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Repairing concrete with epoxy adhesives

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A R T I C L E I N F O

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A B S T R A C T

Epoxy-based adhesives have been widely used for the recovery of concrete structures. This study is aimed at studying the performance of six epoxy adhesives on the bond strength between two conventional concretes of different strengths when subjected to the slant shear test.

First, the physical and mechanical characteristics of the six adhesives and the concrete used were studied. The factors investigated were the viscosity and the compressive strength of the adhesives during their working life, and the variation of the compressive strength of the base and overlay concrete. Later, the specimens were sawn at a 45-degree angle. Afterwards, the shear test was used and the factors affecting the bonding interface were analyzed.

The results indicated that the compressive strength of the concrete studied, the interface roughness of the base concrete, the viscosity of the adhesives and the compressive strength of the adhesives at the time of application have important effect on the ultimate strength and on the bond strength when the mixed specimen is subjected to the slant shear stress. The Analysis of Variance (ANOVA) was used to assess the results.

The performance of commercial epoxy adhesives varies when applied to bond concrete of different strengths. The differences are smaller when applied to concrete of compressive strength in the order of 33 MPa and larger when applied to concrete of compressive strength in the order of 46 and 59 MPa, demonstrating that the concrete strength affects the performance of the epoxy adhesive. In high-strength concrete, the bonding process should be validated prior to application by studying the bonding mechanisms, the substrate roughness and the differences in compressive strength of the substrate and the overlay/repair concrete. In addition, the adhesive adopted should be previously analyzed to verify if it is compatible with the concrete strength.

1. Introduction

Reinforced concrete structures are proving to be extremely susceptible to the action of aggressive agents and, consequently, suffer from the appearance of several pathological manifestations [1]. This susceptibility is related to the increase of new constructions performed in short time periods and to the reduction of the dimensions of reinforced concrete structures. This contributed to the increase of occurrences or failures – mainly those like cracking or damage to reinforced concrete structures [2] – and it is therefore necessary to promote repairs or strengthening of the structures as soon as possible.

The objective of the strengthening or repair service is to regain the original characteristics and the monolithic behavior of the concrete structures [3], and this depends on the quality of the bond at the interface between the substrate concrete and overlay concrete [4]. Most repair and strengthening techniques include coupling new concrete to an existing concrete substrate, and in some cases, the application of a bonding agent [5,6]. To assess the performance of this strengthening or repair, the slant shear test is the most used type of test by researchers [5,7], since it combines the axial compression stress with the shear stress for different angles and allows to determine the bond strength between specimens of different concrete that were bonded with or without adhesive.

The issue addressed in this topic is complex, since several variables affect the bond strength between old concrete (base) and new concrete (overlay). Among these variables are the physical and mechanical characteristics of the base concrete and overlay concrete, as well as the effects of the epoxy adhesive application on concrete adhesion [8,9]. Some studies evaluated the effect of different compressive strengths of the substrate concrete and overlay concrete [6] in relation to the bond

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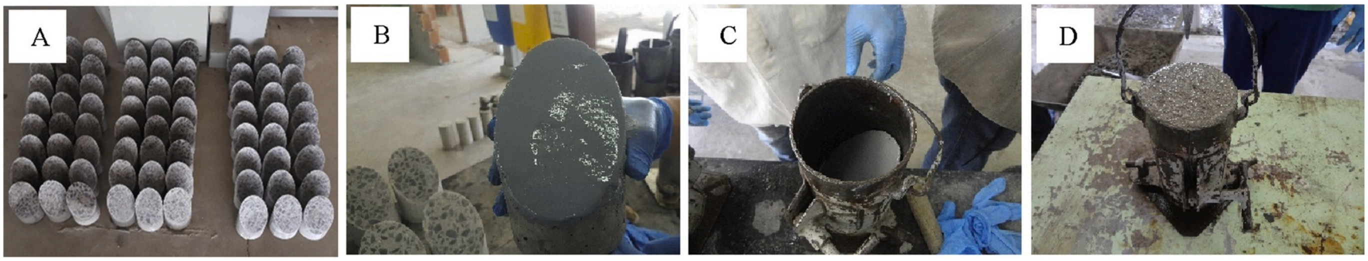


Fig. 1. Shows the specimens (a) cut and drying. b) receiving the layer of adhesive. c) returning to the mold. d) after being molded with the new overlay concrete.

strength between these concretes, while others assessed the effect of the substrate roughness [4,7].

