Comparison of destructive methods to appraise the mechanical integrity of a concrete surface

L. Courard[1], B. Bissonnette[2], A.M. Vaysburd[3], N. Bélair[2], and F. Lebeau[1]

[1] GeMMe Building Materials, ArGEnCo Department, University of Liège, Belgique
[2] CRIB, Civil Engineering Department, Laval University, Québec (QC), Canada
[3] Vaycon Consulting, Baltimore, MD, U.S.A.

ABSTRACT

Depending on the technique being used, the concrete removal operation prior to repair can be harmful to the residual concrete skin left on the structure. Whenever a tight bond between the repair and the old concrete is required, the soundness of the prepared surface should thus be assessed. Although this is widely recognized, there is no standard method intended to characterize the integrity of a concrete substrate after concrete removal. This paper presents the results of an investigation intended to assess and compare quantitatively different test methods, namely the *Schmidt* rebound hammer, the *Capo* and *Accelerated cohesion* pullout tests, and the pull off test, to evaluate superficial mechanical integrity of a substrate after concrete removal operations. Although it does not yield a precise evaluation of compressive strength, the *Schmidt* rebound hammer test is recognized as a useful tool for performing quick surveys to assess concrete uniformity. The pull off test is very well correlated with the splitting-tensile test, but it is not suited for vertical and overhead surfaces. The *Capo* pullout test has limited interest for surface preparation, as it is applicable to flat surfaces only. Conversely, the *Accelerated cohesion* test showed interesting potential as a simple tool for assessing the mechanical integrity of a concrete surface prior to repair for any type of concrete surface. More work is required to refine the procedures and develop statistically based acceptance criteria. Nevertheless, it appears from the results generated in this study that the combination *Schmidt* hammer / pull off tests could fulfill the needs for the evaluation of horizontal surfaces after concrete removal, while the combination *Schmidt* hammer / *Accelerated cohesion* tests could be used effectively on any surface, irrespective of its orientation.

INTRODUCTION

The concrete repair industry is in constant search for improved guidance guidance on the methods available to assess the condition of existing structures and interpret adequately the related data [1-2]. Beyond the stage of visual examination and hammer-sounding (tapping), questionable areas can be subjected to further investigation using a variety of techniques [3-5]. In Table 1, a list of methods to assess in-place concrete strength and/or physical integrity is provided.

Table 1 – Test methods to evaluate in-place concrete [6].

Strength assessment	**Integrity assessment**
Rebound hammer	Visual inspection
Ultrasonic pulse velocity	Stress wave propagation methods
Probe penetration	Ground penetrating radar
Pullout	Electrical/magnetic methods
Break-off	Nuclear methods
Maturity method	Infrared thermograph

As part of the concrete repair process, in order to promote optimal adhesion of the repair material, the concrete substrate must be prepared to yield a rough surface that is free from defects and contaminants [7-8]. Depending on the technique being used, the concrete removal operation can be harmful to the residual concrete substrate. Whenever bond is key to the success of a repair, the soundness of the prepared surface should be assessed after surface preparation. This issue could become even more critical than the condition evaluation carried out before undertaking the repair project.

Although the effect of substrate condition on bond is widely recognized [1,5,7], there is still no standard method intended for characterizing the integrity of a concrete substrate after concrete removal. For one, Belgian guidelines [9] explicitly recommend performing a pull off test [10] directly on the substrate, especially if doubt exists about the quality of surface preparation; a minimum value of 2 MPa is usually recommended. This must be seen as a guiding value. For low strength concrete, a lower value could be specified.

An experimental program has been conducted by the authors [11] to evaluate the influence of various parameters on the measured cohesion of a concrete surface by means of pull off test. The test method shows good potential for a sound quantitative evaluation of a concrete surface mechanical integrity prior to repair, provided that the test parameters are selected properly.

Test location and interpretation of test results [12] must consider the possible variations of material properties within structural members and differences between in-situ and standard specimen strengths. The proper testing layout actually depends on whether it is intended to determine average values for a member (for specification compliance) or to assess the substrate condition in critical areas (for structural adequacy assessment). Furthermore, the number of test locations would vary with the objectives of the test and the expected level of confidence for the overall strength estimates. Typically, between 5 and 8 locations are tested.

This paper presents the results of an investigation intended to assess and compare quantitatively different test methods, namely the *Schmidt* rebound hammer, the pullout test and the pull off test, to evaluate the integrity of a substrate after concrete removal operations.

