Bond characterization between concrete substrate and repairing materials

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ABSTRACT

The purpose of this investigation was to study the effect of bonding behavior of concrete substrate and repair materials. Three different cementitious or modified-cementitious repair materials and three surface roughnesses were studied. Repair materials were ordinary mortar, modified cementitious mortar by silica fume and modified cementitious mortar by styrene butadiene rubber latex. Surface preparations were smooth surface, rough surface and epoxy resin adhesive as a bonding agent. The method used for evaluation of bond strength was pull-off test. the influence of the electrical conductivity of repairing materials was analyzed by rapid chloride permeability test. Finally, the performance of the adhesives was evaluated considering both the bond strength and electrical conductivity.

Results obtained from these tests indicated that the roughness of substrate surface has a main effect on the performance of bond between adhesives and concrete. There are not great differences in bonding strength between various repairing materials but considering electrical conductivity, modified cementitious mortars are better materials for using in corrosive environments to increase service life of repaired structures.

KEYWORDS

Bond strength; Repair material; Roughness; Pull-off test; Chloride permeability; Concrete

1. INTRODUCTION

Some techniques for repairing and strengthening structures involve adding new concrete to an existing concrete substrate. Examples of these applications include highway structures where concrete overlays are used and repair of corrosion-damaged concrete structures, where the deteriorated concrete must be replaced with new concrete. In these applications, The performance of the strengthened structural system depends on the bonding behavior between old and new concretes and this bond usually presents a weak link in the repaired structure. If sufficient adhesion is achieved, the strengthened structure behaves monolithically, being the materials effectively being mobilized [1]. Therefore, bonding behavior plays an important role on the efficacy of this strengthening strategy.

The bond strength mainly depends on adhesion in interface, friction, aggregate interlock, and time-dependent factors. Each of these main factors, in turn, depends on other variables. Adhesion to interface depends on bonding agent, material compaction, cleanness and moisture content of repair surface, specimen age, and roughness of interface surface.

Friction and aggregate interlock on interface depend on parameters, such as aggregate size, aggregate shape, and surface preparation. The common practice consists of first selecting the type of repair materials and second increasing the roughness of the substrate surface. Several methods are used but little information is available on the relative efficiency of each one [2].

Repair materials can be divided into three main groups: cement based, modified cement based, and resin based. In recent years, considering the cost and behavior of resin-based materials, the use of modified-cementitious materials has increased in developing countries. In light of the weak bond strength of cement based materials, modified cementitious materials offer a good compromise in terms of cost and behavior. As a result, there is renewed interest in developing tests to measure the bond of concrete substrates to modified cement-based or enriched cement-based repair materials. Considering the lack of consensus among practitioners, the objective of this study was to examine the pull-off test method for determining bond between concrete substrate and modified or enriched cement-based repair materials with different surface preparation.

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The use of thin overlays of cementitious, resinous and polymer-modified cementitious materials for the strengthening and rehabilitation of concrete pavements, concrete bridges and asphalt pavements is well documented [3,4].
The pull-off test method is one of the tensile test methods commonly used to assess the adhesion between the repair overlay and the existing concrete substrate.
According to the ASTM D4541 standard [5], the general pull-off test is performed by fixing, with an adhesive, a loading fixture (disk) to the surface of the coating. After the adhesive has hardened, a testing apparatus is attached to the loading fixture and aligned, in order to apply a tensile force normal to the surface to be tested (Figure 1).
Concrete jacketing, for example, is one of the most commonly used strengthening techniques for structural elements. The need to prepare the substrate surface is referred to in all the published works on this subject [6]. Bett et al. [7] performed an experimental study on RC columns repaired and strengthened by jacketing, in which they mention that all models were roughened by light sandblasting before jacketing. Alcocer and Jirsa [8] studied the behavior of RC connections redesigned by jacketing. They indicate that the outermost concrete aggregate was exposed using a chipping hammer. Following this research work, Alcocer [9] conducted more experimental tests using the same surface treatment but followed by removal of small particles and dust using a thick brush and a vacuum cleaner. Ramirez et al. [10] conducted experimental research on the repair of RC columns with partial localized damages. In this study the concrete surfaces and the exposed parts of the reinforcing bars of all columns to be repaired were brushed with a stiff wire brush. Rodriguez and Park [11] tested RC columns strengthened by jacketing and subjected to simulated seismic loading. The surface of the as-built columns had been lightly roughened by chipping before the jackets were placed. Stoppenhagen et al. [12] tested severely damaged concrete frames repaired and strengthened by jacketing. In this case the spandrels were roughened with an electric concrete hammer.
The rapid chloride permeability test (RCPT) is virtually a measurement of electrical conductivity of concrete. According to the ASTM C1202 [13] standard RCPT depends on both the pore structure characteristics and pore solution chemistry of concrete. This paper discusses the effects of repairing materials on the electrical conductivity or RCPT results of hardened cement mortars. This test specify the rating of chloride permeability of concrete based on the charge passed through the specimen during 6 hours of testing period.

