Shear behaviour of sprayed concrete

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Abstract

Shear in sprayed concrete (SC) may govern the design criteria in certain applications subjected to seismic loads or in bolted areas. However, it has been scarcely studied given the complexity of reproducing the production conditions in the laboratory and the lack of standardized tests. The paper focuses on the shear characterization of SC using a shear test compatible with the sample production. For that, an experimental program is performed analysing the influence of several parameters and comparing the results to those of a reference concrete. Furthermore, the outcome validates the shear test selected for the characterization of SC.

Keywords: sprayed concrete, shear, Luong test, set-accelerator

1. INTRODUCTION

Sprayed concrete (SC) is a material extensively used worldwide for underground support, slope stabilization and the construction of domes, façades or reservoirs. Despite that, it has been scarcely studied under controlled laboratory conditions if compared with other types of concrete. The main reason for that is the difficulty to emulate in laboratory the production conditions found in practice, which would imply the use of big facilities and equipment to spray and pump concrete. Among the properties of SC that require further studies is the shear behaviour. Especially in elements subjected to seismic loads or in bolted areas, the shear strength might play an important role on the ultimate limit state verifications, as well as on the partial or complete failure of the structure.

The formulations available nowadays in codes and guidelines to conduct the structural verification in shear are derived from extensive studies on either conventional or high performance concrete. Even though all these types of concrete share similarities in terms of composition, relevant differences arise due to the casting procedure in the case of SC. For instance, to assure a good pumpability and decrease the incidence of blockages, a reduction of the relative amount and the maximum size of coarse aggregate is necessary in SC mixes (Agulló et al. 2009). During the spraying process, the introduction of compressed air and set-accelerator admixtures at the nozzle modify the microstructure of the cement paste, affecting the hydrated compounds formed and leading to higher porosity (Galobardes et al. 2014). Moreover, part of the components rebound when the concrete impacts against the substrate. This rebound is higher for bigger particles, like the coarse aggregates. In other words, an additional reduction on the content of this fraction is observed.

Studies on conventional concrete show that aggregate interlock is one of the main mechanisms governing the shear behaviour. Consequently, the higher porosity of the concrete matrix together with the smaller aggregate size and content must affect the shear behaviour. In this context, the direct use of formulation for conventional concrete for the design of SC elements might lead to unsafe predictions. In order to overcome this drawback and promote the efficient use of SC, it is necessary to conduct rigorous experimental studies on the shear behaviour of the material in comparison with equivalent conventional concrete.

The assessment of pure shear behaviour of concrete is a complex task. No standardized tests are available and most of the tests found in the literature require special sample preparation and setups hardly compatible with the execution of SC structures. The selection and adaptation of a simple shear test to these conditions might represent an additional contribution since the results obtained could be used for the quality control of the variability of the material.

Taking that into account, the primary objective of this paper is to evaluate the shear behaviour of SC under controlled laboratory conditions and in comparison with a reference concrete

(REF). The secondary objective of this study is to define a simple test to evaluate the shear behaviour in SC, considering the condition found in most worksites. For that, first an in depth evaluation of the setup of the shear tests available in the literature is performed. Then, an experimental program with a reference concrete mix (manually poured) is conducted to define the parameters used in the test and to obtain reference values for the comparison with SC. Next, an experimental program with SC that is sprayed in laboratory and characterized with the proposed test setup. The influence of the porosity, of the humidity and of the type or content of set-accelerator on the microstructure are evaluated. The results not only shed light on the reductions expected on the shear behaviour in comparison with the reference concrete mix, but also validate a test setup for future studies or for the quality control.

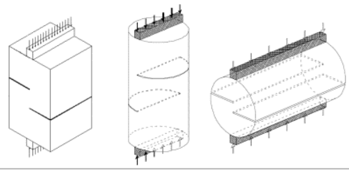
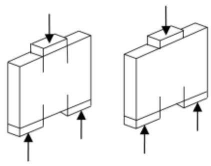
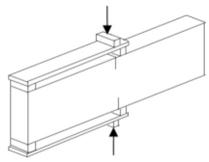
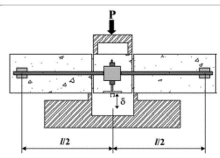
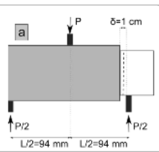
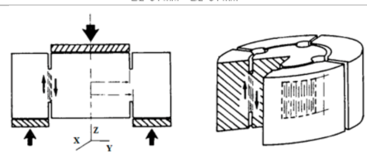
2. SHEAR CHARACTERIZATION TESTS

A common issue in these tests is the difficulty to achieve a situation of pure shear. Most of the setups available in the literature present an eccentricity in the application of the load. As a result, other phenomena such as bending may also appear, leading to a combination of tensile and shear failure. In order to reduce variability and obtain reliable results, it is important to select tests that minimize this effect. Table 1 summarizes the main shear tests reported in the literature.

The push-off tests is the most frequently used to characterize shear (Barr, 1987). They are usually conducted on Z-shaped prism or cylinders with two notches in opposed faces that resemble two L-shaped blocks joined by a common plane. A compression load applied at the top and bottom surfaces generates shear stresses in the common plane. The setup may vary depending on the geometry of the specimens and the location of the notches (Barr, 1987; Allos, 1989). Other procedures reported in the literature are performed in deep beams or panels (Barr, 1987; Shah et al., 1995) with aligned or eccentric notches on the top and bottom surfaces (in some cases the notches are only on the bottom surface) that are subjected to punching.