EXPERIMENTAL PROGRAM

Test methods and parameters

Schmidt rebound hammer (ASTM C 805 and BS 1881 – part 202)

Due to its simplicity of use and low cost, the *Schmidt* rebound hammer (ASTM C 805) is a most widely used device for non-destructive testing of concrete (Fig. 1). It operates as follows: a spring-loaded hammer impacts with a given amount of energy a steel plunger in contact with the concrete surface, and the distance that the hammer rebounds is recorded. The rebound value is primarily influenced by the elastic modulus and strength of the concrete near the surface [6]. While the test may be simple to perform, the relationship between measured rebound and in-place concrete strength is sensitive to a number of parameters. In particular, the results are influenced by the moisture condition, carbonation and surface texture of the concrete, as well as hammer inclination [5-6]. Since the plunger's rebound depends on the energy being restituted from the substrate, it is expected that incidence of bruising and cracking in the surface layer will reflect in the recorded values. Although the evaluation of strength is not an issue in the present study, the test results are expressed in terms of strength.

Fig. 1 – The *Schmidt* rebound hammer

Pullout test

Post-installed test procedures were selected for evaluation in this study, as they are well suited for the intended purpose. In this method, a metallic insert is embedded in the concrete. The insert and surrounding conical volume of concrete are pulled out by a tension jack, which pushes against the peripheral concrete surface through a concentric reaction ring. The device records the ultimate force required to pull out the insert, which values provides an indirect evaluation of the concrete strength. Obviously, the recorded value does not correspond to any fundamental mechanical property of the material, but it definitely reflect the material's compressive and tensile strengths and it is likely to be affected by the presence of damage or defects at the surface, above the expanded steel ring. Among a variety of pullout test procedures [6], two were investigated in the present study. The first one is the standardized *Capo* pullout test (ASTM C 900 and BS 1881 – part 207), adapted from the *Lok* test[1], and where a groove in the predrilled hole allows a

[1] The insert is installed against the concrete form before casting.

compressed steel ring to expand and confine the concrete (Fig. 2). The other investigated test, referred to here as the *Accelerated cohesion test*, is a non-standard procedure that uses a two component adhesive anchor consisting of a self-contained adhesive capsule and a threaded rod with nut and washer. For such experiments, it has been found that a minimum of 5 tests is recommended to yield reliable results [12].

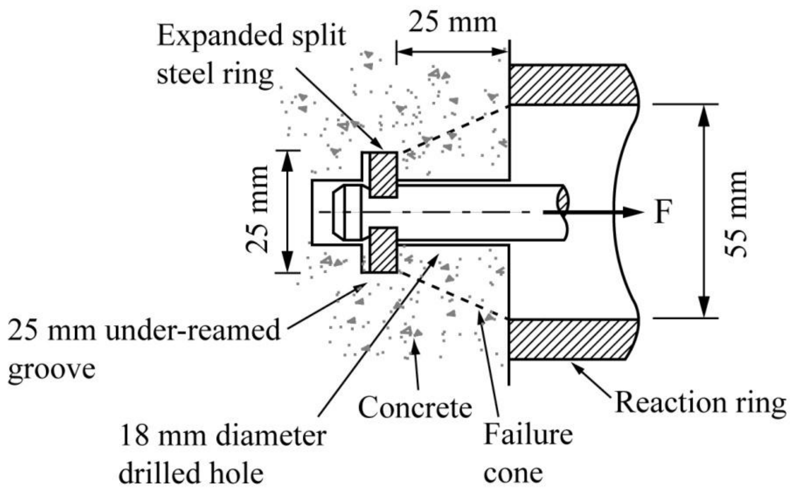

Fig. 2 – Pullout - *Capo* test [13]

Pull off test (EN 1542, BS 1881 – part 207)

The pull off test is commonly used to assess the adhesion of repair systems to concrete. It measures the direct tensile force required to pull off a metallic disk, together with a layer of concrete, from the surface to which it has been epoxy-glued (Fig. 3).

