A New Method for Evaluating (Determining) Steel bar-Concrete Adhesion in Self Compacting Concrete:effect of water to binder ratioand type of concrete.

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ABSTRACT.The resistance to separation of the concrete from its reinforcing steel with which it is in contact is called adhesion .This adhesion constitutes an important property for the use of reinforced concrete. That is why many techniques were developed with the aim of determining this property. Adhesion can be easily found out by standard pullout test machine. However, in this work, the adhesion was measured using Interfacial Indentation test. This technique creates and propagates a crack along the concrete/ steel bar interface and defines the apparent interfacial toughness, which can then be related to the adhesion and mechanical support of the aforementioned interface. Using reinforcing bars, adhesion was measured using Self Compacting Concrete (SCC) and Normal Vibrated Concrete (NVC) specimens. The impact of water-to-binder ratio variations and concrete type on concrete /steel bar adhesion has been the incentive of the present study. Interfacial indentation test on small cylindrical samples have been conducted for 5 SCC and 2 NVC mixtures. Various apparent interfacial toughness have been evaluated. The water-to-binder and concrete type changes seem be better reflected on interfacial toughness, which decrease linearly for higher water content. SCC develops an improved adhesion capacity compared to same strength NVC with similar composition. In this type of studies are rarely those who have tried to characterize the adhesion of matrix/ steel bar reinforcement in Self Compacting Concrete by using the interfacial indentation test as a new methodology. Exclusively, the objective of this research is to fill this gap by characterizing for the first time this concrete/steel bar adhesion by interfacial indentation test and then study the effects of some parameters such as water to binder ratio (w/b) and concrete type on its behavior and on the microstructure of the developed composite material.
In conclusion, the indentation test showed clear advantages over the conventional pullout test and shows once again its aptitude to study the adhesion of concrete/ steel bar reinforcement couple.

KEY WORDS:*Apparent interfacial toughness (Kca); Interfacial indentation test; Water-to-binder ratio (w/b); Nature of concrete; Self compacting concrete (SCC); Microstructure.*

1. Introduction

Self-compacting concrete (SCC) is a composite material, designed to resist compressive stresses (concrete) and tensile stresses (reinforcement steel). To achieve an effective Reinforced Concrete (RC) structure, a good adhesion between concrete and steel bar reinforcement is necessary to enable force transfer between both materials. Its properties rely on the matrix, aggregate, still and the interfacial transition zone (ITZ) between matrix and aggregate, matrix and Steel bar reinforcement. However, different researchers obtained different thicknesses of ITZ from their tests. For instance, the thickness of the transition zone between the aggregate and matrix and between steel bar reinforcement and matrix ranged from 10 μm to about 30μm[1];Olivieretal.[2]arguedthattherewasonlythicknessof15 μm to 20 μm around the aggregates, just equaling to the mean diameter of the cement grains[4]. Diamond and Huang [5]pointed out, that there is no reason to assume the significant negative effects of ITZ on permeance or mechanical properties of concrete, even for concrete with a water/binder ratio of 0.5.The ITZ between the steel bar and matrix was affected by the water/binder (w/b) ratio [6].Mineraladmixturessuchassilicafume[3,6 ,7]and fly ash [8]were also introduced to improve the quality of the steel bar/matrix interfacial zone.Because of the size of applied loads (400 N, 600 N, 800 N, 10000 N and 1200 N), the depth of indentation becomes larger and also the impact of the indent in comparison with the thickness of ITZ [9]. With the importance of these magnitudes, the indentation will directly affect the matrix/steel bar interface, as if there were no ITZ the moment she became a party to have the same properties as the matrix seen the incorporation of silica fume, fine limestone and super plasticizer high water reducer (w/binder reduced) . Tillnow, nano indentation test was widely used to measure elastic modulus and hardness of matrix fabricated at different w/b ratio and steel bar. Micro and macro-indentation was widely used to measure interfacial apparent toughness between matrix and steel bar. Only few research works were focused on the studyingof the interfacial zone between a rigid inclusion and matrix in concrete[10–11].

In literature, many test results of pull-out tests show that the bond strength (which characterize adhesion) of SCC is as high as or higher than NVC [13–18]. Depending on the quality and the compressive strength of the concrete, the bond strength of SCC is about 5–40% higher [14–16]. This increased bond performance can be attributed to a reduced formation of bleed water under the reinforcement bars due to the absence of compacting equipment [15–17]. In addition, previous tests with w/b ratios ranging from 0.33 to 0.41 showed a significant size effect on the interfacial toughness (adhesion): for smaller w/b ratios, higher interfacial toughness (adhesion) are found. As opposed to pull-out test, similar results regarding bond performance are achieved when interfacial indentation test are conducted to examine the bond (adhesion) behavior betweenconcrete and steel bar reinforcement. By means of interfacial indentation tests , The apparent interfacial toughness of the SCC mixes with 16 mm steel reinforcement diameter were found to be about 9,97% and 14,41% higher than those of the reference mixes for the same strength grades (54 MPa and 37 MPa cylinder / 60 MPa and 41 MPa cube) respectively . these results are similar compared to those found by Valcuende and Parra [12] and Looney et all [12] .From these results, it is not possible to conclude that SCC shows worse adhesion behavior than NVC. In order to validate or elucidate the findings mentioned above, this paper evaluates the apparent interfacial toughness and adhesion performance of SCC. Interfacial indentation tests are performed to examine the adhesion behavior between concrete and steel bar reinforcement with different w/b ratios. To investigate the adhesion capacity of SCC, interfacial indentation tests are carried out on seven small cylindrical specimen (five SCC specimens with different w/b ratio: 0,33 ; 0,35 ; 0,37 ; 0,39 ;0,41 and two NVC specimens with different w/b ratio: 0,36 ; 0,51). Good grinding and polishing procedures were finally determined for the indentation test after several trial procedures had been made. Vickers indenter was used to investigate the steel bar/matrix adhesion (apparent interfacial toughness). Then, influence of the compressive strength, water/ binder ratio and the type of concrete on apparent interfacial toughness was investigated.