It's important to highlight that the rough surface increases both the contact area in which the adhesion force can increase the total energy of surface interaction and the strength of the joint separation. In addition, based on the mechanical interlocking theory of adhesion, good adhesion occurs when an adhesive penetrates the pores, holes and crevices, which lock mechanically to the substrate [10]. They are usually used to increase the roughness of the substrate before applying the adhesive or the new concrete layer [4,9]. The roughness pattern is highly referenced when the adhesion between concrete without the use of adhesives is studied [11]. *Guideline n.310.2R-2013* [12] *presents distinct benchmark Concrete Surface Profiles (CSP) produced by surface preparation methods ranging from CSP-1 through CSP-*10 that *replicate degrees of roughness suitable for the application of one or more sealers, coatings, polymer overlay systems or concrete repair materials*.

However, in the present study, the concrete specimens were cut by a professional industrial mechanical slim steel saw blade with 1000 rpm in order to obtain an almost smooth roughness, which allowed to reduce the influence of the roughness of the concrete surface on the performance of the studied epoxy adhesives. Other variables affecting the bond strength between concrete, like the shape (prismatic or cylindrical), the dimensions of the specimen and the variation of the angles of the inclined plane (30°, 45° and 60°), were studied using the slant shear test [6,13].

Many of these variables, in simple or combined form, have already been studied for vibrated and self-compacting concrete applied to substrate and/or overlay concrete (strengthening or repair) and bonded with and without a layer of epoxy resin [4,14,15]. The concrete compressive strength, the bond strength, and the study of the substrate roughness on the bonding of two concretes with different strength are important factors in the strengthening or repair process of concrete structures [7].

However, with the increase of concrete strengths in precast structures, it is necessary to better understand the joint performance of those structural elements that depend on the compressive strength analysis of the concrete, the concrete stiffness and shrinkage, the roughness of the bonded contact surface, the slope of the bond and the adhesive used. All these variables should be studied previously [9].

Based on the study presented, it has been reported the lack of academic study correlating more than one epoxy adhesive on concrete bonding or even preliminary studies of the physical and mechanical characteristics of the adhesives used in the researches. In this regard, the main objectives of the research were to study the performance of six different epoxy resin adhesives on the bond strength at the interface between two different concretes when subjected to the slant shear stress using the slant shear test, and if they provide the same bond strength in different combinations of the influencing factors mentioned above, like the concrete strengths (31, 46 and 59 MPa), maintaining the substrate surface without the influence of the roughness and the bond angle at 45°.

For this purpose, the physical and mechanical characteristics of the six epoxy resin adhesives were analyzed previously, like the viscosity that was assessed and the compressive strengths that were measured every 10 min after mixing the components (epoxy resin and hardener), to determine their characteristics such as working life, if loss of compressive strengths occur during these tests and also to verify if the adhesive match the concrete used in the repair.

2. Experimental program

In this study, some elements were kept constant to reduce the errors of the factors affecting bond strength. Sawing was the pattern established for the roughness of the substrate and is the second-lowest level of roughness, CSP-2 [12]. The concrete stiffness was kept constant with the use of only one type of coarse aggregate (crushed basaltic stone), fine aggregate (sand) and Portland cement (CP–V ARI). Only conventional/traditional vibrated concrete was used. The concretes were prepared with three compressive strengths of 33, 46 and 59 MPa for the bases. The strength of the overlay was kept constant at the highest strength of 59 MPa. The angle of 45° was adopted for the slant shear test.

A total of 168 cylindrical concrete samples were prepared with dimensions of 100 mm × 200 mm. These specimens were composed of the following components: coarse aggregate, fine aggregate, high initial-strength Portland cement, plasticizer (chemical additive), potable water from the public network, and six commercial epoxy adhesives were used in the study developed. The coarse aggregate was crushed basaltic stone with a maximum size of 12.5 mm. The natural river sand had a fineness modulus of 3.03 and a maximum size of 4.80 mm. The plasticizer type GLENIUM® 51 from the manufacturer BASF and high initial strength Portland cement type V were used.

