be highly influenced by the use of accelerators in mix design. Adhesion to the substrate is directly related to its roughness. This dissertation is based on the follow-up of a rehabilitation work, consisting of concrete repairs in a marine environment, where the substrate had two distinct chipping zones and the coating was rebuilt with wet sprayed concrete. It was intended, through the experimental study of samples collected *in situ*, to determine the influence of the substrate chipping method on the adhesion and the influence of the dosage of accelerator admixture on the mechanical and durability properties of the new concrete. Positive substrate molds were produced, digitalized and modeled in 3D, in order to quantify the roughness of the substrate. After concreting, pull-off tests were performed at the same sites, and the results were compared with roughness values. Shooting test panels made out of three types of concrete, containing accelerator dosages of 3%, 5% and 7% of the binder mass were produced and drilled for core extraction. The cores were tested for compression, accelerated carbonation and chloride penetration. It was concluded that the substrate chipping with pneumatic hammer produces higher concrete-to-concrete bond strength than substrate resurfacing with double drum cutter heads. On the other hand, no linear correlation could be established between the accelerator dosage in shotcrete mixture and compressive, carbonation and chloride penetration resistence.

1. Introduction

Concrete spraying has become an important and a widely used construction technique, subject to continuous research to develop materials, equipment and make application procedures more effective [1]. This technique consists of transporting concrete through a hose and projecting it at high-speed onto a surface, avoiding the use of formwork.

The projection gives concrete a compaction that makes it more mechanically resistant to chemical attacks from chlorides, carbonation and freeze-thaw cycles. Shotcrete can often be used as an alternative to molded concrete, depending on convenience and cost. The technique offers advantages over conventional concrete in a variety of new construction and repair works and it is particularly convenient when the use of formwork is impractical, when access to the work area it is difficult, when thin or variable thickness layers are required (or both) and when traditional molding techniques cannot be employed [1].

Despite the increasing use of shotcrete in national works and the increase in the number of companies offering this service, national documentation on the subject is scarce and leaves unanswered questions related to certain properties of the material or with the application of the technique. Therefore, there is a reason for the scientific community to study and document the most relevant works or those with the most peculiar characteristics, in order to dissipate doubts about the properties and application of the material, namely in the rehabilitation of reinforced concrete structures built in a marine environment; here the damage may manifest itself in the form of delamination of the concrete cover, corrosion of the reinforcement steel by wave action abrasion, chemical attack due to carbonation and chloride penetration. These problems can occur in most marine structures, such as bridge platforms, piles, columns, beams, piers, dry docks, dams, lighthouses and tunnels, where, in many cases, shotcrete can be used to repair surfaces of deteriorated structures [2].

Thus, the present dissertation was motivated by the opportunity to follow the rehabilitation work of the dry dock of the naval base of Alfeite (Almada), which included, amongst other works, the repair of the concrete cover of the walls using wet-mix shotcrete. The study program was developed together with the company H Tecnic, speciallized in rehabilitation of built heritage and streigthening of structures, and adapted to the stage of the on-going works. This document aims to evaluate the influence of the substrate preparation on the adhesion of the wet-mix shotcrete cover, as well as the influence of the dosage of setting accelerator used in the mixture in compressive strength and durability, in particular, resistance to carbonation and chloride penetration. The study was carried out aiming at optimizing two aspects: i) the type of substrate chipping to be adopted in order to guarantee the best adhesion of new concrete and ii) the optimum dosage of accelerator for use in future works in marine environment. The study methodology consisted of collecting samples in situ and in the production of samples in the real conditions of the work, which were later subjected to laboratory tests. The results were documented and analyzed, based on the theoretical concepts related to the state of the art.

2. State of the art

2.1. Wet-mix process for shotcrete

The wet-mix shotcrete process is represented in Figure 1. It involves pumping previously prepared concrete or mortar, usually ready-mixed concrete (including fibers and water reductors), into the nozzle (Figure 1-1). The mixture is transported by the hose (Figure 1-2), under pressure, to the projection noozle, where addicional air is introduced (Figure 1-3), in order to increase the projection speed. Liquid accelerator is pumped into this airway (Figure 1-4). The concrete mix, extra air and accelerator meet at the noozle, where high speed projection occurs (Figure 1-5). This process typically produces less rebound, waste (when the material falls to the ground) and dust compared to the dry mixing process. A great advantage of the wet mixing process is that it allows the placement of larger volumes of concrete in less time [1, 3].

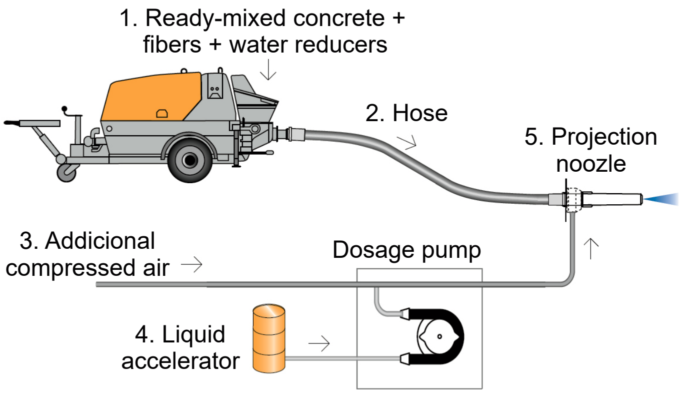

Figure 1 - Scheme of equipment and procedures involved in wet-mix shocreting, adapted from [1, 4].

