Evaluation of concrete-steel bond strength in wet mix sprayed concrete

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Abstract

The high performance obtained in wet mix sprayed concrete has extended the field of applications of this technique. In some of these applications, such as in diaphragm walls or bridge rehabilitation, the structure may be subjected to bending moments, so conventional reinforcement is regularly used. In this context it is important to assure adequate bond between steel rebar and the sprayed concrete. It is well known that sprayed concrete presents smaller size coarse aggregate, higher mortar content and higher porosity than conventional concrete. Therefore, differences in the bond behaviour are expected.

This paper presents a specific procedure in order to evaluate concrete-steel bond strength in sprayed concrete. The proposed test is based on pull-out method using a test panel specimen. The experimental program includes tests performed in conventional and sprayed concrete. The results obtained show the viability of the method, which could be easily applicable in the case of sprayed concrete. The tests performed indicate that, despite the intrinsic scatter, the bond behaviour is similar to that of conventional concrete.

1.- Introduction

The use of sprayed concrete in applications with high structural responsibility has increased in the past years. In order to support this advance, it is necessary to provide reliable estimations of mechanical properties for the design of elements and for the quality control of the material. The particularities in the concrete mixes used and the variations induced by the spraying process should affect the properties of the material in comparison with the obtained for traditional concrete with equivalent strength class.

Although research has already been conducted to assess the repercussion of those particularities on the elastic modulus [] and the compressive strength [], several other relevant properties still require further studies. The bond between the concrete and the steel rebar is one example of that. Such property should be characterized since it determines the compatibility of deformations and the enhanced post-cracking response of reinforced sprayed concrete.

The decrease in the maximum size and the total content of coarse aggregate used in the mix accentuated by the rebound are expected to interfere with the friction and mechanical interaction. This is also highly affected by the spraying process given that depending on the ability of the nozzleman a shadowing effect might be generated behind the reinforcement, leading to a partial contact with the concrete. Even if this imperfection was minimized by improving the technique, a differential compaction of the surrounding concrete would be unavoidable. For all these reasons, it seems reasonable to assume that the spraying process may penalize the bond between concrete and reinforcement.

Despite that, a lack of tests to assess such bond in the case of sprayed concrete is observed mainly due to the difficulties regarding the production of samples representative of the material. In fact, the tests available for conventional concrete require complex sample preparations of the sprayed panels, thus hindering their applicability. Taking it into account, the objective of the present study is to propose a new test to evaluate the bond between sprayed concrete and reinforcement.

The aim is to provide a procedure and a setup compatible with the particularities of the spraying process and the surrounding conditions found in typical worksites. After analysing the possibility of adapting other tests from the literature, a new proposal is outlined and then evaluated through an experimental program. The results obtained show the influence of test parameters and allow the proposal of optimization of the proposal. It is important to remark that the observations and the conclusions included in this work are part of an ongoing research. The content presented here show a general overview of the achievements obtained so far.

2.- Test methods for conventional concrete.

The most widely applied methodologies for evaluating the bond between concrete and rebar are the beam test and pull-out test. In the latter, a specimen formed by two blocks with the rebar partially embedded to the blocks at their lower part is used. A covering is installed around the bars to restrict the contact with concrete to the zone characterized, which should present a length equal to 10 times the bar diameter. As shown in Figure 1, a steel hinge is placed at the top central part of the specimen. A dense reinforcement is placed within the concrete blocks in order to avoid excessive cracking that could interfere with the bond assessment.

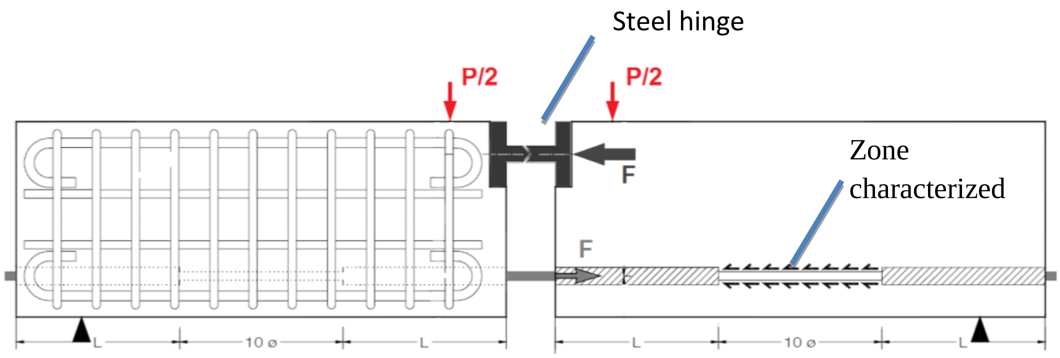

Figure 1. Beam test setup []

Each block is supported at the extremities and receives a load close to the metallic hinge in a setup similar to a 4 point bending test. The load generates a moment and a tensile force at the bar, activating the bond between materials. The displacement of the bar is monitored by means of sensors that measure the relative movement between the ends of the rebar and the extremity of the specimen.