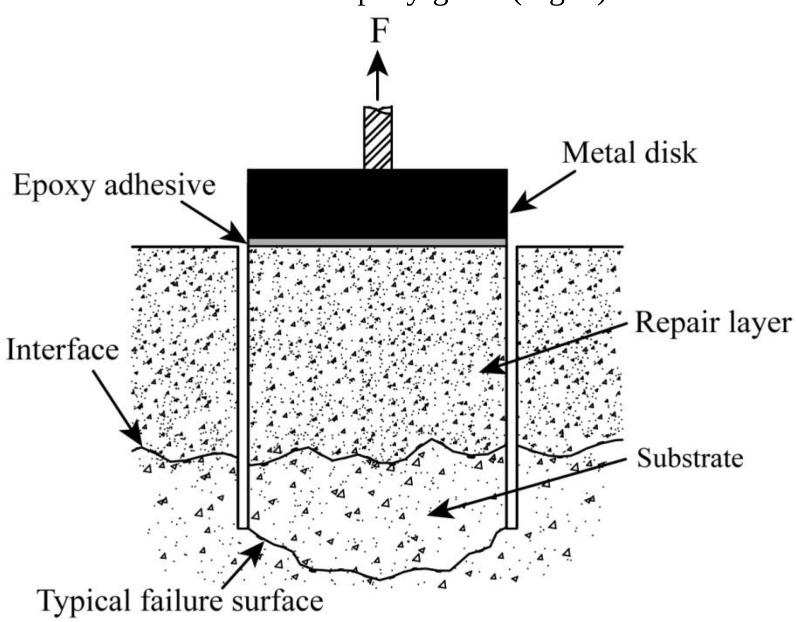

Fig. 3 – Pull off test

The pull off test can also be used to evaluate the cohesion and integrity of a concrete surface to be repaired [9-11,14-16]. An experimental program was conducted in a previous study [11] to evaluate the influence of various test parameters—metal disk thickness and diameter, core drilling depth, loading rate, adhesive type and thickness, and number of tests—to measure the cohesion of a reference concrete surface. A statistical results analysis revealed that disk diameter and core-drilling depth are the most significant parameters, presumably with threshold values (Fig. 4), which actually depend on the maximum aggregate size.

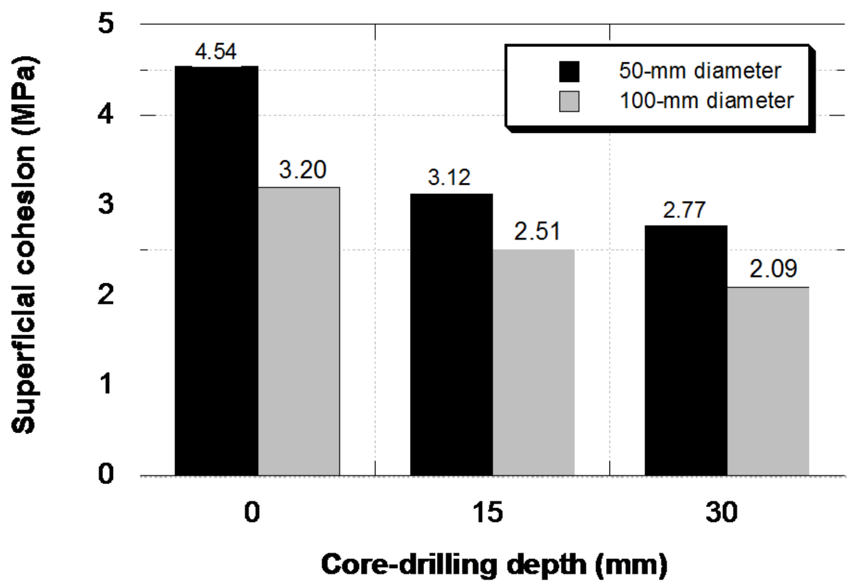

Fig. 4 – Effects of core-drilling depth and metal disk diameter on surface concrete cohesion (loading rate < 0.05 MPa/s)[11]

In order to yield low standard deviation and satisfactory level of confidence in the results (maximum coefficient of variation of 12 %), a minimum of 5 tests is recommended. Other authors [12] recommend a minimum of 6 pull off tests in a specific area to be assessed.

After testing, and depending on the failure mode or value, concrete integrity may need to be assessed further to examine the presence of cracks near the failure surface (mostly parallel to the surface) as a result of surface preparation operations [7].

Test series and materials

Experiments have first been performed on untreated concrete surfaces in order to study the significance and sensitivity of test parameters. Then, test series intended to evaluate the cohesion of concrete after various surface treatments were carried out.

Slab and block test specimens were cast using concrete with 0.40 and 0.48 water/cement ratios, respectively. The former was made using 10-mm crushed granite as coarse aggregates, while the latter used 20-mm aggregates from the same source. Table 2 presents the concrete mixture designs, which had been used as reference materials in other related research projects devoted to repair and rehabilitation issues.

Table 2 – Concrete mixture compositions, plastic concrete properties and mechanical properties at the age of 28 days

Mixture design		Slab specimens S1-series	Slab specimens S2-series	Block specimens B-series
Cement (CSA type 10)	(kg/m^3)	384	383	406
Water	(L/m^3)	156	187	165
Sand	(kg/m^3)	736	734	779
Coarse aggregate (2.5-10 mm)	(kg/m^3)	-	916	972
Coarse aggregate (10-20 mm)	(kg/m^3)	918	-	-
Air-entraining admixture	(mL/m^3)	78	76	78
Superplasticizer				
Polycarboxylate-based	(mL/m^3)	980	1,269	
Naphthalene-based	(mL/m^3)			2,352
W/cm		0.40	0.48	0.40
Air content	(%)	11	9	5.8
Slump	(mm)	145	75	35
Compressive strength (f_c)	(MPa)	32.3	46.0	48.3
Splitting-tensile strength (f_{st})	(MPa)	3.3	4.0	-

Three concrete batches were prepared for the fabrication of 13 concrete slabs and 3 concrete blocks. Two different slab configurations were cast: type S1 (500 × 500 × 90 mm) and type S2 (730 × 730 × 90 mm). After casting, the slabs were covered with wet burlap and a polyethylene sheet for 48 hours. They were then stored in the laboratory at 23 °C and 50-70 % RH for 26 days. The three 610 × 910 × 610 mm block specimens (B-series) were cured for 7 days in a humidity chamber and then air-stored in the laboratory for 21 more days.