In this type of studies are rarely those who have tried to characterize the adhesion of matrix/ steel bar reinforcement in Self Compacting Concrete by using the interfacial indentation test as a new methodology. Exclusively, the objective of this research is to fill this gap by characterizing for the first time this concrete /steel bar adhesion by interfacial indentation test and then study the effects of some parameters such as water to binder ratio (w/b) and concrete type on its behavior and on the microstructure of the developed composite material.

In conclusion, the indentation test showed clear advantages over the conventional pullout test and shows once again its aptitude to study the adhesion of concrete/ steel bar reinforcement couple.

Significance of the work

Tis work has major significance in construction works related to reinforced concrete (RC) and selection of materials and their specification. The experiments performed for measuring the adhesion between concrete and its reinforcing bars can be used for the evaluation of the feasibility using SCC in place of normal vibrated concrete NVC. Moreover, there are several other relevant structural performances, but in this paper, more emphasis has been given on adhesion between concrete and its reinforcing bars and investigation is made in view of the extension of design rules from Normal Vibrated Concrete (NVC) to SCC.

2. Materials, Elaboration and Experimental Methods

2.1. RawMaterials

Two types of concrete to be studied are prepared from the following constituents:

- A composed Portland cement CPJ-CEM II / A 42.5, of Algerian origin, manufactured by the cement factory of Hjar Essoud (Skikda-Algeria) with a compressive strength of 42.5 MPa having good sulphate resistance and low heat of hydration according to NF EN 197-1 standard [19]. The physical properties and chemical analyzes of this cement are presented in table1.

Table1: Physical properties and chemical analysis (w/w %) of cement.

Physical properties		Chemical analysis (%)									
Density (t/m^3)	Specific surface-BET (m^2/g)	SiO_2	CaO	Al_2O_3	SO_3	Fe_2O_3	K_2O	Na_2O	MgO	LAf	I R
3.100	0.3480	24.92	58.6	6.58	2.17	3.65	0.85	0.08	1.21	1.7	0.23

*Chemical analysis of material (ex.cement) expressed as**w/w (%)** = **w**eight of chemical element (ex. Fe_2O_3) in material (ex.cement)/total**w**eight
of this material (ex.cement) **(%).**

***IR: I**nsoluble **R**esidue, **LAF: L**oss **A**t **F**ire**.**

- The silica fume (Sf) (Medaplast HP) is used to replace 8.0% by mass of cement. Most standards and codes [20-21] recommend the use of this silica fume as an additive for the replacement of about 5-10% by mass of the cement. The incorporated silica fume is a pozzolan in the form of a very active fine powder. The chemical analysis and the physical properties of the silica fume used are shown in table2.

Table 2: Physical properties and chemical analysis (w/w %) of silica fume.

Physical properties		Chemical analysis (%)					
Density (t/m^3)	Specific surface - BET (m^2/g)	SiO_2	Al_2O_3	SO_3	Fe_2O_3	K_2O	Na_2O
1.07	21.7	92.1	0.25	0.36	0.79	0.96	0.17

- The limestone powder (lp), having a calcium carbonate (CaCO3) content of 97.6%, with purity and great fineness, are introduced into the mixtures of self-compacting concretes in order to improve the plastic viscosity and achieving the required stability. The chemical analysis and the physical properties of these calcareous fillers are presented intable3.

Table 3: Physical properties and mineralogical composition (w/w %) of limestone powder.

Physical properties			Mineral composition (%)			
Density (t/m^3)	Specific surface- - BET (m^2/g)	finesse modulus	$CaCO_3$	SiO_2	MgO	Fe_2O_3
2.60	0.5226	0.19	97.62	0.81	0.78	0.08

- Three nominal classes of crushed limestone aggregates (Ain Touta, Batna 05, Algeria) and a local sea sand are used for the production of all SCC and VC mixtures: sea sand (ss, 0/3 mm), Crushed sand (cs, 0/4 mm), small gravel (g1, 4/8 mm) and medium gravel (g2, 8/16 mm). All appropriate corrections have been adopted in order for the aggregates to reach the surface-dry-saturated state according to EN 1097-6: 2000 [22]. The physical properties (bulk density, water absorption) of the aggregates used are presented in table4.

Table 4: Physical properties of aggregates (calculated according to [21].

aggregate Type	Sea sand (ss)	Crushed san (cs)	Small gravel (g1)	Medium gravel (g2)
A.d (t/m^3)	2.67	2.52	2.64	2.63
W.a (%)	0.9	0.7	0.28	0.27

***A.d**: Apparent density on an oven dried basis (t/m3). **W.a**: Water absorption (%).

The required fluidity of self-placing concretes is achieved by incorporating suitable doses of Medaflow superplasticizer polycarboxylate (pce) according to EN 934-2: 2009 [23].Super plasticizers are used to improve the fluidity of the concrete and reduce the amount of water to be added. This same super plasticizer is used for the production of mixtures of vibrated concrete.