2. SCOPE

This paper presents the results of an experimental research program aiming at investigating the effect of the strength class of the concrete substrate and the concrete overlay on the bonding performance between these materials. Pull-off test performed to quantify the bond strength between two concrete layers. Twenty eight days after the concrete substrate was cast, the new concrete was added. Twenty eight days later, pull-off test and rapid chloride permeability test were performed. To avoid the tendency of the failure at the lower strength class of the substrate, a maximum difference of one strength class was adopted for the concrete of the overlay and the substrate.
The experimental program was composed by three different categories of repair materials and three different surface preparations. Repair materials were ordinary mortar, modified cementitious mortar by silica fume and modified cementitious mortar by styrene butadiene resin (SBR) latex. Surface preparations were smooth surface, rough surface and epoxy resin adhesive for bonding agent. The test results should be of interest to design and construction engineers involved in evaluating the bond strength between existing and new materials.

Figure 1 Pull-off test.

3. EXPERIMENTAL STUDY

The experimental study had the main purpose of quantifying the influence of repair materials and the surface roughness of the concrete substrate on the bond strength between this and the added new concrete. A supplementary objective was to investigate rapid chloride permeability test.

3.1. Test program

32 specimens were constructed and tested. The tests selected for study, were pull-off test for determining bond strength and rapid chloride permeability test for determining the electrical conductivity of repairing materials. The pull-off test specimens were 150 × 150 × 150 mm cubes (Figure 2). The RCPT specimens were cylindrical with a base radius of 50 mm.

3.2. Specimen preparation

The same mix design was used for the concrete in substrate portion of all specimens. The mix proportions were based on a 28-day compressive strength of f'_c = 35 MPa, w/c = 0.4, slump 75–100 mm, a minimum Type II Portland Cement content of 450 kg/m^3 and a maximum crushed aggregate size of 16 mm. Sand and cement were dry mixed; water and polymer were mixed together and were added to the dry mix. The concrete was manufactured in the laboratory by a 200-l mixer and was placed in lubricated steel molds. Specimens were removed from the molds 24 h after casting and they were cleaned from any extra dust or particles. Table 1 shows the Chemical analysis of Portland cement and silica fume.

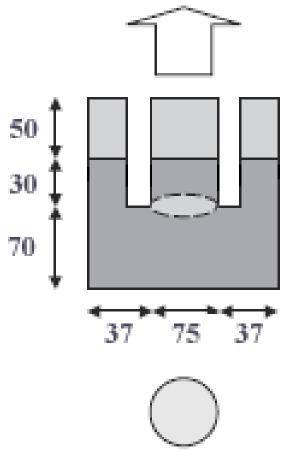

Figure 2 Dimensions of tested specimens in millimeters.

For each of the above three repair materials, surface preparations was used; smooth surface, rough surface and epoxy resin adhesive for bonding agent over smooth surface. The epoxy resin was applied to the interface areas using a brush. The average thickness of the bonding agent was about 1–2 mm. During the 28 days, the cementitious specimens were moist cured at 20°C and the modified cementitious mortar specimens by SBR latex were dry cured at 20°C for the first 3 days and then kept at the same temperature and 100% relative humidity. The specimens were typically removed from the humidity room and allowed to dry for 24 hours prior to testing.

TABLE 1
CHEMICAL ANALYSIS OF PORTLAND CEMENT AND SILICA FUME

Chemical ingredient	Portland Cement (%)	Silica Fume (%)
SiO_2	20.6	91.1
Al_2O_3	5.5	1.5
Fe_2O_3	4.3	2
CaO	62.8	2.3
MgO	1.6	0.6
Na_2O	0.5	-
K_2O	0.4	-
Ignition loss	1.9	2.1
Free lime	0.9	-
SO_3	1.5	0.4

After casting, a series of repairing surfaces were roughened. The roughness was obtained using Styrofoam on the wet substrate concrete to make coarse surface. The estimated amplitude of roughness was 3–5 mm; The concrete specimens were kept in water until the age of 28 days before the repair material was placed. The contact surface of specimens was recleaned using a wire brush and high-pressure air a few hours before placing the repair materials.