In the pull-out test, the tensile force required to cause the bond failure of a partially embedded bar is evaluated commonly in cubic concrete specimens. In the case of the standard EN 10080 the dimension of the specimen has to be at least 10 times the bar diameter (with a minimum of 200 mm) and the adherence length is limited to 5 times the nominal diameter of the rebar, as depicted in Figure 2. Load and rebar slip are motorized during the test.

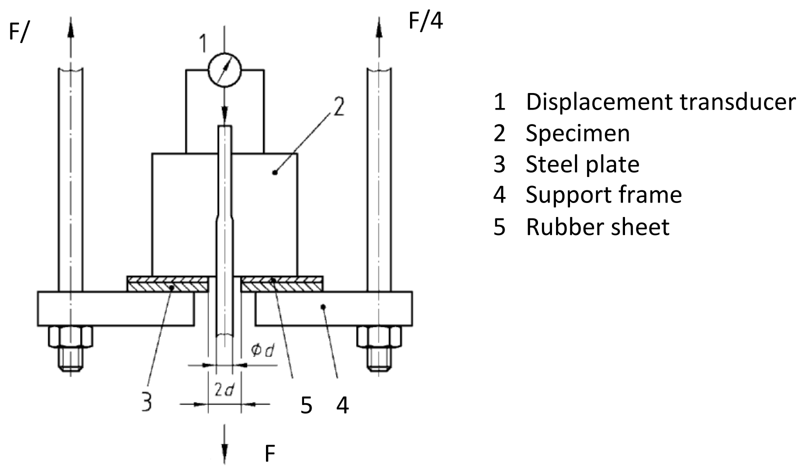

Figure 2. Pull-out test setup [EN 10080]

3.- Preliminary test proposal and experimental program

By the description included in the previous section it becomes clear that the bending test requires a more complicated setup that should be harder to adapt to sprayed concrete specimens. For that, it would be necessary to perform a complex cut of the samples or include barriers to avoid that the sprayed material would occupy the central part. This would affect the quality of the material sprayed at the centre, compromising the execution of the test and the distribution of internal forces in the central sectional.

The pull-out test does not share the same disadvantages and may be easier to adapt to the assessment of bond between sprayed concrete and reinforcement. It would be necessary, however, to increase the size of the sample to minimize the influence of the borders of the sample around the characterized zone. With that intent, a panel with the dimensions established by the EFNARC (600x600x100 mm) was used in a preliminary experimental program.

As illustrated in Figure 3, three bars were embedded in each panel to increase the number of measurements per specimens. Given that it was expected that the bond strength would be less than that for conventional concrete, the rebar was positioned in the middle plane with a constant bond length of 100 mm located in the central part of the panel. A covering is installed around the bars to restrict the contact with concrete to the zone characterized. The extremities of the bars are left outside of the panel.

Figure 3. Frontal view of panel specimen

The test set up adopted is shown in figure 4. A hydraulic jack is positioned with the bar inside the holed piston. An anchorage system attaches the end of the rebar and the stroke side of the jack, which is extended to produce a tensile force on the rebar using the concrete panel as a reaction element.

Figure 4. Test set up.

The rate of displacement of the piston is controlled through a wire transducer that connects and measured the distance between the anchorage and the jack. Since the displacement registered by the wire transducer placed over the jack is also affected by the deformation of the rebars, the rebar displacement relatively to the panel is also measured in the opposite side of the panel with a displacement transducer (see Figure 5). Besides this displacement, the force applied is assessed with a pressure transducer. A special servo-hydraulic 700 bar power unit generates the pressure required to apply the load. The average bond stress applied is calculated by the ratio between the load and the equivalent surface area of the rebar in contact with concrete. The load was applied by displacement control at a rate of 1 mm/min until stroke displacement of 10 mm and 2 mm/min until the rebar slip reached 10 mm.