2.2 Proportions and usedmixtures

Self-compacting concrete consists of a binder (cement + calcareous fillers + a pozzolan type material, i.e. silica fume) and aggregates (sea sand, crushed sand, small gravel and medium gravel). The water to binder ratio (w/b) is equal to 0.35 (for SCC54) and 0.33 (for SCC62) by incorporation of 2.17% by mass of cement of superplasticizer (for both SCCs).The SCC is, according to its properties in the fresh state, a concrete that flows by only gravity effect, capable of completely filling the formwork with its reinforcement, its sheaths while maintaining its homogeneity. The vibrated concrete flows and compacts under the vibrations of a mechanical vibrator used when pouring the concrete into the formwork. It is designed on the basis of a typical composition used in the local construction industry. It represents mobility in an unconfined environment, described by the 70 cm slump flow test,

obtained by incorporating 3.3% by mass of super plasticizer in the cement. VC is a reference mixture having a compressive strength of about 54 MPa. One of the two SCC which is theSCC54 is designed to have the same compressive strength as these VCs, by reducing the amount of the binder, resulting in an increased w/b ratio. The other which is the SCC62 is designed to have water to binder ratio less than that of the SCC54; the mixing proportions of SCC62, SCC54 and VC54 are summarized in table5.
The dry materials are first introduced and kneaded. The water, then 30 seconds later the super plasticizer, are added gradually for 1 minute. The mixing is then carried out for 2 minutes in a planetary mixer. The properties of the fresh concrete were determined according to the standard by the tests: V-funnel, slump-flow and L-box for the SCC mixtures and by spreading test for The VC mixtures[24].

Table 5: Proportions of mixture of calcareous aggregates and super plasticizer (Sp) (in kg/m3) used in the preparation of SCC54 andVC54.

Materials (kg/m^3)	CEM I 42.5 N (c)	ss	cs	g1	g2	Lp	Sf	Effective water	Sp	(w/b) ratio
(VC54)	400	570	243	379	567	–	–	144	13.2	0.36
(SCC54)	368	570	243	328	492	100	32	160	8	0.35
(SCC62)	368	570	243	328	492	100	32	151	8	0.33

***Lp**: Limestone powder, **Sf**: Silica fume, **sp**: Super plasticizer, **w/b**: water to binder ratio.

The hardened properties were identified by the compressive strength ($f_{c,cyl}$) at 28 days. 160/320 mm cylinders are molded and then demolded after 1 day, sealed and stored at (20 ± 2°C, 95 ± 5% relative humidity) until testing. The mean values of the properties of fresh and hardened concrete are summarized in table 6 for all mixtures, as well as the recommended theoretical values [25].

Table 6: Properties and workability of fresh and hardened concretes and EFNARC Recommendations [25].

Properties	Sinking (mm)	Spreading (mm)	L- box(s) (h_2/h_1)	V-funnel (s)	$fc_{28,cyl}$ (MPa)	$f\ c_{28,cub}$ (MPa)
(VC54)	70	–	–	–	53.6±1.6	59.37
(SCC54)	–	695	0.84	10.4	54.3±2.2	60.33
(SCC62)	–	675	0.81	11.7	61.7±3.0	68.55
EFNARC	–	650–800	> à 0.8	(8-14)	–	–

2.3 Reinforcingsteel

The reinforced bars of steel reinforcement showed in figure (1-a) of nominal average diameter 16 mm and grade BE500S, conforming to EN 10080 (2005) [26], are introduced into the concrete samples of the figure(1-b) in order to evaluate the adhesion characteristics.

a)

b)

Figure 1: Rebar of steel type BE500S, **a)**of nominal diameter 16 mm and **b)** the same bar inserted into a 45 mm diameter concrete matrix used for the interfacial indentation test.

A typical steel bar has two rows of transverse ribs uniformly distributed over the circumference and spaced in the long direction of the bar. A steel reinforcement bar was examined and tested in the laboratory to confirm the manufacturer's technical specifications with respect to diameter, cross-section, mass and mechanical properties (table7).

Table7: Geometric and mechanical properties of steel reinforcing bars[26].

Parameter	Symbol	Units	(Standard) values (Average)	Measured values (Average)
Diameter	d	mm	16	15.93
Section	An	mm²	201	199.33

Mass	M	kg/m	1.58	1.56
Limit of Elasticity	Re	MPa	485-650	536
Maximum resistance	Rm	MPa	(1.13-1.38). Re	651

2.4. Samples preparation

The samples preparation used for the mechanical characterization tests must be treated in order to avoid an excessive dispersion of the results [27]. Each coated steel bar is previously cleaned to ensure proper bonding with the concrete. For VC mixtures, the concrete is cast and compacted using conventional hand vibrators. The SCC mixtures are poured into a formwork of 100x.100mm^{2}section which is filled over a length of 1200 mm without vibration. The stripping is carried out one day after the casting and the reinforced concrete elements are immediately put in water for curing for 28 days. Samples for the apparent interfacial toughness study are extracted from the middle part of the reinforced concrete element. Small samples (about 45 mm in diameter and 22 mm high) containing a single steel bar in the center are then cut from the taken samples using a diamond saw. After demolding elements, the surface quality of self-compacting concrete samples is better than that of the vibrated concrete. This observation, also noted by other authors [28], shows the excellent filling capacity of SCCs, even for elements that require only very small amounts ofconcrete.

2.4. Micro structural analysis

Scanning electron microscopy (SEM) images were made on the fractured surfaces at the concrete/steel interface on the cementitious material side to examine the failure modes of the interface.

2.5. Compressivetest:

For each concrete mix, four standard cylinders with a diameter of 160 mm and a height of 320 mm were cast into steel molds and then cured under ambient laboratory conditions (20 ± 2°C, 95 ± 5% relative humidity). At the end of the curing period (28 days), these test pieces are tested on a hydraulic servo pressure frame in accordance with EN 12390-4: 2009 [29] to determine the average compressive strength, $f_{ccyl,}$ and the corresponding standard deviation according to EN 12390-3: 2009 [30]. The results of the compressive strength are given in table6.

2.6. Nanoindentation Tests (Grid IndentationTechnique):

Grid indentation involves the application of a large array of nanoindentation experiments, each with a characteristic indentation depth, h,which elicits a mechanical response from a subsurface microvolume (figure.4-b). Developed at the Massachusetts Institute of Technology (MIT), its application has been extended to evaluation of nanomechanical properties of heterogeneous materials such as cementitious materials, bones, and shales [31].

From the simultaneous measurement of indentation load (P)and displacement (h), elasticity modulus (E) and hardness (H) can be computed [32] at each point.