The concrete specimens of the bases were kept under immersion water curing conditions until the age of 14 days when they were then cut. The specimens of the bases were maintained under immersion water curing conditions until the age of 14 days, when the specimens were removed, leaving them drying for 24 h before sawing them. Then, they

Table 1
Specification of the three concretes C1, C2 and C3 of the base and C3 of the overlay.

Mix (cement: fine and coarse aggregate) (kg/kg)	Concrete identification	Water/cement w/c ratio (kg/kg)	Total aggregate/cement "m" (kg/kg)	Amount Cement (kg/m^3)	Amount sand (kg/m^3)	Amount gravel (kg/m^3)	Amount water (kg/m^3)	Mass specific (kg/m^3)	Compressive strength required (MPa)	Compressive strength achieved (MPa)
1 : 2,60 : 3,07	C1	0.6	5.67	334.00	869.33	1025.37	200.61	2429.67	30	33
1 : 2,00 : 2,56	C2	0.5	4.56	402.00	805.22	1028.89	201.31	2438.03	40	46
1 : 1,40 : 2,04	C3	0.4	3.44	505.00	708.22	1034.23	202.35	2450.68	60	59

Table 2
Characteristics of the six adhesives used in the study.

item #	characteristics of the adesives analyzed in the lab		Adhesive 1	Adhesive 2	Adhesive 3	Adhesive 4	Adhesive 5	Adhesive 6
1	indicated viscosity		low	15.000 cP	medium	medium	medium	medium
2	compressive strenght at 24 h	(MPa)	25	–	60	–	40	–
3	compressive strenght at 7 days	(MPa)	–	70	–	–	–	60
4	total weight of the sample	(kg)	1	1	1	1	1	1
5	weight of part A	(kg)	–	784	670	500	810	–
6	weight of part B	(kg)	–	216	330	500	190	–
7	what's the performance/ consumption	(kg/m^2/ mm)	1.7	1,7 to 1,8	1.7	1.8	0,8 to 1,5	0,8 to 1,0
8	Temperature of use - range	(°C)	5 to 35	5 to 30	10 to 30	25	5 to 35	20
9	working life	(min)	40	30 to 40	35	50	60 to 120	50
10	mixing time	(min)	3	3 to 5	3	–	3	–
11	rotationof the stirrer for misture	(rpm)	–	400 to 500	400 to 500	–	400 to 450	low rotation
12	indicated as structural	(Y/N)	yes	yes	yes	yes	yes	yes
13	component number		two	two	two	two	two	two
14	catalyst composition		amine	polyamide	polyamide	polyamide	amine	polyamide
15	inform to regain monolithic behavior		no	yes	no	no	no	no
16	inform to treat active crack		no	no	no	no	no	no
17	inform to be toxic and requires IPI		glove/glasses/ boot	check safety	glove/glasses/ boot	glove/ glasses	glove/ glasses	glove/glasses/ boot