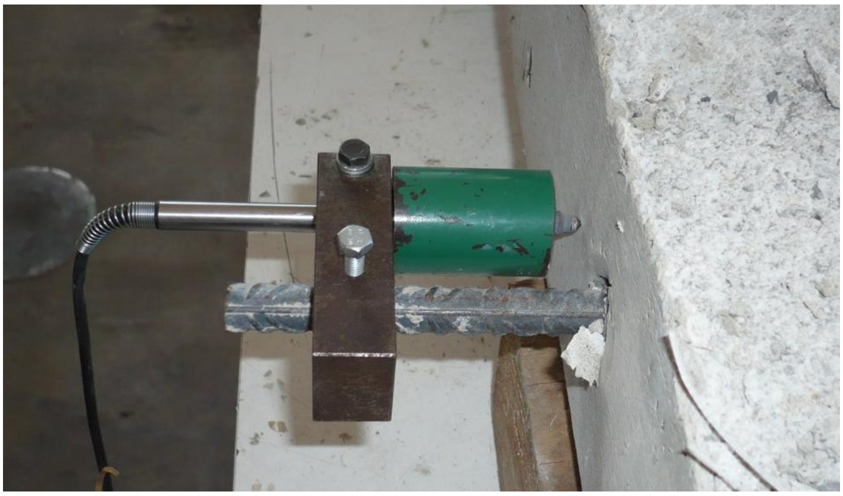

Figure 5. Rebar slip measurement.

Panels were sprayed using laboratory and tunnelling equipment with different concrete types and two rebar diameters to evaluate the influence of this parameter in the results. Notice that some of the panels are reinforced with fibres, while others do not include reinforcement. Table 1 summarizes the cases studied in the preliminary experimental program.

Table 1. Preliminary experimental program.

Panel	Rebar diameter (mm)	Position	Material	Equipment
1	16 12 12	Lateral Centre Lateral	Fibre reinforced sprayed concrete (3 kg/m^3 of polypropylene fibres) Accelerator: Aluminate 3%	Tunnelling
2	12 16 16	Lateral centre Lateral	Fibre reinforced sprayed concrete (3 kg/m^3 of polypropylene fibres). Accelerator: Aluminate 3%	Tunnelling
3	12 12 16	Lateral Centre Lateral	Fibre reinforced sprayed concrete (3 kg/m^3 of polypropylene fibres). Accelerator: Aluminate 3%	Tunnelling
4	16 12 12	Lateral centre Lateral	Unreinforced sprayed concrete. Accelerator: Alkali free 7%	Laboratory
5	16 16 10	Lateral Centre Lateral	Unreinforced sprayed concrete. Accelerator: Alkali free 7%	Laboratory
6	16 10 10	Lateral centre Lateral	Unreinforced sprayed concrete. Accelerator: Alkali free 7%	Laboratory

The typical bond stress-displacement curve obtained in the test is shown in Figure 6. As expected, initially the stress increases for very small displacement as a consequence of the mobilization of the bond between materials. Once a critical load level is achieved, an increase in the displacement rate is identified, evidencing possibly the microcracking of the material around the rebar and the beginning of the slip. After the bond strength is reached, the failure occurs and the acceleration the slip is verified with a consequent decrease in the stress resisted.

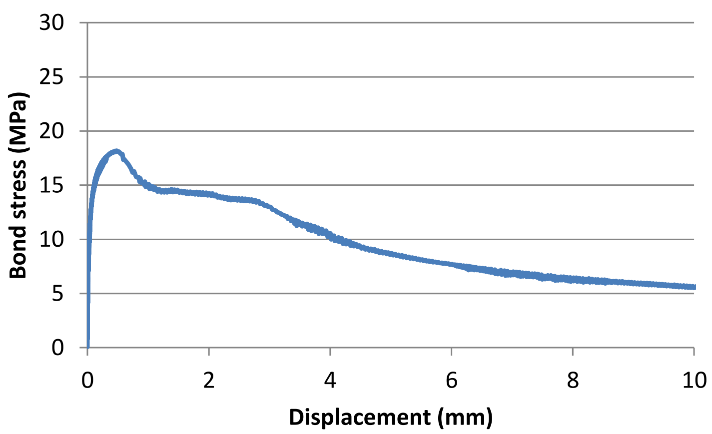

Figure 6. Typical bond behaviour.

Table 2 summaries the results of the pull-out test performed in the panels together with the compressive strength and some observations. High bond strengths were obtained in several bars. Nevertheless, the evaluation of the influence of the type of concrete and the rebar diameter was not possible given that incidents were verified in several tests.

Table 2. Bond test results from the preliminary experimental program.