If, on the other hand, h_{max} is greater than approximately D/10, then a composite mechanical response of multiple phases will inevitably be observed (figures.4-b and 4-c).

In this work, nanoindentation was performed over a grid of 10 × 10 points, evenly spaced by 150 µm. During each test, the load was linearly increased up to a maximum load of 650 mN in 10 s, kept constant for 5 s, and linearly decreased in 10 s.

The nanoindentation experiments of SCC and VC matrices have been performed on a Nano-Indenter XP ™ (MTS Nano Instruments) employing a Berkovich diamond indenter with a load and depth sensing indentation mode .All measurements were performed at room temperature. In Load and depth sensing indentation mode, indentation area of specimens were selected randomly.

2.7. Interfacial indentationtest

Cylindrical samples with a diameter of 48 mm and a height of 22 mm, having a steel reinforcing bar 16 mm in diameter at their center, are manually polished using abrasive papers of grades 40, 120 up to 1200,then using diamonded paste with a grain diameter of 1 µm up to a height of 18 mm in order to eliminate the defects and the residual stresses caused by the sawing (figure. 1-b).The indentation test involves applying a diamond Vickers pyramidal indenter at the two materials interface so as to generate a crack that propagates along that Interface as it is shown schematically in figure.2-a). This test is carried out using a Zwick ZHU instrumented indentation machine which can be used to apply loads between 5 and 2500 N and to record the load-displacement curves (figure.4-a).

The optical system connected to the hardness device makes it possible to aim with very good precision the interface between the concrete and the steel reinforcement. During the tests, loads P between 100and 2500N are applied to each sample type at a constant speed of 2P/min (in N/min). The maximum load is maintained constant for 30 seconds and the imprints (diagonal 2d) and the cracks (length a) are observed and measured with the optical system of the apparatus immediately after unloading. The measurement of the cracks formed at the indented interface is used to evaluate the adhesion between the concrete and the steel bar by means of the

apparentinterfacialtoughness,Kca.ThismethodwhichhasbeenoriginallydevelopedbyChicotetal.[33,34]requires indentations to be performed at least at three different loading levels, with five indentations for each level, to determine an average crack length.
These tests are used to evaluate the adhesion between a thick coating and its substrate such as thermal barrier materials, plasma torch deposits [33, 34, 35]. In a bi-logarithmic frame, the length of crack (a) varies linearly with the applied load, thus giving the so-called crack line. In the same system of axes, Chicot et al. represent the variation of the half-diagonal of the impression (d) with the applied load (P) (figure 2-c). In its principle, this methodology consists in applying a Vickers indenter under a given load in the plan of the interface between two materials. The objective is to create and propagate a crack in this interfacial plan as it is shown schematically in figure (2-a) and (2-b).

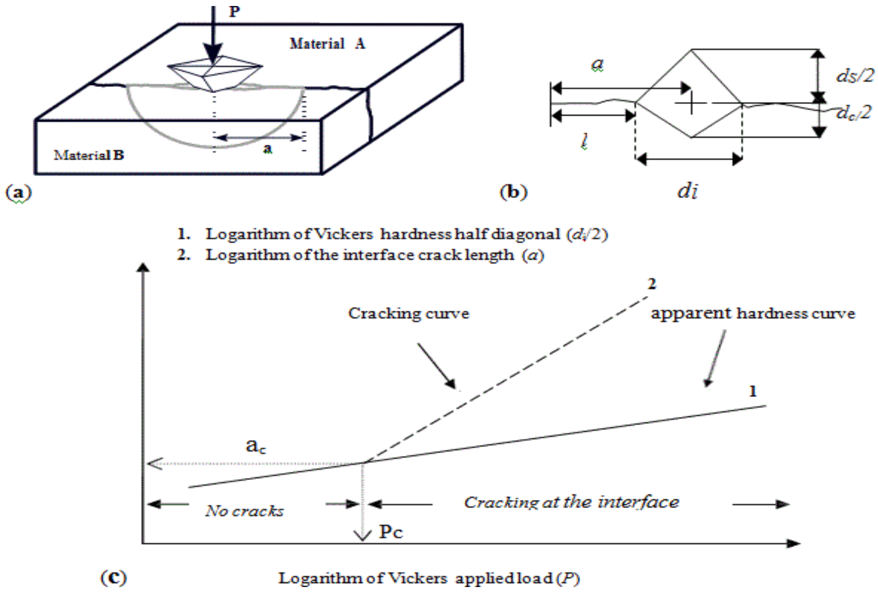


Figure 2: a) Schematic illustration of an interfacial indentation test showing the crack propagation in the plan of the interface, **b**) The dimensions associated to the crack length and diagonal indent measurements and **c**) Bi- logarithmic representation of crack length an apparent hardness versus the applied load and the definition of the critical point (Pc, a_c)used to calculate the interfacial indentation toughness.

The straight line thus obtained is called the apparent hardness straight line by the authors. The intersection point of these two lines corresponds to the moment when the crack begins for a so-called critical load (Pc).The coordinates of the intersection point of these two lines are shown in figure.(2-c). The (Pc, ac) couple which defines the initiation of the interfacial crack is used to calculate the apparent interfacial toughness from equations (1) and (2) according to Chicot *et al*. [33,34]:

$$K_{ca} = 0.015 \left(\frac{E}{H}\right)_i^{\frac{1}{2}} P_c (a_c)^{-\frac{3}{2}} \quad (1)$$

$$\left(\frac{E}{H}\right)_i^{\frac{1}{2}} = \frac{\left(\frac{E}{H}\right)_s^{\frac{1}{2}}}{1+\left(\frac{H_s}{H_c}\right)^{\frac{1}{2}}} + \frac{\left(\frac{E}{H}\right)_c^{\frac{1}{2}}}{1+\left(\frac{H_c}{H_s}\right)^{\frac{1}{2}}} \quad (2)$$

Whose the equation (2) has been proposed by Chicot *et al*. for calculating $(E/H)^{1/2}$ and where E is the Young's modulus, H is the hardness, and the indices (s), (c) and (i) correspond respectively to the substrate (here the steel bar), to the coating (here the concrete) and to the interface.
This apparent interfacial toughness is measured to see if it can be considered as a relevant criterion for estimating the adhesion between the concrete and the steel reinforcement and to replace the conventional tests used to characterize the adhesion between the concrete and its Metalreinforcement.