Three mixes of repair materials were used and three types of boundary interface were tested. Two of the repair materials were ordinary mortars containing 0% and 8% of silica fume. The remaining repair material was modified cement based. The modified cementitious mortar was made by replacing 20% of cement content with styrene butadiene resin (Table 2).

TABLE 2
PROPERTIES OF SBR LATEX

Physical state	Milky white liquid
Total solids (by weight of polymer)	45%
Specific gravity	1.02
pH	10.5
Mean particle size	0.17 µm

For each group of cementitious repair materials, a different moisture condition on the interface boundary was used. For the cement-based materials, the samples were saturated with a dry surface; for the modified-cementitious materials, the surfaces were prepared following the manufacturers' recommendations. Repair material mixes were designed based on the following: a compressive strength of 35 MPa, maximum aggregate size 10 mm, slump 75–100 mm, w/c = 0.4, and a minimum Type II Portland Cement content of 400 kg/m3 . A polycarbolic based superplasticizer was used for the required workability (especially when silica fume was used) with the same w/c ratio in all mixes. The modified mortars were obtained by replacing the cement with the same weight of polymer resins. Table 2 shows the properties of SBR latex.

3.3. Pull-off test method

When compared to other tests, the pull-off test is the simplest and most popular tensile bond test for measuring the bond properties, both on site for quality control and, in the laboratory, to evaluate the material properties and failure modes [14]. To evaluate the bond strength of an adhesive material that bonds a concrete overlay to an existing concrete substrate, the pull-off test with a partial coring technique is usual.

However, this test can be affected by some factors such as the coring depth into substrate, the floor thickness and the strength class of the concrete substrate [14]

The pull-off test involves the application of a direct tensile load (F_t) to a partial core that mobilizes the repair material, the bond line and a portion of the substrate until failure occurs. The tensile load is applied to the partial core through the use of a metal, bronze or aluminium disk with a pull pin, bonded to the overlay with an epoxy resin. A loading device, with a reaction frame, applies the load to the pull pin at a constant rate

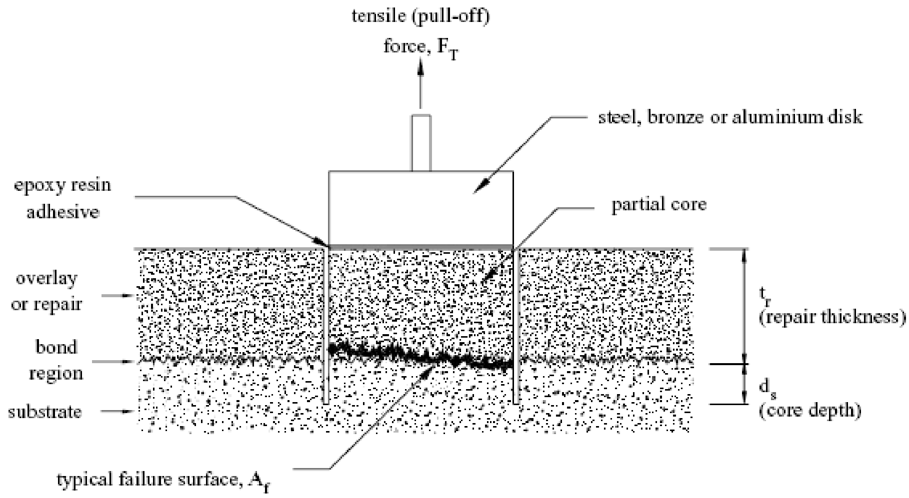

Figure 3 Schematic representation of pull-off test principle.

Figure 3 illustrates the principle of the pull-off test, and sketches a typical failure surface for the case of overlay and adhesion strength higher than the pull-off strength of the concrete substrate. The pull-off strength (S_{PO}) is defined as the tensile (pull-off) force (F_t) divided by the area of the fracture surface (A_f):

$$S_{PO} = \frac{F_t}{A_f}$$

There are other different types of in situ direct tensile tests proposed in the last years to evaluate the bond properties and the performance of repair materials in general. However, the partial core pull-off test is considered to be the appropriate method for evaluating the bond strength in the field . A brief review of the most common tensile bond tests, as well as, an evaluation of three types of direct tensile testing equipment is provided elsewhere. The testing equipment used here has a load capacity of 16 kN, a 75mm diameter disk, an accuracy of 2% and a resolution of 0.10 N/mm^2.s^{-1}. The pull-off tests were conducted complying with the general procedures described in the standards [5].