The design of a mixture for shotcrete seeks the best performance, not only in terms of strength and durability, but also in terms of workability and rebound rate of the material, factors directly dependent on by the water introduced in the mixture. On the other hand, the wear of the equipment and the guarantee of the penetration of the projected concrete between the bars of the existing reinforcement are aspects directly dependent on the granulometry of the aggregates used. It is therefore extremely important, before starting any concrete work, to carry out a study of the composition of the concrete, which should include information about the origin of the components, granulometric analyzes of the aggregates supplied, technical data sheets of the cement, additives and admixtures, as well as such as the results of the compressive strength tests (target stresses f_{cm} at 7 and 28 days of age) and the results of the slump test to check the consistency. On the other hand, due to the rebound, the previous composition of the projected concrete are normally not faithfully reproduced in the concreted surfaces. Therefore, compression strength tests and durability tests (penetration of chlorides and carbonation) are important to understand the performance of the existing material. In order to avoid damage to the newly casted structure, it is recommended to design test panels and collect cores for this purpose [1, 3]. As a general rule, the commonly adopted methodology for determining the compositions for conventional concrete can be applied to shotcrete, and the materials can be designed either by volume or weight. As an example, the consequences of the wet-mix spraying process regarding material losses are shown in Figure 2: 1000 liters/2310 kg of fresh concrete, result in 897 liters/2119 kg of applied material. The causes of losses are rebound (in weight and volume) and compaction (in volume), although the addition of setting accelerator contributes (residually) to an increase in weight and volume. It is concluded that wet-mix shotcreting increases density in applied material, compared to fresh concrete [4].

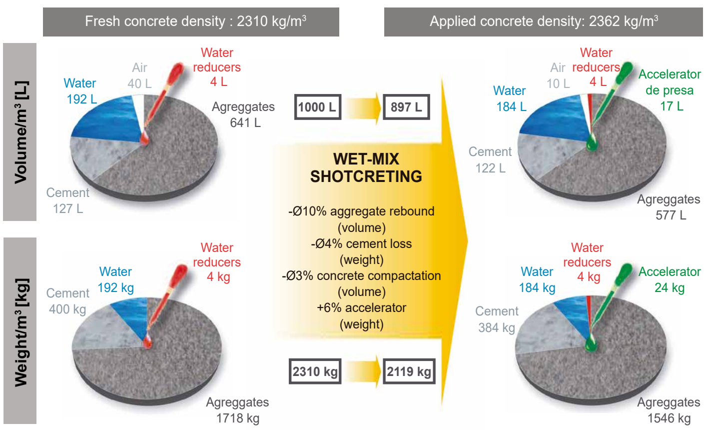

Figure 2 - Material loss in wet-mix shotcreting.

2.2. Adherence

In a concrete-concrete connection, adhesion is a mechanism of physical and chemical nature, being mainly governed by the roughness of the contact surface, the application method and the composition of the new concrete mixture. The connection between the shotcrete and the substrate will be as good as the quality of the two contact faces [4, 5]. In the case of rehabilitation of cover concrete, the surface must be rough, free from loose elements and be moistened to avoid the absorption effect of dry concrete. The strength of the cleaning operation depends on the internal cohesion of the substrate and the need for water depends on the moisture inherent to the adherent surface. All loose, cracked, deteriorated, chipped, damaged, porous and contaminated concrete (chlorides, carbonation and chemical attack) is completely removed. If in doubt, the old concrete should be removed [4, 6]. Another determining factor in the adhering capacity of new shotcrete to old concrete is their composition. The evaluation of the adherent capacity is determined through the direct tension force through the pull-off test. According to ACI 506R-05 [1], shotcrete must develop a minimum tensile strength of 0.7 MPa. When the projection is adequate and ensures sufficient compaction on a well-prepared substrate, a bond strengh of more than 1 MPa generally develops. Test results for dry and wet mixtures, conducted on different types of concrete substrates, indicated that the composition of the sprayed concrete mix has less influence on adhesion than surface preparation. Regarding the classification of substrate roughness, the current design codes and regulations for reinforced concrete structures, such as Eurocode 2, ACI 318-05 and CSA-A23.3-94, propose design expressions to determine the strength to the longitudinal shear of the interface between concrete layers with different ages. Common to all these expressions is its qualitative assessment, which is usually classified as very smooth, smooth, rough, or very rough [7]. However, the examples provided are far from covering all practical applications, with obvious limitations, such as the failure to consider explictly the application of concrete by spraying. For this reason, the logical development of design expressions consists in replacing the qualitative approach to surface roughness with a quantitative approach. In view of the lack of a consensually accepted test to measure the texture of a surface (or "roughness"), several methods have been used to overcome the lack of standardized measuring equipment [7]. The Sand Patch Test, defined by EN 1766, is the simplest quantitative method for assessing the texture of a surface and consists of spreading a known volume of calibrated sand evenly over the surface. Despite being an economical and easy method to perform, both in situ and in the laboratory, it is limited to horizontal surfaces and only allows to characterize the macro-texture of the surface. Other equipment, such as the Circular Track Meter (CTMeter), proposed in ASTM E2157, or the Digital Surface Roughness Meter (DSRM), consists of a laser sensor attached to a camera. The control software allows obtaining information about the surface texture using digital image analysis and calculating several numerical parameters. Another approach is presented by the Slit-Island Method which consists of covering the surface with an additional layer of filling material and then polishing it parallel to a plane. By removing successive layers, several "islands" appear, which grow and group together. For each contour line located at different elevation planes, the area and perimeter of each "island" is determined and the area/perimeter ratio is represented in a log-log graph. Adjusting a linear regression to the set of points, it is possible to determine the fractal dimension and different values of surface roughness. Another method, called the Roughness Gradient Method, was proposed by Abu-Tair *et al.* [7] to characterize the texture of a surface; it allows to determine the surface roughness profile using a texture meter, consisting of 500 needles with a diameter of 0.8 mm and spaced 1.0 mm apart, being allowed to fall freely on the concrete surface. The profile formed by the needles is then photographed. By enlarging the photo, it is possible to make more accurate readings and the roughness profile is then defined by a series of irregular waves, the roughness parameter being dependent on the peak-valley depth and the respective wavelength. Finally, the development of the Laser Rugosimeter equipment aimed to overcome the limitations encountered with the previous method. This method allows obtaining profiles of the substrate surface texture, which can then be numerically defined using roughness and ondulation parameters, based on surface characteristics, such as the height and spacing between peaks and valleys. Bearing in mind that there are numerous and different approaches, it is necessary to continue the studies and create a database, statistically significant, before proposing an expression of design that replaces the current qualitative approach of design codes and regulations [7].