The Iosipescu shear test was originally proposed for metals and welded joints (Iosipescu 1967). Barr (1990) and Schlangen (1993) applied it to concrete and concluded that a failure mode with mixed shear and tensile stress was normally observed. Alternatively, the shear test proposed in the Japanese recommendations JSCE-SF6 (JSCE 1990) is conducted on a beam with two notches. The load is applied by a steel block with two wedges close to the mouth of the notches, generating a stress field (Mirsayah and Banthia, 2002) that favors the shear failure. The LCB test was developed to evaluate the bond between pavements layers of bituminous materials through the shear strength (Miro et al. 2003, Miro et al. 2006) based on the Spanish standard NLT-328/08 (CEDEX 2008). A study performed by Segura and Aguado (2012) to assess the bond between SC and conventional concrete with the LCB showed that a mixed failure was also commonly observed.

Table 1. Summary of shear characterization tests

Shear test	Reference	Specimen	Setup
Push-off test	Barr, 1987; Allos, 1989	Z-shaped specimens	
Punch shear test	Barr, 1987; Shah et al., 1995	Deep beams or panels with notches	
Iosipescu shear test	Iosipescu, 1967	Iosipescu beam	
	JSCE-SF6 1990; Mirsayah & Banthia, 2002	Beam	
LCB shear test	Miro et al. 2003 Miro et al. 2006	Cylindrical specimen	
Luong test	Luong 1990 Montenegro et al. 2008	Cylindrical specimen with diametrical notch	

The Luong test is performed on a cylindrical specimen (100 mm of diameter) with a relatively small height (40 mm) and concentric notches (Luong 1990). The notches may be executed with the same drilling machine used for the extraction of the specimens, changing the core bit for another with smaller diameter. The load is applied in the central area of the top surface (inside the perimeter of the notch) and in the external area of the bottom surface (outside the perimeter of the notch), as indicated in Table 1. In the original setup, the load is distributed over the whole inner and outer surface of the specimen, which might induce additional eccentricity. Montenegro et al. (2008) successfully applied the test to characterize shear behaviour of conventional concrete under a triaxial stress state.

For the selection of the most adequate test, certain limitations with regards to the production of SC specimens have to be considered. The spraying of an extensive surface is usually necessary to assure representativeness and to avoid the characterization of zones close to the borders, which a more likely to present imperfections. The tests are directly applied to panels or to specimens such as beams or cylinders extracted from the sprayed zone. Particularly in the case of beams, the extraction procedure entails the additional difficulty of keeping the faces of the specimen parallel. Another potential inconvenient is the high weight of the beams, which compromise their manipulation and the number of tests performed. On the contrary, drilled cylinders are easier to obtain, requiring simple specimen preparation procedures as the polishing or cutting of both ends. Moreover, the extracted cylinders are easier to manipulate and allow the execution of more tests for the same panel or sprayed zone. Based on the exposed previously, tests that require cylindrical specimens are selected.

From all the methods presented in Table 1 that use this shape of specimen, the LCB is disregarded since it requires cylinders with a height of more than 12 cm, which is bigger than the thickness of the SC layer of some applications. Likewise, the push-off test is disregarded due to the difficulties of performing perfectly parallel and coinciding notches. In this context, the Luong test was selected since it allows the characterization of cylinders with less than 10 cm of length implying a simpler sample preparation procedure.

3. EXPERIMENTAL PROGRAM ON CONVENTIONAL CONCRETE

3.1 Methodology

Given that the Luong test is not standardized and the literature does not report the influence of parameters of the test setup on the results, a preliminary experimental study is conducted to define the most adequate configuration. Considering the difficulties to obtain sprayed concrete specimens in the laboratory, this preliminary study is performed on a reference concrete (REF) that is manually poured. This will also provide reference values for the comparison with equivalent sprayed mixes. After defining the most adequate setup, a second experimental program is conducted on SC.

3.1.1 Materials, concrete mix and basic properties

The concrete mix used to cast the specimens was designed to reproduce the typical composition employed in wet-mix sprayed concrete. For this reason, a water/cement ratio (w/c) of 0.45 and a cement content of 425 kg/m³ were defined. The aggregates were selected according to EN12620:2002 (CEN 2002), considering the limits induced by the spraying pump. The details of the concrete mix are presented in Table 2.

Table 2. Concrete mix

Materials	**Content (kg/m^3)**		
	REF	**SC 1** *(see section 4.1.4)*	**SC 2** *(see section 4.1.4)*
Cement CEM I-42.5R	425	425	425
Water	190	190	190
Sand (0/2 mm)	380	380	380
Sand (0/5 mm)	900	900	900
Gravel (5/12 mm)	380	380	380
Superplasticizer (Polycarboxylate based)	4.25	4.25	4.25
Set-accelerator A1	-	5-7% bcw	-
Set-accelerator A2		-	7% bcw

Cylindrical specimens of 100 mm of diameter and 200 mm of height were produced to evaluate the modulus of elasticity according to EN 12390-13:2014 (CEN 2014) and the compressive strength as indicated in EN 12390-3:2009 (CEN 2009). The dry density and the porosity were measured according with the EN 12390-7:2009 (CEN 2009) in 7 specimens. Cylinders with a diameter of 150 mm and a height of 300 mm were cast to obtain the samples for the Luong test. All specimens were moist cured under a plastic sheet for 24 hours until their removal from the moulds and then were kept in a curing room at 20±2 °C and 95% of relative humidity. Table 3 presents the average basic properties at 28 days and their coefficient of variation for the reference concrete.