COMPARISON AND STATISTICAL EVALUATION OF METHODS ON FLAT FINISHED CONCRETE SURFACES

Schmidt rebound hammer test

The *Schmidt* rebound hammer tests were performed on cast surfaces, before any treatment. To estimate the required number of data for statistical significance, a large number of tests were carried out. Based on the results summarized in Table 3, it seems that the average compressive strength estimated with the *Schmidt* hammer is not significantly influenced by the number of tests, at least beyond 25 replicas. It thus appears that 25 tests are sufficient for the surface investigated.

Table 3 – *Schmidt* rebound hammer test results: influence of the number of tests performed upon statistical parameters (S2 slab specimens)

Statistical parameter	S2-5 slab			S2-6 slab		
	no. of tests			no. of tests		
	61	36	25	61	36	25
Average value (MPa)	32.3	32.1	32.5	30.9	30.9	30.8
Coefficient of variation (%)	10.1	10.8	9.0	8.3	9.3	6.8

The *Schmidt* hammer results obtained for all concrete slabs are presented in Fig. 5. The differences between S1-3 and S1-3* appear to be mostly related to the nature of the support provided underneath the test slabs, either continuous (wooden platform) or discontinuous (2 wood lumbers). Variability, which is evaluated with the coefficient of variation (CV), is lower when the concrete specimen is placed on a continuous support (Fig. 6).

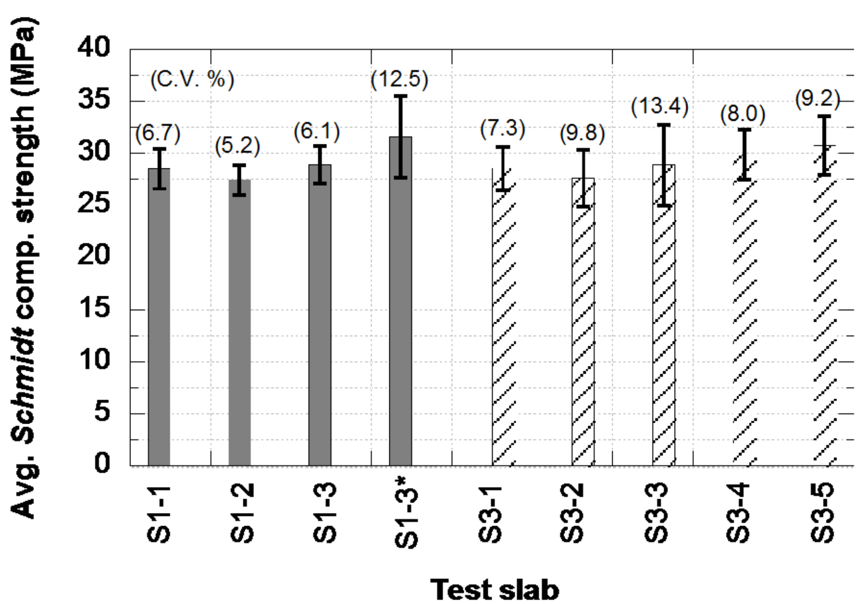

Fig. 5 – Average compressive strength values estimated from the *Schmidt* rebound hammer tests on flat finished slab specimens

Capo pullout test

Capo pullout test series were performed on slabs from both series to account for the coarse aggregate size effect. Results are presented in Table 4.

Strictly from the test result data, no specific trend could clearly be associated to the coarse aggregate size. Nevertheless, the observation of the extracted concrete fragments (conical-shape failure) revealed that larger aggregate size in S1-series slabs altered the cracking pattern, resulting in a much more irregular conical shape (Figure 6 a) and b)).

Table 4 – *Capo* pullout test results (S1- and S2- series slabs)

	Compressive strength (MPa)	
Test no.	S1-series slabs	S2-series slabs
1	26.6	37.3
2	30.2	33.0
3	31.9	27.5
4	25.9	29.4
5	32.7	35.4
6	30.0	33.7
7	29.2	34.5
8	33.3	38.8
Average value	30.0	33.7
Coefficient of Variation (%)	9.0	11.2

a) S1-series slab b) S2-series slab

Fig. 6: Typical pullout conical-shape failure after *Capo* pullout tests

Accelerated cohesion test

The first step was to conduct a parametric study taking into account diameter (6.4 mm and 9.5 mm) and anchorage depth (15 mm and 20 mm). Along the test program, two failure modes were encountered:

1. <u>Type 1</u>: The failure mode is characterized by anchor extraction with little or no concrete near the surface. This can be the result of insufficient polymerization of the adhesive or by the presence of interfacial defects (air bubbles or lack of adhesion between adhesive and concrete), which cause a weak bond between the adhesive and concrete and ultimately trigger failure.
2. <u>Type 2</u>: The failure mode leads to the extraction of a cone-shaped concrete fragment along with the anchor. This type of rupture is known as *conical-shape* failure. Fig. 7 illustrates this type of failure and the corresponding geometrical parameters. In many cases, the extracted cone exhibited two segments, the angle α decreasing sharply near the surface.