1. Results and Discussion

A statistical or grid nanoindentation experiment involving large number of test points has shown to provide micromechanical properties of two types of concrete, SCC and VC, using 100 test points and a smaller indent spacing of 150 µm as it is showed in figure 3-a). Figures(3-b) and (3-c) show the mechanical properties maps for the

28-day hydrated SCC54 matrix as an example.

Young's modulus and hardness of self-compacting concrete (SCC62) are 49.524 ± 22.347 GPa and 2.002 ± 2.147 GPa, respectively. However, for the Young's modulus and the hardness of self-compacting concrete (SCC54) are (47.876 ± 24.667) GPa and (1.943 ± 2.376) GPa respectively, determined by the nano indentation test (figures3 and 4), are slightly lower than those of vibrated concrete (VC54) which are (49.201 ± 25.349) GPa and (1.965 ± 2.402) GPa having similar compressive strength. This difference is not considered significant, although this may be expected due to higher past, reduced amount of coarse aggregates and reduced overall tightening.

a) SEMimage b)Hardnessmap c) Young"s modulusmap

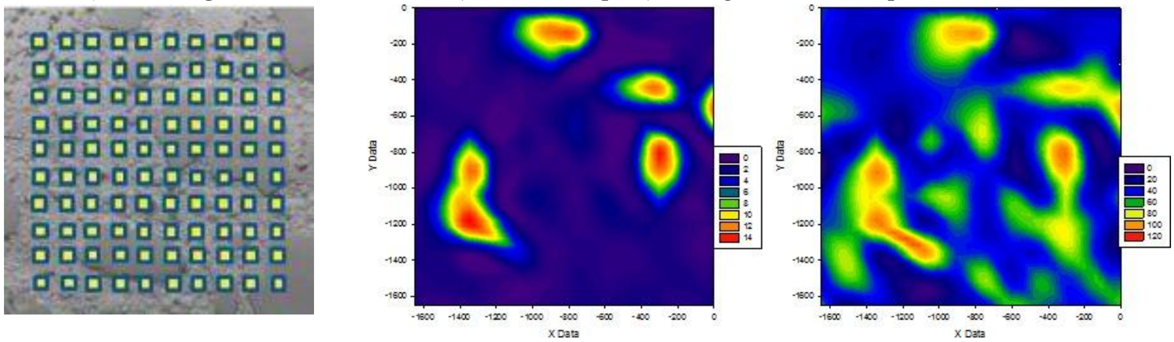
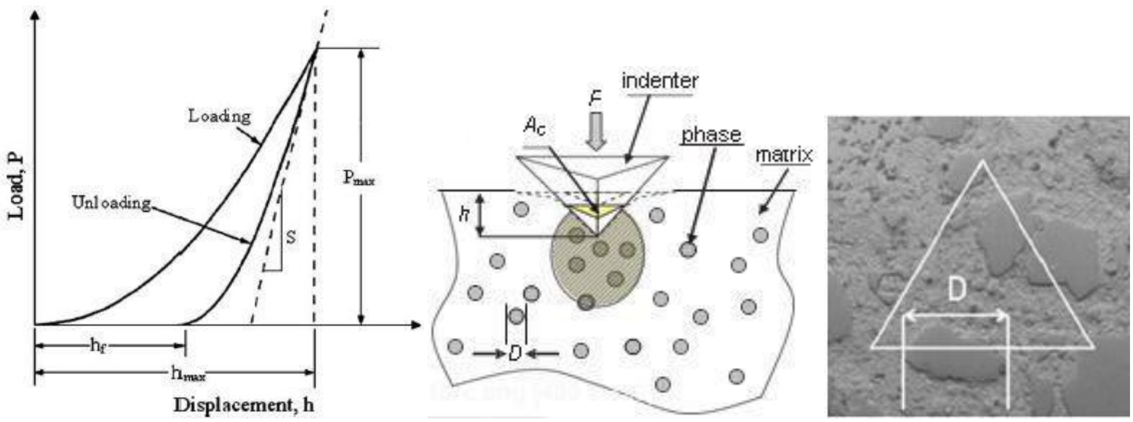


Figure 3: SEM image of the tested area (100 indents) in SCC54 matrix and corresponding mechanical properties maps for *H* and *E*.



a) b) c)

h = depth of indentation, D = grain diameter in the matrix.

Figure 4: a)A typical representation of the indentation load “P” versus indentation depth” h”, **b)**Grid indentation on a heterogeneous system where the probed micro volume (cross-hatched regions below the indenter) is larger than the characteristic length scale, D (h >>D), of the interest concrete matrix, **c)**magnified view of cross-hatched regions below the indenter after testing: wide indent, so average measure.

In other hand, for validate the interfacial indentation test, we have complied with the following experimental conditions:

- The length of the crack (a) must be greater than the half-length of the impression(d/2).
- The thickness of the coating must be at least three times (optimally five times) the half-length of the impression[36].
- The test should be performed with the tip of the indenter located on, or near the interface. It is recommended that the distance between the center of the cavity and the interface be less than the half diagonal of theimpression.

• The distance between the center of the impression and the edge of the sample must be greater than 3 mm. In order to choose the range of loads to be applied to the concrete/steel interface by indentation, we carried out tests with increasing loads between 10 and 2200N. For low loads, only a residual impression is observed at the interface, whereas for higher loads, we observe a crack at the interface between the concrete and the steel reinforcement (figure 5-b). This crack first follows the interface then bifurcates and then propagates in the concrete for even higher loads. The applied load reaches a critical value (failure load), the separation between steel and concrete intervenes (figures 5-b, 5-cand5-d).