2.3. Compressive strength resistence

Like conventional concrete, shotcrete has three time windows for the development of compressive strength: 1) the initial development, 2) the period when the concrete is considered young, and 3) the period when the final resistances begin to stabilize. For the first two periods, that is, up to 24 h after application, the compressive strength is assessed using indirect methods *(in situ)*, namely the Penetrometer Method and the Stud Driving Method (from the manufacturer Hilti). Both methods use equipment that, through the penetration of a needle or threaded screw, respectively, correlates depth with resistance to penetration. Regardless of any recommendation given by the respective documents (NP EN 14488-2 and Hilti brochure), it must be taken into account that any correlation function between the result values and the actual compressive strength will only be an approximation. Finally, the compressive strength of hardened concrete (after 24 h) is tested through compression tests (destructive) carried out in a laboratory environment. The tests can focus on molded concrete cubes or cylinders (pre-projected ready-mixed concrete), or samples from cores taken from projection panels, performed when projecting on site. In Portugal, the compressive strength assessment is regulated by the standard NP EN 206-1 for the test of molded cubes and cylinders and by the NP EN 14487-1 for the core test [4, 8, 9].

2.4. Carbonation resistence

Carbon dioxide exists in the atmosphere with a proportion of 0.03% by volume or 0.04% by weight of air, corresponding to approximately 0.5 mg per liter of air. These values may vary due to local conditions, not only vegetation and other biological factors, but especially due to the pollution caused by combustion in large cities and industrial centers. Carbonation consists of the reaction of this carbon dioxide in the air with concrete compounds, mainly calcium hydroxide. Although it does not cause concrete deterioration, its effects are important, as the loss of alkalinity leads to the depassivation of rebars, exposing the steel to corrosion [10].

The diffusion of a component results from the tendency of different concentrations to balance and is the main mean of transference of carbon dioxide that originates the carbonation of concrete. This phenomenon occurs slowly from the outside to the inside through the unsaturated pores of the concrete. The concentration gradient is due to the reaction of carbon dioxide (mainly) with hydroxides of the hydrated cement mass. The reaction occurs only in the presence of water, that is, the diffusion of carbon dioxide occurs through the water film (which covers the walls of the concrete pores) up to its surface, where it combines with the hydroxides. Consequently, carbonation does not occur in completely dry concrete, nor in fully saturated concrete, where access to the carbon dioxide is prevented. As the process takes place, the calcium hydroxide in the hydrated cement mix becomes calcium carbonate, with a lower pH and therefore the concrete carbonation (it is possible to start with a pH of around 12.5) produces a decrease in alkalinity, that can reach values below 9 when the concrete becomes fully carbonated. Under these conditions, the steel rebars undergo depassivation and risk of oxidation and corrosion. The formation of iron oxide is an expansive process that, in addition to causing the loss of the rebars cross-section, leads to the development of tensile stresses in the concrete, resulting in fractures that cause delamination [10, 11, 12].

The carbonation front is the limit line of the zone where carbon dioxide has reduced the alkalinity of the concrete to pH values below 9. The distance of this line to the surface is defined as the depth of carbonation. The distinction between "healthy" concrete and carbonated concrete is achieved by spraying the material with an acid/base indicator, with phenolphthalein being the most commonly used. Concrete with a pH greater than 9 (alkaline) will have a carmine pink color, while in media with a pH less than 9, phenolphthalein will remain colorless [13]. High carbon dioxide concentrations are used in experimental tests that speed up the concrete carbonation process. To determine the carbonation coefficient, the accelerated carbonation test, regulated in Portugal by the LNEC E391 specification, is used. The test consists of inserting concrete specimens into a chamber with controlled temperature, humidity and CO_2 content. The results provide the values for the carbonation depth and the exposure time, allowing the calculation of the accelerated carbonation coefficient K_a [13].