Table 3. Basic properties of the reference concrete (REF)

Properties		**Sample**	**Average (CV)**
Mechanical properties	Compressive strength (MPa)	Ø100x200 mm	58.4 (11.9%)
	Modulus of elasticity (GPa)	Ø100x200 mm	34.0
Physical properties	Dry density (g/cm^3)	Cores from the shear specimens	2.18 (0.9%)
	Porosity (%)		12.0 (13.7%)

3.1.2 Preparation of the samples

The REF cylinders for the Luong Test were cut into smaller samples with a diametrical notch. Each sample was identified according to their position in the original REF cylinder. The dimensions of the samples selected for the experimental program are 150 mm of diameter and 60 mm of height. Notice that this height differs from the original specimen proposed by Luong (1990). Such modification was adopted to increase the confinement and the area characterized in the test, also respecting the minimum thickness usually found in sprayed layers. The surfaces of the sample obtained after cutting were polished with a diamond blade in order to assure their parallelism. Finally, a notch with a depth of 10 mm was executed perpendicular to the top and bottom surface of each sample. The diameter of the notch is a variable of this study that is discussed in section 3.4.

3.1.3 Test setup

An eccentric load is applied by a hydraulic press at the top and bottom surfaces of the sample by means of two circular steel pieces. The load at the top is located in the external area (outside the perimeter of the notch), whereas the load at the bottom is located in the internal area (inside the perimeter of the notch), as shown in Fig.1. To capture the complete load-displacement curve, a constant displacement rate of the piston press is applied. The shear strength is obtained from the ratio between the maximum load reached during the test and the resistant area (see Fig. 1b). For notation purposes, the height of the notched section will be referred to as effective height.

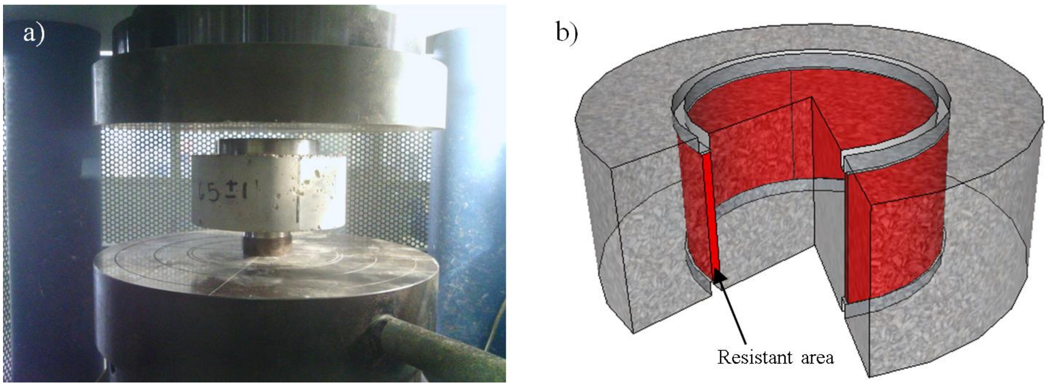


Fig.1 a) Location of the circular steel pieces and b) shear resistant area

The first stage of the test is characterized by a linear-elastic behaviour. When the shear strength of concrete is reached, a crack along the plane of the notch appears and a cylinder is formed in the internal area of the notch. At this stage, the aggregate interlock is the main mechanism governing the shear behaviour. As the stresses generated by the application of load increase and radial cracks appear in the external concrete crown. Notice that for a pure shear failure to take place, the fracture surface in the notched plane should be as vertical as possible.

3.1.4 Selection of parameters

Three parameters of the test setup were selected in order to determine their influence on the results and, subsequently, to identify which values are more suitable. The selection of these values was done in successive phases as shown in Fig.2. The first parameter of the test setup evaluated was the displacement rate given its potential influence over the control of the test and over the maximum load resisted by the specimen. Displacement rates of 0.1 mm/s, 0.2 mm/s or 0.4 mm/s were used considering other studies on shear.

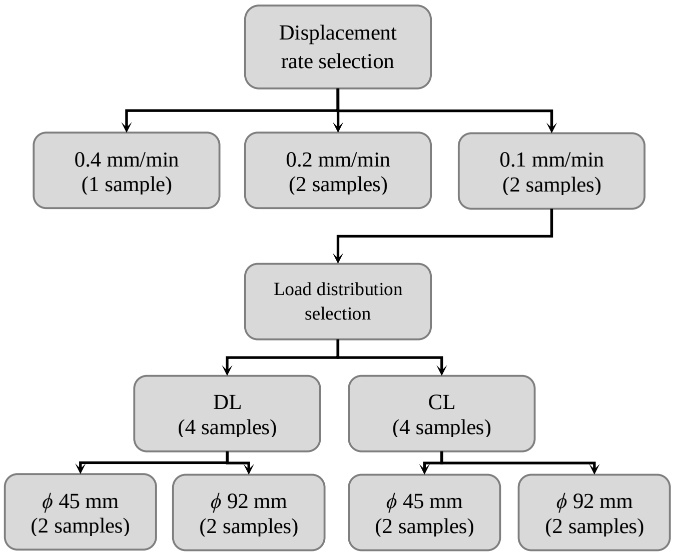


Fig.2 Selection of parameters for the experimental study on conventional concrete

The second parameter was the loading area due to its repercussion in the eccentricity and, consequently, the failure mode. As shown in Fig.3, two load configurations were applied: distributed or concentrated. In the distributed, the load is applied over the whole external area of the notch in the upper surface and the whole internal area of the notch in the bottom surface (see Fig.3a). In the concentrated, loads are located in an area of 10 mm of thickness outside the perimeter in the top surface and inside the perimeter in the bottom surface (see Fig.3b).