An important issue associated with pull-off tests is the depth of the core drilling into the existing concrete substrate, and ignoring the effect of the drilled depth may be one of the main causes of the difficulties in reproducing

Figure 4 disk bonded to the overlay with an epoxy resin.

and comparing test results. The partial core is usually cut by means of a rotary core cutting drill with diamond bits. To avoid cutting damage, it is important to ensure uniform pressure when the core is being drilled through the concrete overlay into the substrate. This operation is mostly dependent on workmanship, thus it is essential that a skilled operator carry out the works.

Reducing the core diameter leads to an increasing influence of internal defects (in the concrete volume) in the specimen pull-off strength. Additionally, when reducing the core diameter, the ratio of cut surface area to volume increases and, at the same time, the intensity of damages occurring in the partial core drilling process increases [14]. Thus, it is expected that pull-off concrete strength decreases when reducing core diameter. In general, the 50mm core diameter is the most common in the specifications, being the maximum aggregate size not taken into account by the standards in the definition of the core diameter. A minimum ratio between the core diameter and the large aggregate ratio of three is generally recognized as acceptable for testing drilled concrete cores. In this work, a core diameter of 79 mm with approximately 20±5 mm of drilling depth into the substrate was adopted, which are commonly applied values [5].

Figure 5 tested specimens.

Before gluing the disk using an epoxy resin, a very thin layer of the concrete surface was removed by a stone wear machine appropriate for this purpose see Figure 4. Afterwards, the concrete surface was cleaned. Failure in the adhesive–concrete interface or disk–adhesive interface was never verified, confirming the excellent performance of this proceeding.

Due to practical and economical reasons metal disks have been selected for all tests. Figure 5 represents the position of the partial cores. The loading rate used in the pull-off tests carried out was 0.±0.01 $N/mm^2.s^{-1}$, in agreement with the British and European Standards.

Finally, load eccentricity is another factor that affects the test results. The load eccentricity in a partial core pull-off test depends basically on the orthogonality of the core drilling (relatively to the substrate) and accuracy in positioning the metal disk on top of the partial core. In this way, if the orthogonality of the core drilling is not guaranteed, the eccentricity of the loading will increase with the depth of the core drilling. It is also believed that by increasing the drilling depth, the core damage generated by the vibration of the cutting drill machine increases, see Figure 5.

3.4. Rapid chloride permeability test (RCPT)

After the curing the thickness of all the mortar and concrete cylindrical test specimens (100 mm diameter × 200 mm thickness) were reduced to 50 mm by cutting on both the ends.

The specimens were then evacuated by following procedure as described in AASHTO T 277-89 [15]. The test procedure followed in the present study was in conformity with the AASHTO specification T277-89 [15] and ASTM C 1202-94 [13]. The positive reservoir of the cell was filled with 0.30 N sodium hydroxide (NaOH) solution, while the negative reservoir was filled with 3.0% NaCl solution. A direct current (DC) of 60+0.10 V was applied across the specimen and the resulting current was recorded at 5-min interval covering a total period of 6 h. Knowing the current and time history, the total charge passed through the specimen was computed by Simpson integration. During the RCPT, temperatures of the specimens were monitored (the Joule effect) manually during the test period and were observed to be close to the room temperature.

4. Test results

All specimens reported in this article were loaded at the age of 28 days. Each series of specimens is identified with two characters. The first character or number refers to the repair material and the second character to the interface surface preparation. Table 3 gives the test results, including the mean bond strengths, repair materials compressive strengths, and the number of the specimens that tested. the average of two tests is reported.

Table 3
Results of Pull-off Test specimens

σ = Mean bond strength (MPa), N= number of samples failed in bond, SF = silica fume, Epoxy = epoxy adhesive, SBR = styrene butadiene resin.

Figure 6 shows comparisons of the measured bond strength between repair materials. Results indicate that regardless of surface preparations, there are not many differences in bonding strength between various repairing materials. But modified cementitious mortar by silica fume and SBR latex provide higher bond strength. This can be attributed to bonding properties of modified materials that increased tension strength. It can be concluded that addition of silica fume increases the bond strength six times greater than ordinary mortar because silica gel provides better bonding agent at the interface between substrate concrete and repairing material. The use of SBR latex in cementitious mortar has more affect because polymer strings that are products of resin reaction, provide vigorous linkage at the interface.