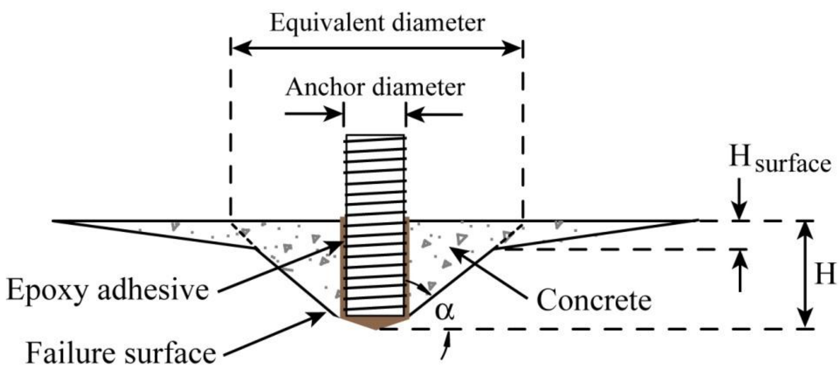

Fig. 7 – Schematic diagram of the conical-shape failure observed in *Accelerated cohesion* tests

The test results are presented in Table 6. Overall, the recorded variability is quite low for such a test in concrete. Taking into consideration both the coefficient of variation and the percentage of cone-type failures, the most effective combination appears to be a 9.5-mm diameter anchor embedded down to a depth of 15 mm.

Table 6 – *Accelerated cohesion* test results (B-series specimens)

Test no.	Pullout load (kN)			
	6.4-mm ϕ anchor		9.5-mm ϕ anchor	
	Anchorage depth		Anchorage depth	
	15 mm	20 mm	15 mm	20 mm
1	4.0	5.8	4.3	6.7
2	4.3	6.0	4.1	7.1
3	3.5	6.2	4.5	6.4
4	4.1	5.5	3.9	7.2
5	4.3	5.7	4.5	7.5
6	3.6	5.8	4.5	7.2
7	4.3	6.5	4.5	7.6
8	3.7	6.6	4.8	6.6
Average value	4.0	6.0	4.4	7.0
Coefficient of Variation (%)	8.4	6.5	6.4	6.1
Conical-shape failure (%)	38	50	100	63

In order to compare the results of the pull off and *Accelerated cohesion* tests, the surface area of the failure cone in the latter was evaluated to determine the effective tensile cohesion stress. The tensile load-bearing surface was calculated by evaluating the horizontal projection of the cone area, less the steel anchor cross-section. In determining the equivalent diameter at the surface, the assumption was made that the cone angle (α) was constant from the bottom up to the surface (enlargement near the surface neglected). Equivalent surfaces and corresponding stress values for tests conducted with 9.5-mm diameter anchors at a depth of 20 mm are presented in Tables 7 and 8.

Table 7 – *Accelerated cohesion* test results (S1-series slabs)

Test no.	Pullout load (kN)	Angle α (°)	H (mm)	Equivalent diameter (mm)	Equivalent surface (mm²)	Pullout stress (MPa)
1	5.2	29.6	10.3	45.8	1,576	3.30
2	4.8	25.5	14.4	69.9	3,768	1.27
3	5.1	39.8	17.6	51.7	2,032	2.51
4	6.6	31.5	16.9	64.6	3,204	2.06
5	6.2	33.6	13.5	50.1	1,900	3.26
6	5.7	19.2	20.0	125	12,093	0.47
7	5.0	23.1	11.6	63.9	3,136	1.59
8	5.7	39.1	16.8	50.8	1,956	2.91
Average value	5.5	30.2	15.1	65.2	3,708	2.17
Coefficient of Variation (%)	11	24	22	39	94	47

Table 8 – *Accelerated cohesion* test results (S2-series slabs)

Test no.	Pullout load (kN)	Angle α (°)	H (mm)	Equivalent diameter (mm)	Equivalent surface (mm²)	Pullout stress (MPa)
1	7.1	30.2	19.4	76.2	4,494	1.58
2	6.4	36.1	17.1	56.5	2,435	2.62
3	7.2	13.6	19.2	168	22,030	0.33
4	7.2	20.0	20.5	122	11,623	0.62
5	7.6	20.0	19.6	118	10,765	0.71
Average value	7.1	24.0	19.2	108	10,269	1.17
Coefficient of Variation (%)	6.1	38	6.5	40	75	80

While recorded pullout load values again exhibit little dispersion, the corresponding cohesion stress values are quite variable owing to the variability of the calculated surface values. Again, the use of larger coarse aggregates clearly induces a wider dispersion of results. Larger aggregates alter crack propagation, particularly at the base of the cone, yielding a greater angle α and a smaller failure surface. This limits the interpretation of the near-to-surface characteristics, given the observed dispersion. In the remainder of this study, *Accelerated cohesion* test results will therefore be analyzed based on the raw pullout load values.