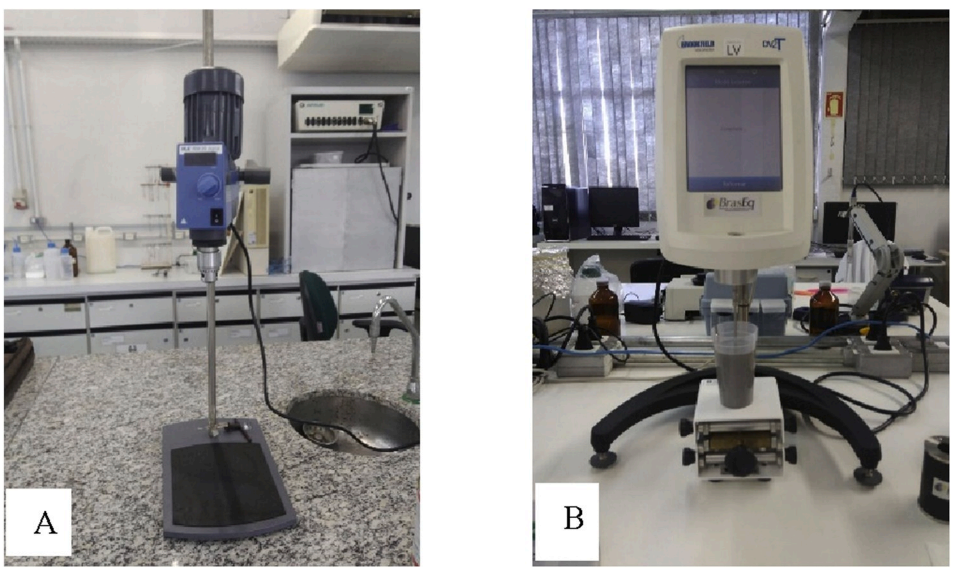


Fig. 2. Viscosity measurement of the 6 epoxy adhesives studied using a) IKA mechanical stirrer model RW20 digital b) DV2T Brookfield rotational viscometer.

were kept in the shade during the next 24 h to dry the surface pores without apparent humidity (Fig. 1 A). On the following day, the bases received a 1-mm layer of adhesive (Fig. 1 B). The specimen was returned to the mold (Fig. 1C) and the overlay was cast (Fig. 1 D). The appropriated adhesion with the new concrete (overlay) depends on the hardener characteristics of the adhesive. For this reason, water-resistant hardeners like amine and polyamide were chosen. The 168 repaired specimens were kept for more 28 days in immersion water curing conditions until they were subjected to the slant shear test.

2.1. Characteristics of the concrete mix

Table 1 summarizes the mix proportions of the three conventional concretes used to cast the base and overlay concrete. The mix, w/c ratio, aggregate/cement ratio, consumption of cement, sand, gravel, water and specific mass are presented. The expected and actual results of the compressive strengths at 28 days are also shown. Fifty-six specimens were cast from each concrete base.

2.2. Adhesive characteristics according to manufacturer's technical bulletins

Six two-component type epoxy-based adhesives chosen from those commercially available and indicated as suitable for structural repair or structural adhesive were used in the experimental program. Table 2 shows the characteristics reported by the manufacturers.

2.3. Physical and mechanical characteristics of the epoxy resin adhesives studied

Only the two-component epoxy adhesives were studied. The adhesives were stored for five days in the lab with controlled temperature of 23 °C for their stabilization, meeting the recommendation of the manufacturers. The two components (1 L) of the six adhesives studied were mechanically mixed for 5 min in an IKA mechanical stirrer model RW20 digital at 500 rpm (Fig. 2A). The container of the resin received the hardener according to the preparation instructions until the adequate point of use was reached, like color change, paste uniformity and temperature increase. Immediately after homogenization, a sample of 200

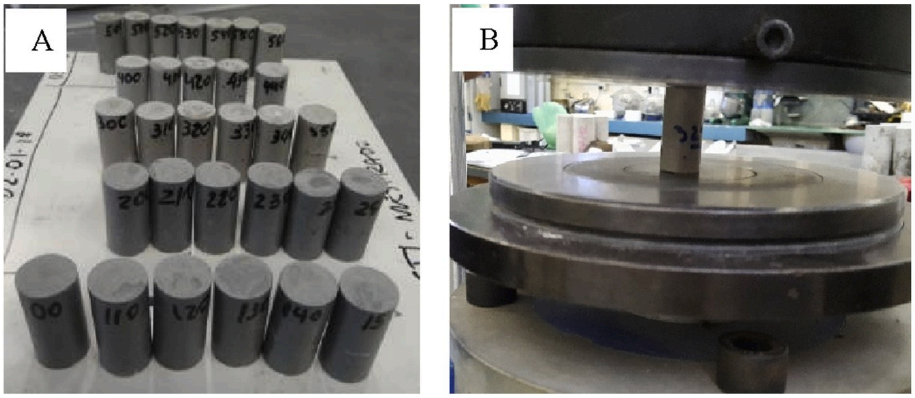


Fig. 3. Shows a) cylindrical specimens of epoxy adhesives used to measure the axial compressive strength. b) the compressive strength test.