2.5. Chloride penetration resistence

In a marine environment, the penetration of chlorides into the concrete can be processed by three different mechanisms: a) diffusion due to differences in chloride concentration; b) absorption of water with chlorides by capillary suction or cracks; or through c) permeation for pressure differences and, in special conditions, for electro-emigration for differences in electrical potential [14]. In the case of a new shotcrete, sufficiently compact and without cracks, the diffusion phenomenon is the most important. It occurs in the water film that lines the surface of the larger (unsaturated) pores and in the water of the saturated pores, the former always having a film of water molecules absorbed on its surface and the latter (usually micropores) will exist in greater or lesser quantity. The relative humidity of the air influences both the thickness of the water film in the unsaturated pores and the amount of micropores. The greater this thickness and the more micropores are saturated, the more intense the diffusion process will be. In the case of total immersion, the penetration into water concrete with chlorides occurs primarily due to the absorption mechanism and, most likely, by pressure differences (permeation). The movement of water and the consequent transport of chlorides dissolved in it will continue only if there is evaporation on concrete surfaces exposed to air. The speed of water transport through the concrete pore and crack network will then depend on the relationship between the evaporation rate, capillary suction and hydraulic pressure. The chloride content on the concrete surface tends to increase considerably in environmental conditions where the concrete is subjected to alternating drying and wetting cycles with chloride contaminated water. At the beginning of the wetting, the dissolved chlorides penetrate the concrete by capillary absorption, passing some of them to the cementitious paste by diffusion, and during drying, they remain inside the pores fixed by absorption, together with water molecules that form the film which lines the interior of the pores (even if the relative humidity is low). The chloride ion diffusion process therefore continues even in the drying period, albeit at a different rate. In the next wetting period, with the penetration of more water with chlorides, the ions absorbed and not yet diffused into the paste increase the concentration of chlorides on the pore surface and the diffusion process to the interior is more intense. Thus, the chloride profile is, in general, different for alternating wetting / drying conditions or conditions in which the relative humidity is approximately constant [10].

For the evaluation of the performance of a shotcrete against the penetration of chlorides, it is possible to use the migration test in a non-stationary regime, regulated by the LNEC E463 specification [15]. The method requires cylindrical specimens with a diameter of 100 mm and a height of 50 mm, obtained from cylinders extracted from projection panels, with a minimum length of 100 mm. The test consists of applying an electrical potential between the tops of the specimen, immersed in a NaCl solution. Through migration, the generated current will force the transport of chloride ions through the concrete. After a certain test period, the specimen is broken and, similarly to the determination of the carbonation depth, it is sprayed. In this case, with a silver nitrate solution. The solution will react with the contaminated concrete, resulting in a visible silver chloride precipitate, white in color, the depth of which corresponds to the penetration of a given chloride content. Based on this measurement, and on the Fick's laws of diffusion, it is possible to calculate the chloride diffusion coefficient for the tested concrete [15].

3. Case study

Located in Almada and integrated in the Lisbon Naval Base, the dry dock at Arsenal do Alfeite was built about 40 years ago. It is an enclosure dug on the south bank of the Tagus River in order to receive one or more vessels simultaneously for inspections, manufacture, cleaning or construction (Figure 3).

Figure 3 - General view of Arsenal do Alfeite dry dock (view from West).

Regarding the concrete vertical walls of the dry dock, pre-rehabilitation inspection revealed several types of anomalies such as rebar corrosion and concrete cracking and delamination, with special incidence on wedges along access stairs, on concreting joints and above the level of high tide. Also, several water entry points, divided in two types: point water inlets and water inlets associated with waterstop systems, located in the expansion joints close to the bottom slab.

The main deterioration mechanism in progress was associated with the electro-chemical corrosion of the rebars, being the origin of this process, most likely, the depassivation resulting mainly from the migration of aggressive agents (carbon dioxide and chlorides) to the interior of the concrete sections. The depassivation of the rebars can be explained: i) by the carbonation front having reached their depth, ii) by the chloride content having reached the critical value, that is, the value necessary to sustain a localized damage of the passivation film or iii) both cases. The age of the dry dock and the severe conditions of exposure to the wetting and drying cycles provided by the filling and emptying of the dock, possibly associated with less compacted concrete areas (which usually occur at the edges of the elements and at the joints of concreting), together with insufficient concrete cover, have promoted the extensive and profound damage observed.

To determine the depth of the contaminated concrete, and the consequent thickness of the cover to be repaired, two tests were performed *in situ*: i) carbonation test (determination of the carbonation depth) and ii) Rapid Chloride Test - (determination of the chloride penetration depth). Both are based on drilling the concrete to be tested. In the case of the carbonation test, after being cleaned using compressed air, the perforated area was sprayed with a phenolphthalein solution. Using a graduated ruler, the carbonation depth was measured, delimited by the color contrast. In the case of testing for the presence of chlorides, drilling was carried out at different depths and the resulting powder was collected and subjected to tests to determine whether or not there was contamination of the concrete. The test was done by reacting the powder with a silver nitrate solution. The results led to two concrete repair zones. Consequently, two areas of the dry dock wall were considered for demolition purpuses (Figure 4): i) the surface that is mostly exposed to air (Zone 1) and ii) the one that is predominantly immersed in sea water (Zone 2). For each zone, a different demolition process was adopted, each one with its type of chipping. It was found out that Zone 1 had greater number of pathologies (concrete delamination) than Zone 2. With the criterion of removing the deteriorated cover until healthy concrete was found, a deep chipping of about 7 cm was adopted, as as a general rule, for Zone 1 and a superficial chipping of about 3 cm for Zone 2. Consequently, the chipping in Zone 1 exposed the concrete rebars, unlike the chipping in Zone 2. In all vertical walls of the dry dock, all the degraded surface concrete was removed, eliminating the existing traces of corrosion. The chipping of Zone 1 was done using a pneumatic hammer operated remotely, in order to bypass the rebars, avoiding their degradation, and also minimizing the damage to the healthy substrate concrete [1]. The chipping of Zone 2 was performed using a milling head applied in a mini rotary track. The use of the milling machine was justified by the possibility of operating at ground level up to a height of 5.5 m (approximately) and by the production of small diameter residues, without excessive vibration in the surrounding area [36]. After the surface preparation, the entire area subject to repair was cleaned using a water jet machine, in order to remove all loose materials, as well as any contamination elements, including oils, paints, dust, debris, concrete curing agents and similar products [16].