Even though the majority of the studies from the literature with the Luong test use the distributed load, it might induce higher eccentricities than the concentrated load. Consequently, mixed stress states are more likely to occur in the former. In both cases, the load was applied with two steel cylindrical plates with 3 cm of height in order to avoid deformations that could affect the results.

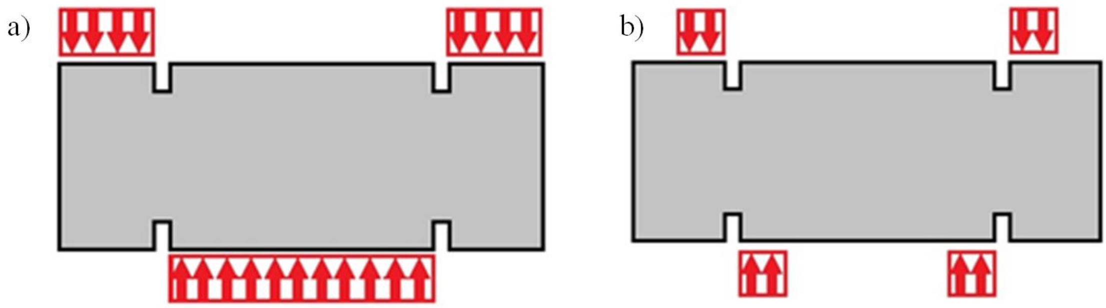


Fig.3 Loading area: a) distributed and b) concentrated

The third parameter was the diameter of the notch. As this diameter increases, the crown of concrete outside the perimeter of the notch becomes smaller, thus reducing the confinement provided to the failure plane and affecting the test results. Based on the typical dimensions of commercial drills available, the diameters of 45 mm and 92 mm were choosing. Both values ensure that the thickness of the external concrete crown is at least two times bigger than the maximum aggregate size in the mix.

The notation used to designate the samples corresponds to the main parameters selected for the study. Hence, the notation of each sample indicates the type of concrete (REF or SC), the diameter of the notch (45 mm and 92 mm), the displacement rate (0.1 mm/min, 0.2 mm/min or 0.4 mm/min) and the load application area (distributed loads or DL and concentrated loads or CL). A final number is added to the notation to differentiate between samples from the same type (e.g. REF_92_0.1_CL_1 and REF_92_0.1_CL_2).

3.2 Results and analysis

3.2.1 Influence of the displacement rate

The displacement rate was evaluated by testing 5 specimens with a notch of 45 mm of diameter and a distributed load. Two specimens were tested at each displacement rate, except for the case of 0.4 mm/min due to the evident problems observed throughout the test (see Fig.4). Fig.4 presents the stress-displacement curves for each of the samples as well as the average values of shear strength depending on the displacement rate.

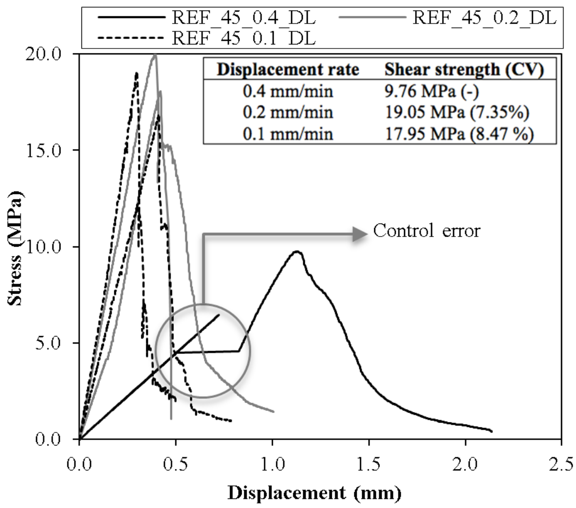


Fig.4 Influence of displacement rate on shear stress-displacement curves and average shear strengths

In general, the curves exhibit a first stretch of a linear-elastic behaviour until the shear strength of the concrete is reached. At this moment, a circumferential crack appears along the perimeter of the notch, thus leading to a loss of stiffness that is represented in the curves of Fig.4 by a sudden drop in the stress. Subsequently, the aggregate interlock mechanism starts providing a residual strength that is represented by the last stretch of the curves. This stage is characterized by a progressive reduction of in the value of stress.

It is clear that the sample loaded at a displacement rate of 0.4 mm/min (REF_45_0.4_DL) does not follow the described trend. Instead, it shows a linear behaviour with high values of displacement up to a first peak, after which the stress drops and then increases again up to a second peak. This response indicates that the control of the test at 0.4 mm/min was not adequate and that a sequential failure occurred. Conversely, the curves obtained for the samples tested at 0.2 mm/min and 0.1 mm/min present a similar trend with no significant differences and no evidences of an unsuitable control or failure.

The strength values displayed in Fig.4 reveal that when the samples are tested at lower displacement rates, the average shear strength increases. Notice that a displacement rate of 0.4 mm/min leads to values around 10 MPa, whereas when the rate is reduced to 0.2 mm/min or 0.1 mm/min, the strengths increase by 95% and 83%, respectively. In view of the results obtained, both 0.2 mm/min and 0.1 mm/min could be adopted. In this case, 0.1 mm/min is selected to assure an adequate recording of the complete curve, especially in the residual stretch.