Pull off test

The pull off tests were performed on the S1- and S2-series slabs using a core-drilling depth of 20 mm. The test results are summarized in Table 9. The aggregate size appears to have a limited influence on cohesion strength and variability. Nonetheless, the location and shape of the failure surface were more variable for the larger size aggregate concrete.

Overall, the recorded values are very close to the corresponding splitting tensile strength data (see Table 2). This is consistent with the results of a previous program [11], where pull off testing was shown to be an effective technique for evaluating the mechanical integrity of horizontal surfaces after concrete removal. For quality control purposes, an acceptance criterion corresponding to a fraction of the average splitting-tensile strength (f_{st}) result could be specified.

Table 9 – Pull off test results (S1- and S2-series test slabs)

Test no.	Pull off stress (MPa)	
	S1-series slabs	S2-series slabs
1	3.42	3.92
2	3.06	3.60
3	3.35	4.19
4	3.24	4.10
5	3.30	3.92
6	3.30	3.67
7	3.12	4.05
8	3.40	4.01
Average value	3.27	3.93
Coefficient of Variation (%)	3.91	5.12

COMPARISON OF METHODS FOR ASSESSMENT OF PREPARED CONCRETE SURFACES

Surface preparation techniques

The following concrete surface treatments were performed on the B-series specimens to carry out in this part of the experimental program:

- sandblasting;
- concrete cover removed using a 9-kg handheld concrete breaker;
- concrete cover removed using a 11-kg handheld concrete breaker; and
- concrete cover removed using a 34-kg handheld concrete breaker.

On all three block specimens, two lateral surfaces were prepared by sandblasting (SB) while the two other ones were left unprepared (none) to provide a reference. The top surface of each of the three blocks was then prepared using a different concrete breaker (CB): 9-kg breaker (CB9), 11-kg concrete breaker (CB11) and 34-kg concrete breaker (CB34). The resulting surface roughness characteristics and the influence on the repair material bond strength were not addressed in this part of the project. Information in that regard can be found elsewhere [17-18].

Schmidt rebound hammer tests and *Accelerated cohesion* tests were conducted for a comparative assessment of physical integrity on the treated and reference surfaces. The *Capo* pullout test and the pull off test were left out of that part of the program, as the former absolutely requires a flat surface, while the latter has already been investigated in-depth for the same purpose in a previous study [11].

Schmidt rebound hammer

Figure 8 presents the average results and coefficients of variation respectively of the *Schmidt* hammer soundings performed on all testing surfaces (avg. of 60 results for ref. and SB treatment; avg. of 25 results for CB treatments).

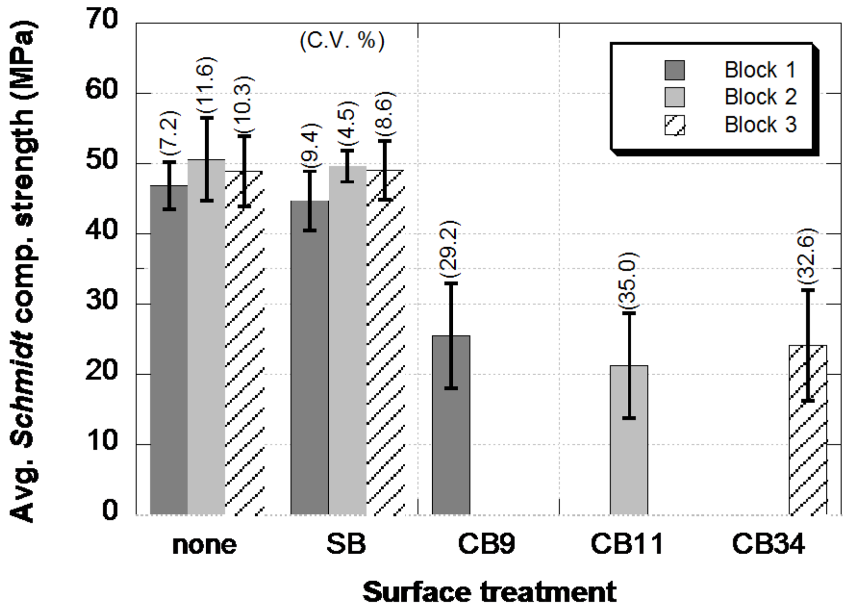

Fig. 8 – Average compressive strength values estimated from the *Schmidt* rebound hammer tests on slab specimens after different surface treatments (SB: sandblasting; CB9: 9-kg concrete breaker; CB11: 11-kg concrete breaker; CB34: 34-kg concrete breaker)

Again, the compressive strength values calculated from the recorded *Schmidt* hammer rebound data are strictly used here on a comparative basis. As shown in Figure 8, the results obtained for the surfaces prepared with concrete breakers exhibit much more variability, which can be attributed to the following:

- variability in the procedure (applied force, duration);
- angle between the axis of the hammer and the concrete surface; and
- surface topology (the hammer tip can hit an aggregate, cement paste or both).