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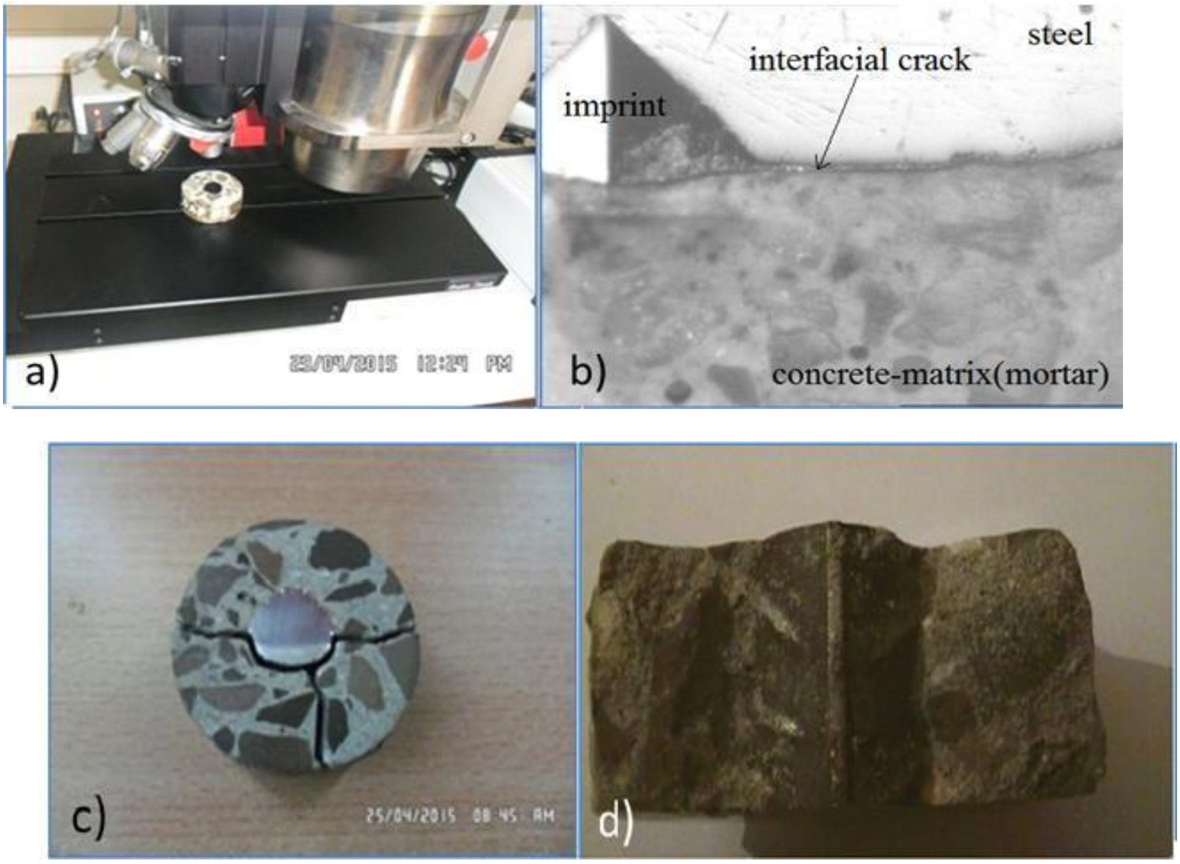


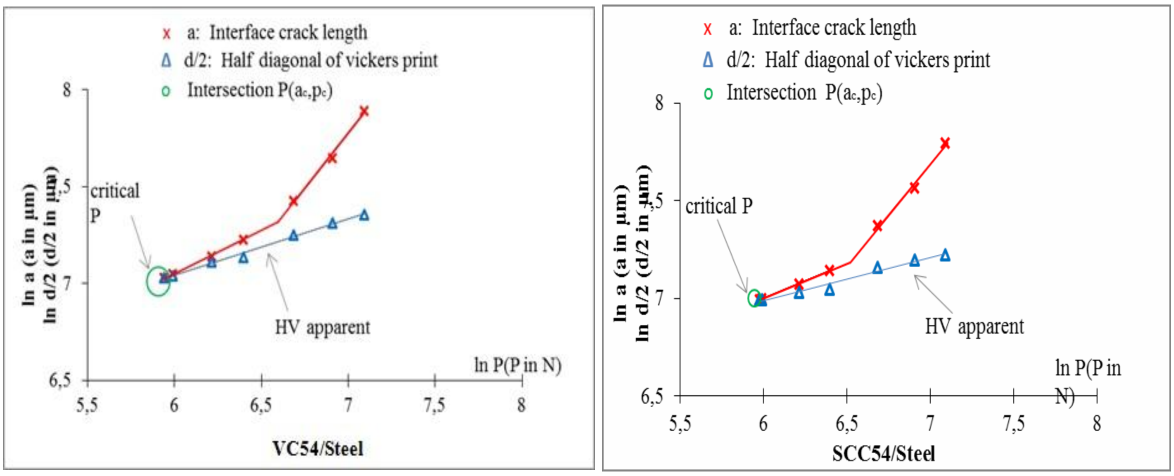
Figure 5: a- Experimental device used for the indentation test at the concrete-metal reinforcement interface, **b**- Example of indentation at the interface showing the creation of a crack (the impression is clearly visible in the steel and little in the concrete); **c** and **d** - Indentation test performed with an applied load greater than the critical value and causing decohesion between the matrix and the steel bar.

These critical (failure) loads are 2030 ± 15 N for (SCC54/Steel) and 1855 ± 10 N for (VC54/Steel). In order to apply only an interfacial crack (no total decohesion), we have considered, in applying equation (1), that loads less or equal to 1200 N, which corresponds to 65% of the critical failure load of (VC/Steel) couple.