Panel	Rebar diameter (mm)	Position	Compressive strength (MPa)	Bond strength (MPa)	Observations
1	16	Lateral	45.2 (2.5%)	19.81	
	12	Centre		18.05	
	12	Lateral		17.92	
2	12	Lateral		18.34	Rebar failure
	16	Centre		18.18	
	16	Lateral		18.65	
3	12	Lateral		15.94	
	12	Centre		17.85	
	16	Lateral		17.76	
4	16	Lateral	33.82 (8.6%)	16.46	The panel cracks
	12	Centre		21.01	The panel cracks
	12	Lateral		17.22	
5	16	Lateral		19.45	The panel cracks
	16	Centre		17.20	
	10	Lateral		14.84	
6	16	Lateral		11.87	The panel cracks
	10	Centre		8.24	
	10	Lateral		10.25	

For once, some of the panels with unreinforced sprayed concrete cracked during the pull-out. The crack appeared in the rebar plane due to the dilatancy induced by the slip and to the busting forces applied to the panels by the jack. Evidently, the bond behaviour measured in these cases cannot be considered valid. The fact that such failure did not occur in the panels with fibre reinforced sprayed concrete indicate that the external reinforcement may be required to guarantee enough internal confinement to derive valid results. Another incident observed in one of the panels tested was the breakage of the rebar instead of the failure of the bond between materials. This suggests that the bond length initially used must be reduced.

4.- Modified specimen definition

Based on the observations derived from the preliminary experimental program, some modifications were introduced in the test proposed. Figure 7 shows the modified mould used to produce the samples.

Figure 7. Modified panel.

Notice that the faces of the panel in contact with the jack and the face parallel to the latter were maintained perpendicular to the back of the mould. This was necessary to assure an approximately flat surface would exist to apply the pull-out load during the test and to measure the rebar slip. On the other hand, the perpendicular faces received a 45° inclination with the back of the mould in order to reduce the influence of the rebound in the nearby area.

Some restrictions were also adopted to avoid one rebar influencing the results of the adjacent ones and to reduce the influence of the borders. For that, the minimum distance between bars was set to 2 times the thickness of the panel. Moreover, the minimum distance with respect to the borders of the panel should be bigger than 1 time the thickness of the panel.

To provide enough confinement during the test and to mitigate the cracking of the concrete during the test, a steel frame composed by ϕ 12 mm bars was included in the panel. As indicated in Figure 5, the frame is placed nearby the edges of the mould to diminish its influence on the test results. In addition to that, the bond length was reduced to 5 times the nominal diameter of the rebar to reduce the probability that the failure do not occur by debonding.

5.- Influence of panel thickness

The thickness of the panel is one of the relevant variables that may affect the results. To evaluate its influence and properly standardize an adequate thickness, an experimental program was performed. Considering that a more accurate control of the thickness would be attained, panels were produced with normal concrete and traditional casting methods.

In total, three panels were cast with thickness of 80, 100 and 120 mm. Furthermore, to assess the reliability of the test proposed here, 3 cubic specimens with 200 mm of side were produced in order to evaluate the bond strength following the standard pull-out test for conventional concrete according with the EN 10080. Only 12 mm rebar diameter were used. The characterized length was 5 times the rebar diameter in all cases (60 mm).

A concrete mix proportion similar to that used in sprayed concrete was defined according with Table 3. The panels were filled in one layer and the compaction was applied in several points of the surface of the mould until a uniform distribution of material was achieved. Then, the surface was regularized. The cubic specimens were cast in two layers and each layer rodded 20 times. Cylindrical specimens with Ø100x200 mm2 were also produced to the evaluation of the compressive concrete strength according with the EN 12390-3. All samples were cured in environmental laboratory conditions and tested at 28 days.

Table 3. Mix proportions.

Component		**Content (kg/m^3)**
Cement	CEM I 42.5 R	425
Sand 0-5	Limestone	900
Sand 0-2	Limestone	380
Gravel 5-12	Limestone	380
Water		190
Superplasticizer	Polycarboxylic	4,25

The compressive strength of concrete was 59 MPa (C.V. 1.58%). Table 4 summarizes the results obtained in the panel and cubic specimen tests. The bond strength measured in the panels with 100 and 120 mm thickness were very similar. In fact, they show differences of only 9.4% on the average, which may be neglected bearing in mind the scatter of the results. This is not the case for the panels with 80 mm of thickness that shows bond strength 19.55% and 14.50% smaller than the obtained for the panels with 100 and 120 mm, respectively. Such differences may be considered significant if compared with the scatter measured in the test, thus suggesting that the smaller confinement provided by the slender thickness affected the results. On the contrary, the use of thickness equal or bigger than 100 mm does not seem to affect the results. It is also interesting to remark that no clear difference in behaviour was identified between the bars located closer to the centre and those located close to the edges.