Although this test can yield significant average values when performed over large surfaces, the data recorded in the present study suggest that variability, not in as much as the absolute values, provide a reliable indication of the presence and importance of defects in the substrate. Based upon the results generated with the various investigated surface preparation methods (see Table 3, Figs. 5 and 8), it appears that a threshold C.V. value of the order of 15 to 20 % could discriminate between prepared surfaces where significant bruising has been left or not.

***Accelerated cohesion* test**

Table 10 summarizes the results obtained on side and top faces of the concrete block specimens (B1, B2 and B3), which had received the different surface treatments as described previously.

No statistical differences were found between the reference and sandblasted (SB) surfaces. The coefficients of variation are relatively low and the test method appears to be suitable for vertical surfaces. Although the average pullout strength values obtained for the surfaces prepared with concrete breakers are only slightly lower than those obtained on the reference and SB surfaces, the coefficients of variation are substantially higher.

Table 10 – *Accelerated cohesion* test results (block specimens)

Surface treatment	Average pullout load (kN)			Coefficient of variation (%)		
	B-series specimen			B-series specimen		
	B1	B2	B3	B1	B2	B3
none[a]	4.9	5.5	5.4	8.4	2.4	7.1
SB[a]	5.4	5.6	5.0	6.9	4.7	12.7
CB9[b]	5.0	-	-	24.7	-	-
CB11[b]	-	4.9	-	-	18.0	-
CB34[b]	-	-	4.9	-	-	24.9

[a] each reported value is the average of 8 test results

[b] each reported value is the average of 12 test results

The higher pullout strength result variability in the case of the surfaces prepared with concrete breakers can obviously be explained by their irregular profile, but also by the presence of microcracking within the surface concrete layer. In previous investigations [7], it was found that the number of cracks and total crack length are usually significantly higher (2-4 times and 4-25 times, respectively) on substrates prepared with concrete breakers than on those prepared with most other common techniques. Moreover, increasing the hammer weight—and therefore its impact energy—significantly increases both length and number of cracks.

Overall, the coefficients of variation of the data generated with the *Accelerated cohesion* test are comparable to those characterizing the the Schmidt hammer data. Again, a threshold C.V. value of the order of 15 to 20 % could discriminate between prepared surfaces where significant bruising has been left or not.

CONCLUSIONS

Surface preparation is often a critical step in concrete repairs. While it is well acknowledged that the concrete removal operation can induce bruising and cracking in the substrate, there are still no simple practical means available to assess the integrity of a prepared surface. The investigation reported in this paper intended to evaluate different test methods for that purpose: the *Schmidt* rebound hammer, the *Capo* pullout test, the *Accelerated cohesion* test, and the pull off test.

Although the *Schmidt* rebound hammer test cannot systematically yield a reliable evaluation of the in-place compressive strength of concrete, it was shown to provide valuable comparative data for detecting superficial defects on a concrete surface [5]. The rebound hammer method is thus recognized as a useful tool for performing quick surveys to assess concrete uniformity and mechanical integrity over freshly prepared substrates.

The *Capo* pullout test has limited interest for surface preparation, as it can only be carried out on smooth surfaces.

Conversely, the *Accelerated cohesion* test exhibited interesting potential as a simple tool for assessing the mechanical integrity of a concrete surface prior to repair. Not only can it be used on any concrete surface, but it is also simpler and much faster than the pull off test. Obviously, the test procedure requires some optimization; within the variables investigated in this study, the most reproducible results were obtained with a steel threaded rod having a diameter of 9.5 mm and anchored in a 15-mm deep drilled hole. In the quest of such a test for the field evaluation of surface concrete integrity, the use of commercially available chemical anchors would certainly be desirable.

The pull off test provided results that are very close to the actual splitting-tensile strength of the material. Moreover, it was shown in a previous study that it can effectively capture the presence of bruising. Still, it is difficult to perform adequately on vertical or overhead surfaces and in practice, its use is essentially limited to horizontal surfaces.

Finally, it appears from the results generated in this study that the combination *Schmidt* hammer / pull off tests can fulfill the needs for the evaluation of horizontal surfaces after concrete removal, whereas the combination *Schmidt* hammer / *Accelerated cohesion* tests can be used effectively on any surface, irrespective to its inclination. For quality control purposes, acceptance criteria could be specified for both the hammer soundings (ex. C.V. < 20 %) and cohesion strength test results (ex. *pull off test*: cohesion strength > 0.75 f_{st} ; *Accelerated cohesion test*: C.V. < 20 %).