3.2.2 Influence of the load distribution

Based on the previous results, the influence of the load distribution was assessed by testing samples with a displacement rate of 0.1 mm/min, diameters of the notch of 45 mm and 92 mm and two load distributions shown in Fig.3. A total of 4 samples were tested, 2 for each case of diameter of notch and load distribution. Table 4 presents the average shear stresses and the corresponding coefficient of variation.

Table 4. Shear strength values for concentrated and distributed load (MPa)

Load	Specimen	Ø45 mm		Ø92 mm	
		Single values (MPa)	Average (CV)	Single values (MPa)	Average (CV)
CL	REF_Ø_01_CL_1	18.08	15.32	9.88	10.94
	REF_Ø_01_CL_2	12.56	(25.5%)	12.00	(13.7%)
DL	REF_Ø_01_DL_1	18.83	18.13	2.36	4.53
	REF_Ø_01_DL_2	17.44	(5.4%)	6.70	(67.7%)

The results obtained in Table 4 reveal that the influence of the load distribution depends strongly on the diameter of the notch. For the case of 45 mm, the shear strength is 18.3% higher for the DL than for the CL. In addition, the scatter is significantly smaller for the former. Nevertheless, this behaviour does not apply for the samples with 92 mm of diameter. In this case, samples with CL exhibit the highest shear strength and smaller scatter. Notice that the highest scatter is obtained for samples of 92 mm in the DL configuration.

In terms of the failure mechanism observed during the test, the DL leads to cracking outside the vertical notched plane (see Fig.5a and 5c). Therefore, a DL generates cracking planes that start at the edges of the top surface and progress to the centre of the bottom surface, thus leading to a failure mode affected by eccentricities (see failure lines highlighted in Fig.5a). Conversely, under concentrated loads, the cracking occurs in the plane of the notch (see Fig.5b and 5d) since the tension lines progress from the centre of the top-loading surface to the centre of the bottom-loading surface. This generates almost vertical cracking planes, approaching a failure due to pure shear.

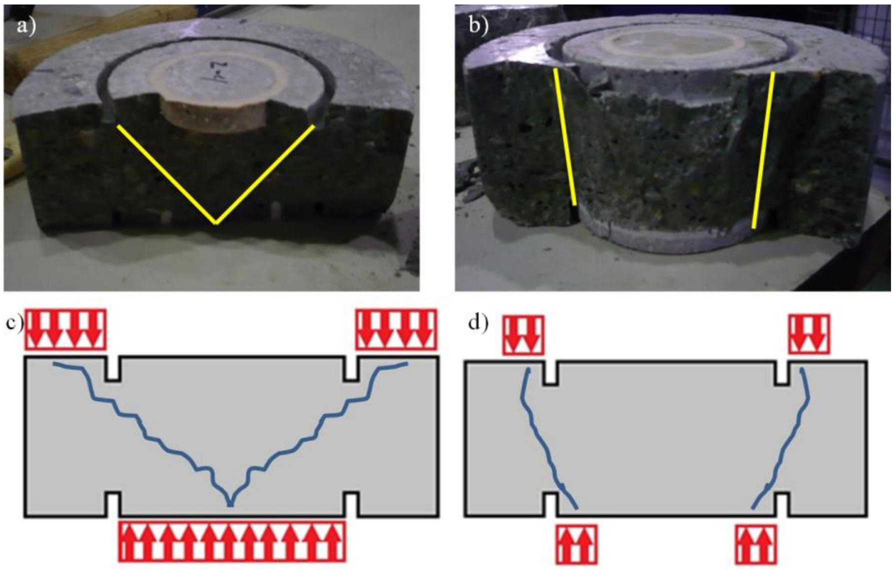


Fig.5 Failure planes in the Luong test: a) c) distributed and b) d) concentrated loads.

The visual inspection of the samples after the test confirms that the setup with concentrated load (CL) yields a mechanism closer to ideal shear failure than that found in case of the setup with distributed load (DL). Therefore, in the second stage of the experimental program, the CL configuration is adopted to evaluate shear of sprayed concrete.

3.2.3 Influence of the diameter of the notch

The repercussion of using a diameter of the notch of 45 mm or 92 mm was evaluated by performing 8 tests with concentrated and distributed loads. The results are included in Table 4. The samples with a diameter of the notch of 45 mm exhibit higher average shear strength for both load configurations due the bigger confinement provided by the external crown. Notice that the external crown is the volume of concrete outside the perimeter of the notch, which is 1.8 times thicker in the case of the samples with the notch of 45 mm. However, despite the results, no conclusive outcome may be obtained from the results on which diameter is more suitable for the performance of the tests. This is due to the high scatter observed in the case of the samples with 92 mm of diameter and distributed load. For that reason, both diameters are further evaluated in the subsequent stages of the experimental program (on SC samples).

4. EXPERIMENTAL PROGRAM ON SPRAYED CONCRETE

4.1 Methodology

In previous sections, the parameters associated to the Luong test setup were assessed in conventional concrete cylinders. This section describes the methodology proposed to evaluate the influence of the SC characteristics on the shear behaviour of the material. It is known that the main factors affecting the shear behaviour of concrete are the aggregate and the mortar characteristics. Given the limitations regarding maximum aggregate size due to the spraying procedure, only the characteristics of the mortar were accounted as a variable.

The porosity of the mortar is highly influenced by the type and the content of the set-accelerator admixture used during the spraying process. For this reason, two alkali-free set-accelerators were added in two contents at the nozzle. The aim is to achieve different levels of porosity. Another parameter that might affect the shear performance of SC is the degree of humidity of the material. In some application, the structure will remain in constant contact with water from the surroundings, being saturated during the service life. In others, the material will present a low degree of humidity. To evaluate the repercussion of this parameter, two extreme conditions were considered: dry and saturated. The dried samples were introduced in an oven at 50ºC for 24 hours after which they were allowed to cool during 30 minutes before the test. The saturated samples remained under water during 24 hours until the execution of the test.