In total, 35 interfacial indentation tests are carried out for each concrete/steel couple. Knowing the lowest failure load of the two samples ($P_{failure}$ = 1846 N), we selected seven loads, with a 100 N pitch for the interval (300 - 600 N) and a 200 N pitch for the (600 -1200 N). The curves (crack length-applied load) for each type of couple (concrete/steel) are shown in figures (6-a, 6-band6-c).

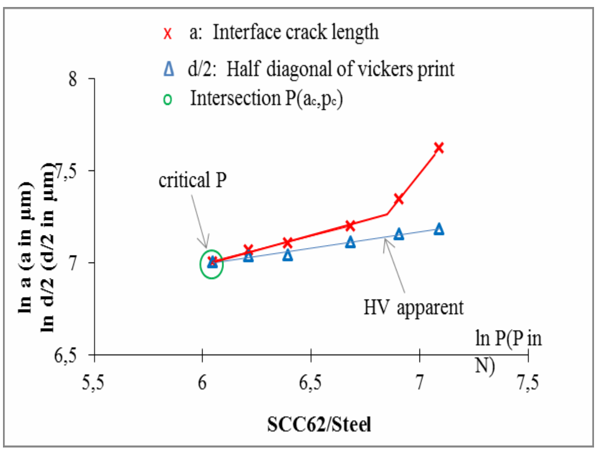
The interfacial apparent toughness of (SCC62/Steel) and (SCC54/Steel) couples are respectively 2.53 MPa.m$^{1/2}$ and 2.38 MPa.m$^{1/2}$(table 8). The (SCC62/steel) couple has an apparent interfacial toughness about 6.72 % higher than that of the (SCC54/Steel) couple. This may be related to the low water content of the SCC62 in front of that of the SCC54, ie its porosity in order to reduce the accumulation of sweat water around the reinforcement bars embedded in the structural elements. In the other hand, the interfacial apparent toughness of (SCC54/Steel) and (VC54/Steel) couples are respectively 2.38 MPa.m$^{1/2}$ and 2.18 MPa.m$^{1/2}$(table 8). The (SCC54/steel) couple has an apparent interfacial toughness about 10% higher than that of the reference couple. This can be related to the lower water content of the SCCs, and in particular to the large volume of ultrafine particles (silica fumes and calcareous fillers) introduced in order to reduce the accumulation of sweating water under the bars of reinforcement horizontally embedded in the structural elements. The porosity, clearly lower at the matrix/reinforcement interface, corresponds to a more compact structure with a smaller number of defects without visible segregation. It should also be noted for these concretes, a higher fluidity which results in a better covering of the rebar.

The results obtained with the interfacial indentation test show that for the different water to binder ratio, so different compressive strengths, and the best adhesion is attributed to the SCC with lower water to binder ratio and/or with higher compressive strength. The results obtained with the interfacial indentation test show that for the same compressive strength, the adhesion of the SCC to the steel reinforcement is higher than for the VC. On the basis of conventional tensile and flexural tests, to characterize the adhesion, it should be mentioned that various researchers have achieved variable or even contradictory results, but it seems nevertheless that the adhesion between the



concrete and the steel reinforcement is higher for SCCs than for VCs [37, 38].

a) **b)**



c)

Figure 6: The bi-logarithmic plots of the indentation half-diagonal, d, (Δ) and crack length, a, (x) formed at the interface between the concrete and the steel reinforcement, as a function of the load, P, applied to the Vickers indenter. (a): Plotted curves for vibrated concrete/steel couple (VC54/St), (b): Plotted curves for self- compacting concrete/steel couple (SCC54/St) and (c): Plotted curves for self-compacting concrete/steel couple (SCC62/St).

Table 8: Adhesion properties comparison

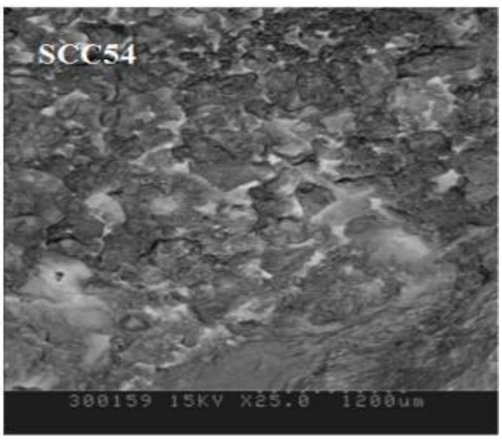
Adhesion properties	VC54	SCC54	SCC62
w/b ratio	0.36	0.35	0.33
w/c ratio	0.36	0.47	0.44
$fc_{28,cyl}$ [MPa]	53.6 ± 1.6	54.3 ± 2.2	61.7 ± 3.0
Kca [$MPam^{1/2}$] : IITs (This study)	2.18	2.38	2.53
($\tau_{max}/fc^{1/2}$) :POTs (Literature Valcuende and Parra [29])	2.367	2.585	/

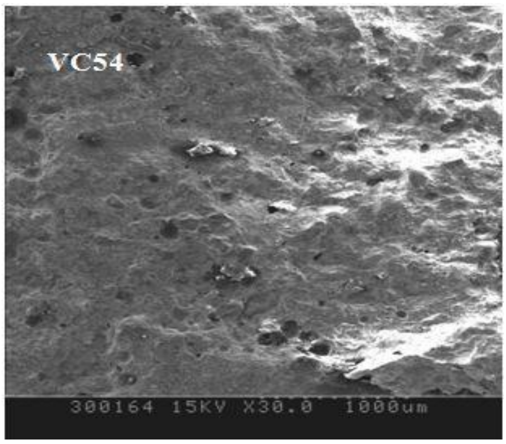
*Kca [$MPam^{1/2}$] **IITs:** Apparent interfacial toughness measured using **I**nstrumented **I**ndentation **T**ests. ($\tau_{max}/fc^{1/2}$) **POTs:** Normalized bond strength measured using **P**ull **O**ut**T**ests.