From the Figure 6, adverse effect on the bond strength is noticeable when the epoxy adhesive used for bonding agent. In other words, the behavior of repairing materials besides epoxy resin are unfamiliar. It may occur of using superplasticizer beside epoxy resin. In relation to the influence of results seemed to indicate that its effect is significant and supplemental test should be done.

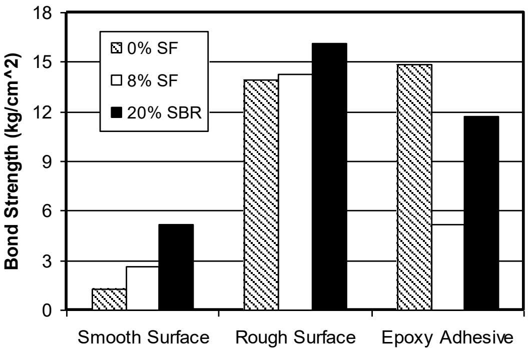

Figure 6 Results of Pull-off Test specimens.

From the Figure 7, it is verified that increasing the roughness of substrate surface increases bond strength for the three repairing materials, meaning that surface preparation plays a key role and bond strength is sensitive to the interface roughness. This can be attributed to mechanical linkage that produce higher interlock and increase the adhesion.

Figure 7, shows the increase in the bond strength for high roughness specimens compared to those with the low roughness. Providing a rougher bonding surface resulted in an increase in bond strength for all three repair materials. This indicates that all repairing materials are sensitive to the interface roughness.

Specimen series	Repair material	f'c (Mpa)	Roughness	σ (Mpa)	N
0S	0% SF	36	Smooth	1.3	2
0R			Rough	13.9	2
0E			Epoxy	14.9	2
8S	8% SF	42	Smooth	2.6	2
8R			Rough	14.3	2
8E			Epoxy	5.2	2
LS	Modified by SBR latex	38	Smooth	5.2	2
LR			Rough	16.1	2
LE			Epoxy	11.7	2

Figure 7 also shows that the bond strength of different repair materials that used on the rough surface is very close and higher than the other two surface preparations.

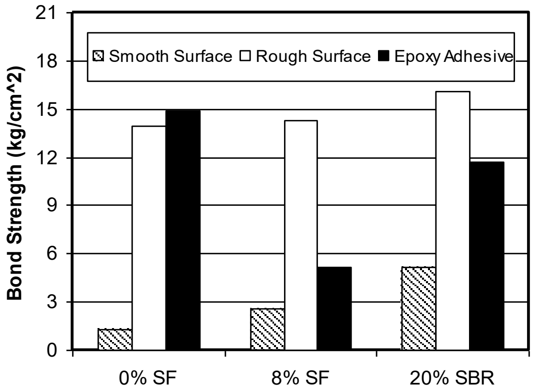

Figure 7 Test results of Pull-off Test specimens.

Figure 8 demonstrates the relationship between the total charge passed (coulombs) through mortars, considering the type of material, electrical conductivity is related to concrete permeability. From this figure, it is evident that for a given curing period, an increase in concrete permeability leads to greater amount of charge passed through the mortar specimens. In other words, the resistance of mortar specimens against chloride penetration decreases with increasing permeability of the mix as a result of the porous microstructure.

TABLE 4
TEST RESULTS OF RCPT SPECIMENS

Repair material	Total charge Passed (coulombs)
0% SF	4915
8% SF	1001
20% SBR	2060

the charge passed through the ordinary mortar is higher by at least a factor of 5 than that through the modified cementitious mortar by silica fume. chloride ion permeability of ordinary mortar is high and modified cementitious mortar by silica fume is low Since the higher the charge passed the lower is the resistance against chloride penetration [9], This implies that the resistance of the mortar against chloride penetration is lower than the modified cementitious mortar by silica fume. Therefore silica fume decreases permeability of mortar against chloride penetration. Total charge Passed (coulombs) through modified cementitious mortar by SBR latex is lower than the ordinary mortar and chloride ion permeability is moderate. Thus, modified cementitious mortars are suitable materials for using in corrosive environments and repairing structures.