ACKNOWLEDGMENTS

This project has been financially supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Québec FQRNT Research Fund and the industrial partners of the Industrial Chair on Durable Repair and Optimized Maintenance of Concrete Infrastructures at Laval University (BASF Building Systems, City of Montreal, City of Québec, Euclid, Hydro-Québec, King Packaged Materials, Lafarge, Ministry of Transportation of Québec, St-Lawrence Cement, W.R. Grace & Co. Support was also provided by the Belgium (Wallonia Brussels International) and Quebec governments through the Wallonie-Bruxelles-Québec Scientific Cooperation Program.

REFERENCES

1. Silfwerbrand, J., "Improving Concrete Bond in Repaired Bridge Decks," *Concrete International*, V. 12, No. 9, 1990, pp. 61-66.
2. Vaysburd, A. M., and Emmons, P.H., "How to Make Today's Repairs Durable for Tomorrow – Corrosion Protection in Concrete Repair," *Construction and Building Materials,* V. 14, No. 4, 2000, pp. 189-197.
3. Robery, P.C., "Investigation Methods Utilizing Combined NDT Techniques," *Construction Repair*, V. 9, No. 6, 1995, pp. 11-16.
4. Garbacz, A., and Garboczi, E., "Ultrasonic Evaluation Methods Applicable to Polymer Concrete Composites," United States Department of Commerce, Report No. NISTIR 6975, Gaithersburg, MD, 2003.
5. Courard, L.; Bissonnette, B.; and Trevino M., "Condition Evaluation of the Existing Structure prior to Overlay," *Bonded cement-based material overlays for the repair, the lining or the strengthening of slabs or pavements,* Report of RILEM TC 193-RLS, 2011, pp. 17-50.
6. Carino, N.J., "Non Destructive Test Methods to Evaluate Concrete Structures," Sixth CANMET/ACI International Conference on the Durability of Concrete, Special Seminar, Thessaloniki, Greece, 2003, 75 pp.
7. Bissonnette, B.; Courard, L.; Vaysburd A.; and Bélair, N., "Concrete Removal Techniques: Influence on Residual Cracking and Bond Strength," *Concrete International*, V. 28, No. 12, 2006, pp. 49-55.
8. Courard, L.; Michel, F.; Schwall, D.; Van der Wielen, A.; Garbacz, A.; Piotrowski, T., Perez, F.; and Bissonnette, B., "Surfology: Concrete Substrate Evaluation prior to Repair," *Materials Characterization: Computational Methods and Experiments IV*, A. Mammoli and C.A. Brebbia eds., Wessex Institute of Technology Press, The New Forest (U.K.), June 17-19, 2009, pp. 407-416.
9. Belgian Construction Certification Association, "Technical Prescriptions for Concrete Repair Mortars," Belgian Guidelines PTV 563, Brussels, Belgium, 2007.
10. CEN European Committee for Standardization, "Products and systems for the protection and repair of concrete structures - Test methods - Measurement of bond strength by pull-off," EN 1542, Brussels, Belgium, 1999.
11. Bissonnette, B., and Courard, L., "Pull Off Test for the Evaluation of the Superficial Cohesion of Concrete Substrates in Repair Works: Analysis of the Test Parameters (in French)," *Materials and Structures*, V. 37, 2004, pp. 342-350.
12. Bungey, J.H., "Assessment of In-Situ Concrete Strength: Overview of Test Procedures," University of Liverpool, 2000.
13. Bungey, J.H., and Soutsos, M.N., "Reliability of Partially-Destructive Tests to Assess the Strength of Concrete on Site," *Construction and Building Materials,* V. 15, 2001, pp. 81-92.

14. Hindo, K.L., “In-Place Bond Testing and Surface Preparation of Concrete,” *Concrete International*, V. 12, No. 4, 1990, pp. 46-48.
15. Emberson, N.K., and Mays, G.C., “Significance of Property Mismatch in the Patch Repair of Structural Concrete Part 1: Properties of Repair Systems,” *Magazine of Concrete Research*, V. 42, No. 152, 1990, pp. 147-160.
16. Austin, S.; Robins, P.; and Pan, Y., “Tensile Bond Testing of Concrete Repair,” *Materials and Structures*, V. 28, No. 179, 1995, pp. 249-259.
17. Perez, F.; Bissonnette, B.; and Courard L., “Combination of Mechanical and Optical Profilometry Techniques for Concrete Surface Roughness Characterization,” *Magazine of Concrete Research*, V. 61, No. 6, 2009, pp. 389-400.
18. Garbacz, A.; Gorka, M.; and Courard L., “Effect of Concrete Surface Treatment on Adhesion in Repair Systems,” *Magazine of Concrete Research*, V. 57, No. 1, 2005, pp. 49-60.