In particular, Valcuende and Parra [39] studied the adhesion between (SCC/Steel) and (VC/Steel) couples, for different water to binder ratios (w/b), different compressive strength values and Steel bar with 16mm diameter. These authors observed that the mean Normalized bond strength ($\tau_{max}/fc^{½}$) is greater for the (SCC/Steel) couples than for the (VC/Steel) couples. For the 54 MPa class cylinders (60 MPa cube), the difference is about 10%:2.58 instead of 2.37, which confirms the results obtained in our study. The difference for the normalized bond strength, weighted by the compressive strength, is only 5% according to Daoud et al. [40]. For both parameters (strength and toughness), there is therefore a good coherence of our results with those of the literature. In both cases, we find that the adhesion properties of (SCC/Steel) are better than those of (VC/Steel).

In this study, all samples were then fractured (failed) by indentation under loads greater than those used for the interfacial indentation test. For example, for the (SCC54/Steel) sample, it has been observed that the crack begins to propagate along the (steel/concrete) interface under a progressive load and then deviates from this interface to the matrix of the concrete, which causes it to failure, followed by loss of connection between the reinforcement and the concrete once the ultimate load close to 1855 N has been reached. A similar trend is observed with the (SCC54/Steel) combination for a slightly higher applied load (2030 N).

To improve the resistance as well as the apparent interfacial toughness, it is essential to prevent the initiation and propagation of cracks in an effective way. The (water/binder) ratio plays an important role in restricting the appearance and then the propagation of the micro cracks, which has resulted in a significant improvement in the mechanical strength of the SCCs. The interface between the concrete and its steel reinforcement is considered the most crucial element of reinforced concrete because it establishes a connection between the two heterogeneous phases. We have observed this interface in scanning electron microscopy (SEM). The micrographs of the interfaces on the SCC-matrix and VC-matrix sides are shown in figures (7-a,7-b).





a) **b)**

***SCC**: SelfCompactingConcrete; **VC**: VibratedConcrete.

Figure 7: Micrographs (SEM) obtained for the concrete interface in contact with the steel reinforcement after decohesion caused by an interfacial indentation with an applied load, P, greater than the critical value,

(a) SCC: Self Compacting Concrete; (b) VC: Vibrated Concrete.

The microstructure of the (steel/concrete) interface is a small transition zone similar to that between the cement paste and the aggregates. Figure (7-b) shows a representative area of the interfacial layer of the VC54 mixture after the steel bar has been removed. This interface in the (VC54/Steel) couple is less resistant to cracking than that of the (SCC54/Steel) couple. One of the reasons for the low performance of the latter interface is a greater porosity resulting from the inability of the cement particles to effectively cover the steel reinforcement. This phenomenon is called "wall effect". This porosity, which is greater in the interface of VC/Steel (figure.7-b) than in that of SCC/ Steel (figure 7-a), makes it less resistant to the propagation of cracks.

The weakness of this interface can be associated at the migration of water that accumulates around the steel bar and creates the porosity. The high volume ultrafine particles (silica fume, cement and calcareous fillers) contained in the interface (SCC54/Steel) effectively fill micro pores, forming a thick, non-porous, compact matrix that is more resistant to the propagation of Cracks than the VC54 matrix. Silica fume and calcareous fillers in the cementitious matrix, due to their large surface area and high surface energy, absorb a large amount of water and reduce the possibility of forming films of water. This decrease of water films in the interfacial zone decreases its porosity.

The total thickness of the coating is about 16 mm. With reactive cement incorporated into the surface of the coating, cement hydration reactions can occur at this level, allowing the phases of the paste to integrate into the coating and give a microstructure with a more uniform transition between the matrix and the steel reinforcement. Thus, the reinforcement of the bond between the steel reinforcement and the cementitious matrix is obtained at the same time as the improvement of the resistance of this interfacial zone against cracking. Even if the thickness of the transition zone is very small compared with that of the cementitious matrix, the modification of this weak link can lead to remarkable improvements in strength, stiffness, and toughness of these cementitious composites[41].

Conclusions

This work deals with the use of interfacial indentation to determine the adhesion between High-Performance Self-Compacting Concretes HPSCC (SCC62 and SCC54) and their steel reinforcements, with 16mm diameter, then the influence of the water to binder ratio on this adhesion with the comparison between the HPSCC and High-Performance Vibrated Concrete(HPVC) with respect to this adhesion, when they have the same compressive strength.The experimental results yielded the following conclusions:

- There is a correlation between the apparent interfacial toughness measured by interfacial indentation tests and the normalized bond strength measured by pull-out tests of the literature. The interfacial indentation test therefore seems to be a characterization method that can be used to estimate the adhesion between the concrete and its steelreinforcement.
- The improvement of the behavior of the adhesion of High performance self-compacting concrete (HPSCC)with respect to High performance vibrated concretes (HPVC) for the same compressive strength class can be attributed to the greater quantity of ultrafine particles and higher workability, which results in a better covering of the reinforcing bars by theconcrete.
- The resistance to initiation and propagation of the cracks at the interface is a function of the water/binder ratio of theconcrete.
- Lower adhesion capacities of SCC were measured for decreasing water compressive strength ($fc_{28,cyl}$). An increase of 13.62 % is observed, when ($fc_{28,cyl}$) increases from 54.3 to 61.7 MPa. This improvement can be attributed to the influence of the compressive strength ($fc_{28,cyl}$) which shows that there is a close relationship between compressive strength and thisadhesion.
- Due to the improvement of the apparent interfacial toughness Kca for Self Compacting Concrete (SCCs), the application of self-compacting concretes in place of the vibrated concretes (CVs) in the construction can produce significant advantages.

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