The third parameter evaluated was the influence of the anisotropy of the sprayed layer induced by the differential rebound. The rebound is particularly significant at the initial stage of the spraying procedure, when the material impact directly at the substrate. Once a SC bed is formed over the surface, the new particles are more likely to be retained, leading to a reduction in the rebound (Agulló et al. 2009). Consequently, the SC layers closer to the surface of the panels are likely to present a smaller content of coarse aggregate than layers farther from the surface. To assess this potential anisotropy, the samples extracted from each core were identified depending on the distance from the surface as bottom (closer to the panel) and top (farther from the panel). The rough layer of the top part of the samples was cut to remove the irregularities (always less than 1 cm) and, afterwards, the top and bottom surfaces were polished.

4.1.1 Materials and concrete mix

The composition of the SC was the same as the used for the experimental program with conventional concrete, shown in Table 2. In addition to that, a set-accelerator admixture was added to simulate the typical composition of the SC similar to that applied in tunnels. In this case, two alkali-free set-accelerators, A1 and A2, were considered (see Table 2). The set-accelerator A1 was added in two different contents 5% and 7% by cement weight (bcw) in the mixes named SC1_LP and SC1_HP, respectively. The content of set-accelerator A2 was 7% bcw in the mix named SC2_HP.

4.1.2 Spraying setup and procedure

The concrete was sprayed outdoors (see Fig.6a) with a MEYCO Altera compact wet-mix machine, which is an oil-hydraulically driven twin-piston pump with a peristaltic dosing unit for accelerators. A 10-m^3/min diesel air compressor was employed during the spraying. A concrete flow of 4.4 m^3/h (equivalent to 20 strokes per minute) and an air pressure of 4 bars were used. The accelerator-dosing unit allowed a flow between 4.0 and 4.5 l/min. The concrete was sprayed on metallic panels (500 x 500 x 150 mm and 1000 x 1000 x 150 mm) placed at an angle of 20º with the vertical plane, according to the EN 14488-1:2006 (CEN 2006). The distance between the nozzle and the test panels was approximately 1.5 m (see Fig.6b).

Fig.6 Special outdoor area to spray concrete: a) general view and b) detail of the spraying.

After the spraying, panels were covered with a burlap-curing blanket to avoid water evaporation from the surface until the unmoulding, 24 hours later. Subsequently, the pieces were piled together in outdoor conditions and covered with sacking. In order to maintain humidity, the pieces were wetted continuously. Cores were drilled the day after production from the pieces by means of a core extracting machine with 75 mm and 140 mm diameter drills. The distance between cores followed the minimum requirements defined in EN 14488-2:2007 (CEN 2007). The rough face of the cores was cut to obtain a slenderness close to 2 for the specimens of 75 mm of diameter, which is the recommended slenderness by many standards for the compression test (CEN 2002, CPH 2008, fib 2013). Next, both surfaces of the samples were polished to maximize the contact and assure a good load distribution between the testing machines and the cores before being stored in a curing room at 20 ± 2ºC and 95 ± 2% of relative humidity until the age of testing.

The analysis of the diameter of the notch is conducted on the mix SC1_LP by performing 4 tests for the samples with a diameter of 45 mm and 4 tests for the samples with 92 mm of diameter, both in dry conditions. The assessment of the degree of the humidity and the distance from the surface was assessed in the concrete mixes SC1_HP and SC2_HP by testing 12 samples in each case. Notice that from the 12 samples, 6 correspond to the bottom part of the original cylinder and the other 6 were originally located in the top part of the cylinder.

4.1.4 Basic properties of the SC

The assessment of the compressive strength, modulus of elasticity and porosity were performed according with the same standards described in section 3.1.1. Cylindrical cores with a diameter of 75 mm and a height of approximately 150 mm extracted from the sprayed panels were used. The average results of these tests and their corresponding coefficient of variation are presented in Table 5.

Table 5. Basic properties of sprayed concrete (SC)

Properties		**Average (CV)**		
		SC1_LP	**SC1_HP**	**SC2_HP**
Mechanical properties	Modulus of elasticity (GPa)	23.5 (3.9%)	21.1 (9.2%)	25.5 (0,7%)
	Compressive strength (MPa)	34.2 (4.8%)	33.6 (6.6%)	32.8 (7.8%)
Physical properties	Dry density (g/cm^3)	2.13 (0.5%)	2.07 (4.6%)	2.10 (1.8%)
	Porosity (%)	14.6 (3.9%)	17.0 (6.5%)	16.9 (6.6%)

By comparing the average properties of the SC mixes with those of the reference concrete (see Table 3), it is clear that the spraying procedure leads to a material with higher porosity. Notice that the average porosity for reference concrete is 12.0%, whereas the average of all three SC mixes is 16.2%. This represents an increase of 35% that affects other properties such as the compressive strength and the modulus of elasticity, which are significantly reduced in the case of the SC mixes.

According to the results from Table 5, the lowest porosity and highest mechanical properties were found in the mix with 5% bcw of set-accelerator A1, that is, SC1_LP. The increase in the dosage of set-accelerator (regardless of the type) led to an increase in porosity and a consequent decrease in the long-term mechanical properties. This is evident in mixes SC1_HP and SC2_HP.