Table 4. Bond strength in panels and cubic specimens.

Panel					
Thickness (mm)	**Left (MPa)**	**Centre (MPa)**	**Right (MPa)**	**Average (MPa)**	**C.V.**
80	22.10	19.58	20.42	20.70	6.19%
100	26.31	25.50	25.39	25.73	1.95%
120	22.74	26.75	23.13	24.21	9.14%
Cubic specimen (EN 10080)					
L (mm)	**1 (MPa)**	**2 (MPa)**	**3 (MPa)**	**Average (MPa)**	**C.V.**
200	19.63	20.76	22.91	21.10	7.90%

It is interesting to remark that the bond strength assessed with the pull-out test of the panels presented results in the same order of magnitude of those obtained with the cubic specimen. Such difference might be attributed to the higher degree of confinement achieved in the panels due to the use of a bar frame, which is not present in the case of the cubic specimen. Despite that, the proximity of results indicate indicates that the new test proposed here might deliver fair estimations of the bond strengths in comparison with traditional test methods.

6.- Application of final test setup to sprayed concrete

An analogous verification in concrete panels sprayed in laboratory conditions was conducted considering the minimum thickness obtained in section 5. The equipment used in the spraying process was a compact wet-mix machine Meyco Altera and a 10 m^3/min diesel portable air compressor. The wet-mix machine includes a control unit for pumped concrete flow and accelerator dosage, and a valve system to control the pressure of the air in the nozzle. For this application the pumped concrete flow and the air pressure were set to 4.4 m^3/h and 4 bars, respectively.

The mix proportion of the base concrete was the same presented in Table 3. An alkali free accelerator at dosage of 5% by weight of cement weight was incorporated for the spraying. In total, two panels were sprayed: one for the pull-out tests using 12 mm rebar and the other for evaluation of the compressive strength. The panel for pull-out test was sprayed with the rebar in vertical position. The operator started spraying the corners and edges of the panel, filling it in a single layer. After 24 hours the panels were demoulded and cured in environment laboratory condition until test date. After 7 day of the spraying, cores were extracted and cured in the same panel conditions for the evaluation of the compressive strength.

The setup of the pull-out test is showed in Figure 6. Notice that the thickness of the panel varied between 100 and 120 mm. The moulded edges showed a good finishing, with complete filling of concrete and absence of voids. All tests were performed 28 days after the spraying, following the same procedure described previously.

Figure 6. Final test setup.

The results achieved in the pull-out test are included in Table 5. The Table also includes the bond strengths obtained with conventional concrete in the study of the effect of the panel thickness. The compressive strength of extracted cores of sprayed concrete was 37 MPa (C.V. 3.6%). This value is approximately 37% smaller than the obtained in the study of the thickness panel effect using normal concrete with the same composition (see section 5).

Table 5 presents the bond strength measured for the sprayed concrete using the final test configuration.

Table 5. Bond strength in sprayed concrete.

Thickness (mm)	Left (MPa)	Centre (MPa)	Right (MPa)	Average (MPa)	C.V.
100-120	19,31	19,59	20,38	21,1	7,90%

The average bond strength measured in this case is smaller than the obtained for the normal concrete. However, the differences observed are in line with the variations in the compressive strength. Such outcome was already expected since the spraying process leads to a reduction in the coarse aggregate content – caused by the rebound – and to an increase in the air content of the material – caused by the spraying process.

7.- Conclusions

A new test was proposed in the present study to assess the bond between sprayed concrete and reinforcement. This test has proven compatible with the spraying procedure found in practice and may be used for the evaluation of properties of the material. It may be also used for the quality control and the nozzleman evaluation, since ensuring a good compacting of the concrete around the rebar is one of the qualities that best demonstrate the operator ability. Even though further studies are being conducted to validate this proposal, the following conclusions may be derived based on the results obtained in the experimental programs performed.

- A reinforcement frame should be used in the panels in order to provide enough confinement and avoid concrete failure during the test.
- The operator must ensure that the panels have a thickness of at least 100 mm. An influence of the thickness on the results should be expected for slenderer panels.
- The tests performed in panels and cubic specimens with conventional concrete have shown similar bond strength, indicating that the new method provides a fair prediction of the bond.
- Despite the singularities of the material, the bond strength between sprayed concrete and steel rebar could achieve values in the same order of magnitude of those obtained for conventional concrete.

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