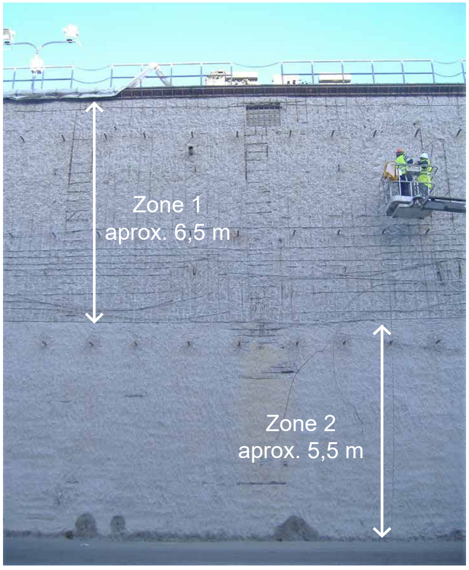

Figure 4 - Location of the chipping zones.

The composition of the concrete used in the reconstruction of the sections of the structural elements was specially designed to guarantee the following characteristics: high compressive strength, high tensile strength, low shrinkage, good adhesion to the existing concrete and high resistance to chloride penetration [38]. Mix design consisted of the following parameters:

(i) The hydraulic binder used was a mixture composed of Portland cement CEM II / AL 42,5R and fly ash, equivalent to a cement type CEM IV with suitability established in the LNEC E-464 specification [40] and in table 1 of NP EN 197-1 [16]. The CEM II / A-L 42.5R cement used is of the trademark SECIL, from the Outão plant and the fly ash was supplied by CPPE from the Sines plant. The dosages used were 408 kg/m^3 of cement and 72 kg/m^3 of fly ash, resulting in a binder dosage of 480 kg/m^3;

(ii) Three aggregates were designated, in ascending order of granulometry: Thin Sand, Coarse Sand and Limestone gravel 0.5;

(iii) Water for the manufacture of concrete was supplied from the existing recycler at the plant and the water/binder ratio used was 0.375;

(iv) The maximum dimension of the aggregate is 6.30 mm.

(v) In a fresh state, the concrete mixture tested at the plant, presented 200 mm in the slump test, classifying it in the workability class S4. In order to prevent the consistency from being lower than what is recommended by the concrete specification, the use of water-reducing adjuvants were used. Simultaneously, the plasticizer CHRYSOPLAST 775, from the manufacturer CHRYSO, in dosages of 2.40 kg/m^3, and the superplasticizer GLENIUM SKY 511, from the manufacturer BASF, in dosages of 4.32 kg/m^3, were used according to the dosages recommended in the respective technical sheets [17, 18].

vi) In the production plant, FIBTEX polypropylene fibers were added to the concrete mix in order to increase the tensile strength and reduce cracking [16].

vii) In the projection nozzle, the MEYCO SA172, chloride free, alkali-free setting accelerator from BASF was added. As for the dosage, the manufacturer [19] recommends 5 to 9 kg per 100 kg of cement, which is equivalent, respectively, to 5% and 9% of the mass of binder used. However, the accelerator "may be sensitive to the type of cement", namely that "the setting characteristics may be too slow with some type II-III cements", precisely the type of cement used. Recommendations also include carrying out preliminary tests to determine the optimal dosage. In this sense, and given the academic nature of this dissertation, the opportunity was given to study in greater depth the influence of the setting accelerator on the mechanical properties of the overlay concrete and its durability. Samples with different dosages of accelerator were produced and a test plan was carried out to determine the optimal dosage of the adjuvant. This study is part of the experimental campaign. Notwithstanding, the context of the work implied taking an early decision regarding the dosage of setting accelerator to be used. Taking as main considerations the workability, the efficiency, the percentage of rebound, the costs and the manufacturer's recommendations, the dosage adopted was 33.6 kg of accelerator per m^3 of concrete, equivalent to 7% of the binder mass. The accelerator container was connected to the dosing pump that is part of the projection apparatus in order to be pumped by compressed air to the projection nozzle.

According to Costa *et al.* [20], the durability of reinforced concrete structures exposed to the marine environment is essentially affected by the penetration of chlorides into the concrete. In the case of a dry dock where one of the surface areas is immersed in sea water and the other exposed to air, the LNEC E464 specification [21] stipulates that the exposure class to be considered is XS3 - Tidal zone, from surf and splashing. For the exposure class considered, and taking into account that the binder used is equivalent to a cement type CEM IV, the specification also indicates that the minimum dosage of cement to be used is 380kg/m^3, which corresponds to a minimum class of concrete strength C35/45, a minimum cover of 45 mm and a maximum water/binder ratio of 0.45. The cement dosage used and the applied coating thickness are higher than the minimum values recommended by the aforementioned standard and the water/binder ratio is within the required maximum limit. The designation of the supplied concrete is therefore NP EN 206-1: C35 / 45 S4 Dmax 6.30 XS3 (PROJ.).