Notice that the terms “LP” and “HP” used in the notation refer to the low and high level of porosities, respectively. The notation employed to designate each sample also includes the diameter of the notch (45 mm or 92 mm), the location of the sample in the original specimens (T for top sample or B for bottom sample) and the humidity conditions (D for dry conditions or S for saturated conditions). A number is included to differentiate the samples with the same properties and conditions. For example, the notation of a sample from the mix with 7% bcw of set-accelerator A1, with a diameter of the notch of 45 mm, cut from the upper position and tested under dry conditions would be: SC1_HP_45_T_D_1.

4.2. Influence of characteristics of SC on Shear Strength

4.2.1 Distance from the substrate

Table 6 presents the average shear strengths of the samples and the coefficient of variation (CV) depending on their location regarding the surface of the panel (top or bottom). No clear trends on the influence of the distance from the substrate were found since the samples exhibit similar shear strengths regardless of their location. In terms of scatter, the samples located near the surface of the panel show higher values of coefficient of variation than the ones located at the top. Considering all the previous analyses, the possible differential rebound does not seem to affect significantly the shear response.

Table 6. Influence of the distance from the substrate in the shear strength of SC

Mixes	**Shear strength in MPa (CV)**	
	Top	**Bottom**
SC1_LP	15.20 (1.9%)	14.55 (7.6%)
SC1_HP	13.23 (6.6%)	13.53 (6.1%)
SC2_HP	13.79 (4.9%)	13.91 (14.1%)

4.2.2 Porosity

Table 7 presents the shear strength for all SC samples with low porosity (LP) and high porosity (HP) listed from the sample with highest porosity (SC2_HP_45_B_D_7) to the lowest (SC1_HP_45_B_D_5). Furthermore, the results of porosity of the reference concrete (REF) studied in previous section is also included at the bottom of the table. Notice that all samples included in Table 7 correspond to dry conditions and a diameter of the notch of 45 mm.

Table 7. Influence of porosity (dry conditions): individual and average values grouped by porosity range

Specimen	Individual values		Avarage considerin porosity range	
	Porosity (%)	**Shear strength (MPa)**	**Porosity (%)**	**Shear strength (MPa)**
SC2_HP_45_B_D_7	19.0	11.67	18.3	13.02
SC1_HP_45_T_D_2	18.2	13.38		
SC1_HP_45_T_D_8	18.0	14.02		
SC1_HP_45_B_D_7	18.0	13.02		
SC1_HP_45_B_D_1	17.8	14.49	17.5	13.80
SC2_HP_45_T_D_8	17.5	13.82		
SC2_HP_45_T_D_10	17.1	13.11		
SC1_HP_45_T_D_6	16.8	12.29	16.5	14.02
SC2_HP_45_B_D_9	16.7	15.32		
SC2_HP_45_T_D_12	16.0	14.45		
SC2_HP_45_B_D_11	15.9	14.74	15.5	14.50
SC1_LP_45_T_D_6	15.6	14.99		
SC1_LP_45_B_D_1	15.0	13.77		
SC1_LP_45_B_D_5	14.9	15.32	14.5	14.61
SC1_LP_45_T_D_2	14.7	15.40		
SC1_HP_45_B_D_5	14.0	13.09		
RC_45_D_2	12.9	12.56	12.8	15.32
RC_45_D_1	12.8	18.08		

The results shown in Table 7 reveal that the higher porosity of the mix, the lower the value of shear strength. Such outcome was expected given that more porous matrices tend to exhibit lower stress bearing capacity than denser matrices. These differences, as previously described, are due to the type of set-accelerator used and its content, which influences the microstructure of the material. No significant difference was found between the mixes with different accelerator type and the same dosage. This indicates that the porosity is the main parameter governing the shear strength.

Such strong correlation between both parameters is confirmed by the results in Fig.7, where the shear strength is plotted against the porosity of all samples grouped by the type of mix: SC2_HP_D, SC1_HP_D, SC1_LP_D and REF_D. The average grouped by porosity range from Table 7 is also included in Fig.7 (see markers with black fill). The strong correlation between the shear strength and the porosity of the mixes previously mentioned is confirmed by the high R^2 of the trendline in Fig.7.

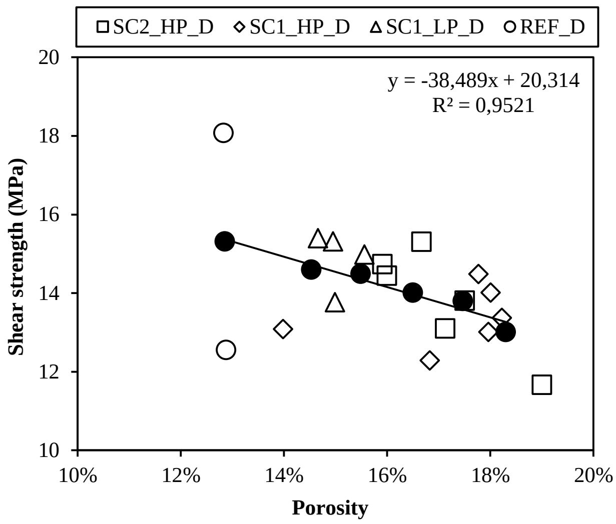


Fig.7 Shear strength vs. porosity for samples with diameter of 45 mm and dry conditions (for average values see markers with black fill).

4.2.3 Humidity

The influence of the degree of humidity of the SC mixes on the shear response is evaluated in the mixes with high porosity since it should be more evident in the presence of more pores. Table 8 presents the average shear strengths of all samples tested under dry and saturated conditions.

Table 8. Influence of humidity for SC1_HP_45 and SC2_HP_45.