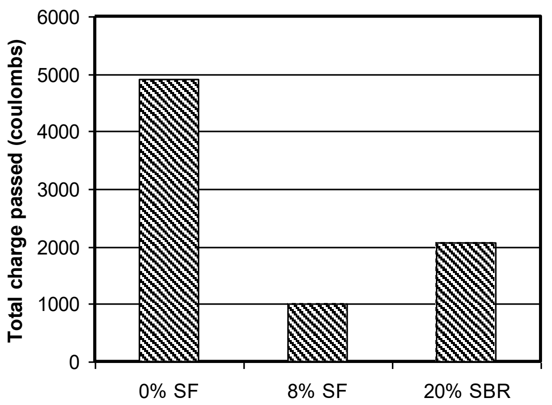

Figure 8: Test results of RCPT specimens

Considering both the bond strength and the electrical conductivity of repairing materials present that the best technique for repairing structures is increasing surface roughness of substrate concrete and using modified repairing materials for increasing the service life of repaired structures against corrosion. Therefore The performance of the strengthened structural system improves.

5. Summary and Conclusions

The short-term bond strength of specimens constructed with three different repair materials and three different surface preparations have been reported. The specimens were tested under pull-off test and RCPT. Based on the results obtained, the following conclusions can be drawn

1. Bond strength is greatly dependent on the roughness of substrate surface and has a main effect on the performance of bond between adhesives and concrete.
2. Bond strength increases with silica fume content of modified cementitious mortar.
3. Bond strength increases with the use of SBR latex in cementitious mortar.
4. The influence of surface roughness is more pronounced when the repair materials have low adhesion, e.g., cementitious materials.
5. Adverse effect on the bond strength is noticeable when the epoxy adhesive used as bonding agent
6. Silica fume and SBR latex decrease permeability of mortar against chloride penetration.
7. considering electrical conductivity of repairing materials, modified cementitious mortars are better materials for using in corrosive environments and increase service life of repaired structures

6. References

[1] A. Momayez, M.R. Ehsani, A.A. Ramezanianpour, H. Rajaie, "*Comparison of methods for evaluation bond strength between concrete substrate and repair materials*", *Cement and concrete research*, vol. 35, pp. 748-757 **2005**.

[2] *Standard Test Method for Bond Strength of Epoxy Resin Systems Used with Concrete,* ASTM C 882-78, American Society for Testing

[3] KnabLI. "*Factors related to the performance of concrete repair materials*", Technical report REMR-CS-12, US Army Corps of Engineers, Washington, DC, March **1988**.

[4] S. Austin, P. Robins, V. Pan, "Tensile bond testing of concrete repairs", *Mater Structure*, vol.28, pp. 249–59 **1995**.

[5] *Standard test method for pull-off strength of coating using portable adhesion testers.* ASTM D4541. American Society for Testing and Materials; **2002**.

[6] Julio ES, Branco F, Silva VD. "*Structural rehabilitation of columns using reinforced concrete jacketing*", *Prog Struct Engng Mater*, vol.5, pp. 29–37 **2003**.

[7] Bett BJ, Klingner RE, Jirsa JO. "*Lateral load response of strengthened and repaired reinforced concrete columns*", *ACI Struct J*, 85(5):499–508 **1988**.

[8] Alocer S, Jirsa J. "*Assessment of the response of reinforced concreate frame connections redesigned by jacketing*", *Proceedings of the Fourth US National Conference on Earthquake Engineering.* vol. 3. May; pp. 295–304 **1990**.

[9] Alcocer SM. "*RC frame connections rehabilitated by jacketing*". *J Struct Eng,* 119(5):1413–31**1993**.

[10] Ramirez JL, Barcena JM, Urreta JI, e Sanchez JA. "Repair *of concrete columns with partial localized damages*", Report T 2.1 and 2.2 BREU–0186–C, April **1991**.

[11] Rodriguez M, Park R. "*Seismic load tests on reinforced concrete columns strengthened by jacketing*", *ACI Struct J*, (March– April):150–9 **1994**.

[12] Stoppenhagen DR, Jirsa JO, Wyllie Jr LA. "*Seismic repair and strengthening of a severely damaged concrete frame*", *ACI Struct J* (March–April):177–87 **1995**.

[13] *Electrical indication of concrete's ability to resist chloride ion penetration,* ASTM C1202, Annual

Book of American Society for Testing Materials Standards, vol. C04.02, **2000**.

[14] E. Bonaldo, J. Barros, P.B. Lourenco, "*Bond characterization between concrete substrate and repairing SFRC using pull-off testing*", *International Journal of Adhesion & Adhesives,* vol. 25, pp.463-474 **2005**.

[15] *Rapid determination of chloride permeability of concrete, standard specification for transportation materials and methods of sampling and testing,* AASHTO T277-89, American Association of State Highway and Transportation Officials, Washington, DC, **1986**.