A U2 class finish, usually called a "trowel" finish, was performed. For the dosage of 7% of used setting accelerator, material losses by ricochet occurred in the order of 25%. The material wasted in the projection is considered to be contaminated concrete, having been collected and treated as waste. The curing of the concrete started immediately after projection and was guaranteed by sprinklers installed on the guardrails at the top of the dry dock walls, ensuring continuous wetting. The sprinklers were programmed to water for 7 consecutive days, in order to obtain a certain impermeability of the surface area of the concrete and to avoid cracking due to shrinkage. The process took place during December and included the atmospheric conditions characteristic of the season (rain and high relative humidity). The maximum temperature of the concrete during hardening remained below 70 °C and the difference between the temperatures of new and existing concrete was below 12 °C. The temperature difference between the center of the mass and the surface remained below 20 °C, in order to avoid surface cracking caused by the heat developed in the concrete.

4. Experimental study

The objectives defined consisted in the evaluation of: i) the influence of the substrate preparation method on adhesion; ii) the influence of the setting accelerator dosage on the compressive strength and durability in terms of carbonation and chloride penetration in the wet sprayed concrete.

4.1. Test plan and sampling

Table 1 presents the summary of the test plan carried out, the testing facility where each test was performed, the quantity, format and the age of the concrete tested, as well as the respective standard followed.

Table 1 - Tests plan.

Test	Testing facility	Number of samples		Sample shape	Concrete age	Standard / norm
3D scanning / modeling and calculation of the substrate interface area	*In situ:* Alfeite's dry dock	Zone 1	7	Prismatic plaster reproductions (12 x 12 x 4) cm^3	-	-
		Zone 2	7			
		Total	**14**			
Adhesion (pull-off)	*In situ:* Alfeite's dry dock	Zone 1	7	Ø=50 mm tablets	73 days	NP EN 14488-4
		Zone 2	7			
		Total	**14**			
Compression resistence	IST Laboratory	[1]AC3%	12	Ø=75 mm / h=75 mm cylindrical cores	3, 7 and 28 days	NP EN 12504-1 NP EN 12390-3
		AC5%	12			
		AC7%	12			
		Total	**36**			
Accelerated carbonation resistence	IST Laboratory	AC3%	15	Ø=100 mm / h=75 mm cylindrical cores	344 days	LNEC E 391
		AC5%	15			
		AC7%	15			
		Total	**45**			
Cholide penetration resistence	IST Laboratory	AC3%	3	Ø=100 mm / h=75 mm cylindrical cores	485 days	LNEC E 463
		AC5%	3			
		AC7%	3			
		Total	**9**			

[1] *AC3% stands for Accelerated Concrete with 3% accelerator dosage. Tested samples are identified with this nomenclature.*

The developed test plan required two types of samples: i) positive substrate molds to determine the areas of influence A_i; and ii) cores of the various concrete compositions (cylindrical) for the compression strength tests, carbonation and chloride penetration. In the latter case, test panels were produced during the concrete projections of the dry dock walls. The panels were then cured, drilled and the cores were transported to the IST laboratory to be rectified according to the requirements of the tests. For the first case, 7 areas were defined in each of the chipping zones. The criterion for choosing these areas was the absence of rebars, since the site would be, after the shotcreting, the target of the pull-off adhesion test. In total, 14 positive molds were made, with internal dimensions 12 x 12 x 4 [cm^3]: 7 corresponding to Zone 1, where the chipping was carried out using a pneumatic hammer, and 7 corresponding to Zone 2, where a chipping was applied with milling head. The location of each mold was previously defined and noted, in order to serve as a guide and allow the rigorous performance of pull-off tests, in the same location of each mold, after shotcrete application of the new covering concrete. Each of the 14 areas were reached using an elevating platform. In each area, a frame with a plasticine ball was applied. The plasticine was then pressed manually until it filled the frame boundaries. The frame and the pressed plasticine were carefully removed, revealing a negative mold of the substrate surface. Then, the negative plasticine mold was placed back inside the frame, with the rough surface facing upwards. Using these molds, positive prismatic plaster reproductions of the chipped surface were produced (Figure 6). Plasticine was brushed with release oil in order to facilitate the separation of the plaster material (Figure 4.2).

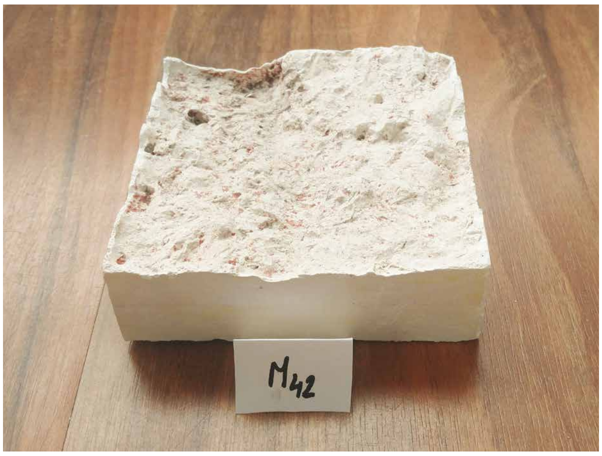

Figure 6 - Positive prismatic plaster reproductions of the chipped surface.

Regarding the concrete samples needed to perform the compression tests, carbonation and chloride penetration resistance, three processes were performed: i) the execution and curing of the test panels (Figure 7); their ii) drilling and their iii) rectification, to meet the requirements of the test standards.

Figure 6 - Shotcrete test panel being shot.