Humidity conditions		**SC1_HP_45**		**SC2_HP_45**	
		Top	**Bottom**	**Top**	**Bottom**
Saturated	*Average per location (CV)*	12.34 (5.9%)	12.53 (5.4%)	13.62 (7.0%)	12.70 (12.2%)
	Average per humidity conditions (CV)	12.43 (5.1%)		13.16 (9.5%)	
Dry	*Average per location (CV)*	13.23 (6.6%)	13.53 (6.1%)	13.79 (4.9%)	13.91 (14.1%)
	Average per humidity conditions (CV)	13.38 (5.8%)		13.85 (9.5%)	

The samples under dry conditions exhibit higher shear strength than the saturated samples. In fact, these differences are 7.6% for the mix SC1_HP_45 and 5.2% for the mix SC2_HP_45. This is consistent with the literature about conventional concrete, which reports that under saturated conditions the compressive strength is 5% lower than in dry conditions. This may be attributed to the weakening of the bond between the phases of hydrated cement and the reduction of interstitial forces due to the presence of water.

4.2.4 Diameter of the notch

Table 9 presents all values of shear strength from samples with 45 mm and 92 mm notch as well as their average and coefficient of variation. The average values indicate that the shear strength for samples with 45 mm of diameter is 54.3% higher than the strength for the samples with 92 mm of diameter. Again, such outcome may be attributed to the bigger confinement provided by the external crown of the sample.

Table 9. Influence of the diameter of the notch (SC_LP)

Location	**45 mm**		**92 mm**	
	Shear strength (MPa)	**Average per location (CV)**	**Shear strength (MPa)**	**Average per location (CV)**
Top	15.40 14.99	15.20 (1.9%)	8.58 9.86	9.22 (9.8%)
Bottom	13.77 15.32	14.55 (7.6%)	10.15 9.96	10.05 (1.3%)
Average per diameter (CV)	14.87 (5.1%)		9.64 (7.4%)	

5. COMPARISON OF SPRAYED CONCRETE WITH CONVENTIONAL CONCRETE

In this section the results obtained in the different stages of the experimental program for conventional concrete and sprayed concrete are compared in Table 10. It should be highlighted that there are small differences in the dimensions of the specimens used to characterize the mechanical performance of the materials. These small differences are due to the casting procedure and the method employed to obtain the specimens (moulded or drilled from panels). Their influence in the results is assumed to be negligible.

Table 10. Shear strength of reference concrete and sprayed concrete mixes

Mixes	**Shear strength (MPa) (Average (CV))**	
	Ø45 mm and dry conditions	**Ø92 mm and dry conditions**
SC1_LP	14.87 (5.1%)	9.64 (7.4%)
SC1_HP	13.38 (5.8%)	Not evaluated
SC2_HP	13.85 (9.5%)	Not evaluated
REF	15.32 (25.5%)	10.94 (13.7%)

In general, the shear strength of the reference concrete (RC) is higher than for sprayed concrete mixes. The differences are only 3.0% for the mix SC1_LP, 14.5% for the mix SC1_HP and 10.6% for the mix SC2_HP, in dry conditions and for a diameter of 45 mm. These results reveal that, despite the spraying procedure, the SC mixes achieve shear strengths that are close to that of the reference concrete. This is observed particularly in the mixes with low porosity (LP). In fact, from the previous analyses, it may be derived that the main factor for the reduction in shear strength in the SC mixes is the porosity of the matrix. Notice that spraying the concrete may increase the porosity of the mix up to 43% (according to Table 7), depending on the type and content of set-accelerator used for the spraying procedure.

6. CONCLUSIONS

The present study focused on the assessment of shear behaviour of SC through and adaptation of Luong tests. The main conclusions derived from this work are presented subsequently.

- The proposed testing method has proven to be compatible with the conditions associated to the sprayed concrete in terms of typology and dimensions of the specimens. In terms of the displacement rate applied, values of 0.1 mm/min or 0.2 mm/min are recommended to ensure a satisfactory control of the test and reliable results.

- The load distribution has great repercussion on the failure mode of the specimens in the Luong test. The application of loads distributed over the whole surface leads to an inclined cracked plane that suggests the influence of normal stresses in addition to tangential stresses. On the contrary, the application of concentrated loads produces a cracking governed mainly by shear stresses and a failure that occurs within the weak area defined by the notch. For this reason, the setup with the concentrated load distribution is recommended.

- The diameter of the notch influences significantly the value of the shear strength due to the confinement effect provided by the external crown of concrete outside the perimeter of the notch. The smaller the diameter of the notch, the greater the confinement and thus the shear strength. A diameter of 45 mm is recommended based on the experimental results.
- The porosity of the concrete mixes is a relevant parameter that influences the shear strength, particularly for the sprayed concrete mixes which exhibit higher porosity due to the casting procedure. The results confirm that the sprayed concrete mixes with lower porosity present higher shear strength.
- The humidity has a small influence on the results of the shear strength. Samples in dry condition show shear strengths between 5% and 7% bigger than equivalent saturated samples.
- The potential anisotropy of sprayed concrete - indirectly assessed by the location of the specimen in the sprayed concrete panel - does not have noticeable influence in the shear strength.
- The comparative analysis of the shear response of reference concrete (same mix poured instead of sprayed) and the SC mixes reveals that the values of shear strength do not differ significantly. The variations observed are related to the increase in the porosity of the SC. This means that the porosity might be the main parameter to be considered in

the correction of the shear strength predicted with the formulations applied in codes and guidelines to RC.

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