4.2. 3D scanning/modeling and interface area

It was intended to determine an area of the substrate that could be in contact with the new concrete. Within the scope of the present experimental study, this parameter was defined as the *interface area* and is considered a measure of roughness quality and, even so, it is the area where the applied tension in the pull-off test is distributed, in the cases where rupture occurs through the concrete-concrete interface. To determine this parameter, an experimental procedure was performed, since there is no adequate standard for the conditions inherent to the nature of the vertical walls of the work in question. In fact, the Sand Patch Test, defined by EN 1766, is limited to horizontal surfaces. On the other hand, it was not possible to access the Circular Rail Meter (adopted in ASTM E 2157), the DSRM (Digital Surface Roughness Meter), the Laser Rugosimeter, or any equipment used to perform the Gradient Roughness Method. Thus, a 3D scan of the positive surface reproductions was made and, through the use of 3D modeling software, a simplified adaptation of the Slit-Island Method (or area-perimeter analysis) was applied.

The interface area considered corresponds to the surface area of the mold contained in the 45 mm diameter circumference (corresponding to the core diameter used in the pull-off tests), centered at the point of intersection of the two diagonals of the sample bounding square, dimensions 12 x 12 [cm^2]. This test consisted of: i) 3D scanning of the plaster reproductions of the surface, using a 3D scanner of high resolution (up to 0.5 mm) and high precision (up to 0.1 mm); ii) in modeling the 3D images using Blender and Solidworks software by intersecting a cylindrical volume, 45 mm in diameter (corresponding to the core diameter resulting from the pull-off test), with the scanned image of sample (Figure 7) and iii) isolating the resulting surface and calculating its area (interface area A_i).

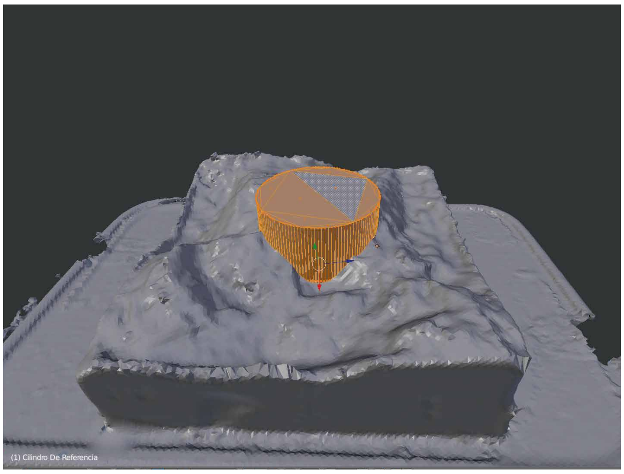

Figure 7 - Scanned image of surface reproduction, intersected with a cylindrical volume of Ø45 mm.

4.3. Adhesion - pull-off test

The adhesion of the shotcrete to the substrate was determined through the pull-off test. The purpose of this test is to evaluate the adhesion force of a concrete coating of layer by determining the greatest perpendicular force that the cross-sectional area of a partial drilled core can withstand, before the separation of a layer occurs. The failure occurs along the weakest plane of the system composed of the metallic insert and the layers of substrate, coating and adhesive (epoxy resin) [4]. The test was carried out according to standard NP EN 14488-4 [22]. The values obtained were evaluated in relation to the nature of the failure mode and classified as belonging to one of the three types: a) failure in within the adhesive layer (epoxy resin), for the special case in which no information is obtained about the connection between (new and old) concrete layers; b) failure through the adhesive/cohesive interface, which corresponds to the bond strength between the two concrete layers (directly associated with surface preparation method) and c) failure whose surface is not entirely in the connection zone (substrate or covering concrete), which means that the bond strength is greater than the final stress value obtained in this case [22]. Only values resulting from failure modes b) and c) were considered valid.

4.4. Compression strength

The compression strength test was carried out in accordance with NP EN 12390-3 [23] and consisted of applying a gradual load to the cores of hardened concrete, until their rupture, in a compression testing machine, in accordance with NP EN 12390-4.

4.5. Accelerated carbonation resistance

The test of resistance to accelerated carbonation had the objective of evaluating the performance of the three concretes with different dosages of setting accelerator and to evaluate their effectiveness as covering materials, in relation to the CO_2 penetration resistance. The test was carried out according to the LNEC E 391 specification [13] and was based on the measurement of the carbonation depth, which is the average distance measured in millimeters, from the concrete surface to the carbonation front, in the concrete samples exposed to CO_2, in a chamber with CO_2 inlet/outlet and humidity and temperature control.

4.6. Chloride penetration resistance

The resistance to chloride penetration was quantified by the diffusion coefficients in the different types of concrete, which, in turn, were determined by the non-stationary migration test. The analysis of the results of this test provides information on the evolution of penetration over time, the influence of the quality of the concrete and the conditions of exposure on the penetration speed. Using the LNEC E 465 specification, it is possible to estimate the service life of the concrete, regarding chloride attack.

For this test, the specification LNEC 463 [15] was followed, which has the principle of applying an electrical potential between the tops of the specimen, forcing the transport of chloride ions through migration through the concrete. The test took place inside the dry chamber of the IST Construction Laboratory, whose temperature is controlled, allowing the test pieces and solutions to be kept between 20ºC and 25ºC.

4.7. Results and discussion

4.7.1. Surface preparation influence on concrete coating adhesion

The results of the tests to calculate the interface area of the substrate, as well as the pull-off tests, allow to conclude that:

i) The pneumatic hammer chipping method, which produces higher and more homogeneous interface areas than the milling head method, is associated with higher pull-off tension values, suggesting that the surface preparation using this method contributes to a greater adhesion of the covering concrete to the substrate;

ii) Chipping of the substrate with a pneumatic hammer generated better areas of interface when compared to the chipping with a milling head. However, the difference between the areas generated is not significant (2.6%). Thus, the use of the preparation method with a milling head is justified in Zone 2 due to the accessibility of the mini track swivel up to the 5.5 m elevation, avoiding the use of lifting means, thus allowing a higher efficiency, regarding the use of the pneumatic hammer in this area;

iii)The A_i parameter can only be considered as the pullout force distribution area in the pull-off tests in cases where the failure occurred at the concrete-concrete interface (1 test in Zone 1 and 2 tests in Zone 2).

4.7.2. Influence of accelerator dosage on compressive strength

According to several authors and manufacturers [4,19], increases in the setting accelerator dosage in shotcrete mixtures negatively influence the compressive strength, both at young ages and in cured concrete. In this sense, the results of the compression tests are somehow contradictory with available literature. The concrete with lower and higher dosages of setting accelerator (AC3% and AC7%) presented higher compression strength than that of concrete with intermediate dosage (AC5%). This fact was translated into the conformity analysis, with the AC3% and AC7% concrete verifying both criteria, while the AC5% concrete did not fulfill the first criterion. The results may, however, have a causal link related to the AC5% tray projection process from which the cores tested for compression were extracted and not be directly associated with the setting accelerator dosage. As mentioned, there are determinant factors for the success of the projection process (in this case by the wet-mix technique), depend on the quality control, such as the angle, distance and / or the projection speed and consequent degree of compaction of the projected layers. The presence of untected voids or higher porosity is a possible justification for the low performance of the AC5% cores, which have lower masses than other concrete specimens (different accelerator dosage) and which, in turn, can be explained by the "corner effect" or irregularities in the air supply when projecting.

4.7.3. Influence of accelerator dosage on the resistance to accelerated carbonation

Similarly to the results of the compression tests, accelerated carbonation tests also did not revealed a direct proportionality between the accelerator dosage and the carbonation resistance of the concrete. Regarding the measurement of carbonation depths, the concrete specimens with the lowest dosage of admixture, AC3%, presented the highest average value; the AC5% concrete test samples had the lowest value and the AC7% test samples showed intermediate values, although very close to the average values measured in the AC5% samples. It is concluded that AC5% concrete offers the greatest resistance to carbonation, followed by AC7% and, finally, AC3%. It was expected that the results obtained would follow the same order of compression strength, in which case AC3% concrete is the most resistant (highest f_c), followed by AC7% concrete and, finally, AC5% concrete. It was not possible to point out a reason for this result other than experimental variability.

4.7.4. Influence of accelerator dosage on chloride penetration resistance

The results of the chloride penetration tests show that there is also no direct proportionality between the setting accelerator dosages and the resistance to chloride penetration. The concrete with the greatest depth of penetration of chlorides (lowest coefficient of diffusion) was AC5% concrete, which has an intermediate adjuvant dosage compared to other concretes. The concrete with the lowest chloride penetration depths and the highest chloride diffusion coefficient was AC3% concrete, which contains the lowest adjuvant dosage of the three tested concretes. In turn, AC7% concrete, with the highest dosage of setting accelerator, presented intermediate values for the chloride penetration depth and for the calculated chloride penetration coefficient. Unlike the results of the accelerated carbonation tests and similarly to the results of compressive strength tests, the results in the penetration tests of chlorides by diffusion follow the order (from the most resistant to the least resistant): concrete AC3 % - concrete AC7% - concrete AC5%. The results are consistent with the f_c values: best performance of AC3% concrete (highest f_c) and the worst performance of AC5% (lowest f_c).

5. Concluding remarks and future developments

Table 2 presents a summary of the performance of the substrate preparation methods and the tested shotcrete.

Table 2 - Performance evaluation of the substrate preparation methods and concretes with different accelerator dosages.

Performance	Tests on the quality of substrate preparation		Tests on concrete with dosages of 3%, 5% and 7% of accelerator		
	Larger interface area	Adhesion	Compressive strength	Resistance to accelerated carbonation	Resistance to chloride penetration
Best	Pneumatic hammer	Pneumatic hammer	AC3%	AC5%	AC3%
Intermediate	----	----	AC7%	AC7%	AC7%
Worst	Milling head	Milling head	AC5%	AC3%	AC5%

The use of wet shotcrete in the repair of reinforced concrete wall coverings, in a maritime environment, offers great advantages in terms of saving time and resources, which translates into a very competitive cost / benefit ratio.The use of wet-mix shotcrete process does not contemplate variatons on the w/b ratio, which allowed the study to be centered on the analysis of the influence of the substrate preparation on adhesion and the influence of the setting accelerator admixture on the performance of the shotcrete. The coordination between the academic environment and industry creates opportunities to study and document the behavior of materials and processes in real situations, the results of which give a pragmatic and real applicability use, contributing to the evolution of the quality of construction.

Regarding future developments, it would be of great interest to deepen the study of the influence of the preparation of surfaces on the adherence of the wet-mix sprayed concrete, namely the study of the roughness generated by other demolition methods, in addition to the chipping method with pneumatic hammer and milling. The compilation of the results of these works would certainly contribute to the normalization of an expeditious test method, practical and viable for use on site. Following the study of the influence of the accelerator dosage on the mechanical characteristics and durability of the shotcrete, the dosage analysis in the range 7% - 10% of the binder mass (corresponding to the interval between maximum dosage studied in this work and the dosage recommended by the manufacturer), would certainly bring more information as to the optimal dosage to use. Furthermore, the study of the influence of accelerator dosage on fire resistance and ice/thaw cycles remains to be deepened. Finally, regarding the influence of other types of components of the mixture on the performance of the sprayed concrete and the study of mixtures with the addition of fibers from recyclable materials would be an important step towards making the concrete spraying more sustainable at the environmental level.

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