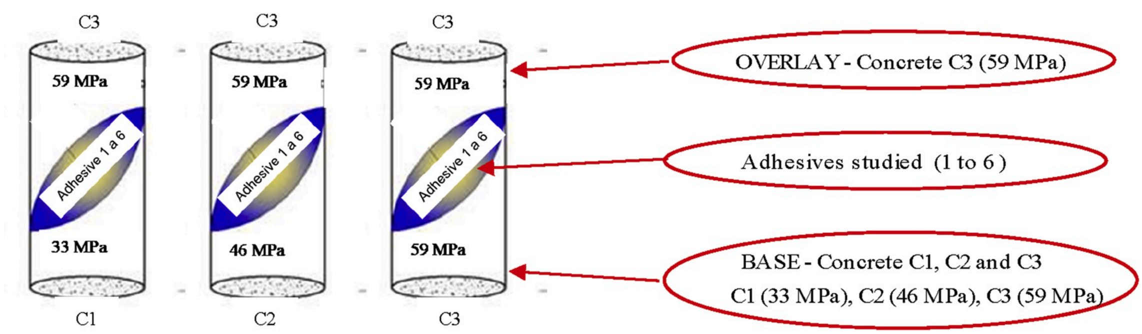


Fig. 4. Scheme of compressive strength of the mixed specimens (MPa).

Fig. 5. Shows a) base samples cut at 45°. b) epoxy adhesive layer applied over the base. c) mixed specimens (with or without adhesive).

ml of each adhesive was used to determine the viscosity, using a DV2T Brookfield rotational viscometer (Fig. 2 B). For this test, the water is the reference because its viscosity is 1 centiPoise (cP). The epoxy adhesives tested were classified as Type V, Grade 3 and Class C [16].

After measuring the physical characteristics of the adhesives (viscosity), specimens were molded to determine the mechanical

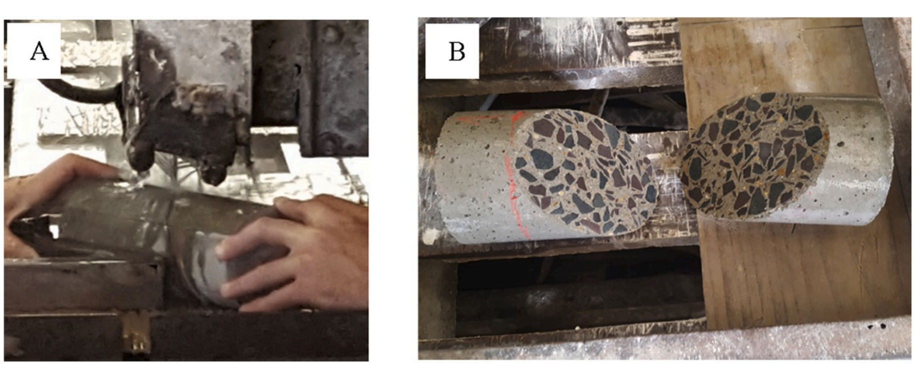


Fig. 6. Shows a) a concrete specimen being cut at 45°. b) a specimen after being cut at 45° and the roughness profile of the concrete surface obtained by grinding was CSP-2 [16].

Table 3
Results of the average compressive strength at 28 days and results of the absorption and porosity tests of concrete C1, C2 and C3.

Concrete	Avarage Strength (MPa)	Standard Deviation (MPa)	Variation Coefficient (%)	Absorption Test(%)	Standard Deviation (%)	Variation Coefficient (%)	Porosity Test (%)	Standard Deviation (%)	Variation Coefficient (%)
C1	33	1.09	3.27	5.14	0.15	2.95	11.75	0.33	2.81
C2	46	1.46	3.19	4.68	1.26	0.48	10.71	0.48	4.48
C3	59	2.26	3.84	3.43	0.33	2.79	7.95	0.37	4.59

Table 4
Absorption formula is =(damp-dry)/(dry) and Porosity formula is =(heated-dry)/(heated-hydrostatic).

	CONCRETE - C1						
	Dry	Damp	Heated	Hydrostatic	Absorption	Density	Porosity
A	–	–	–	–	–	–	–
B	3662.00	3844.60	3842.70	2258.90	4.99%	260.99%	11.41%
C	3612.10	3793.60	3794.20	2216.00	5.02%	258.73%	11.54%
D	3634.60	3825.70	3824.50	2239.40	5.26%	260.51%	11.98%
E	3609.70	3800.10	3798.70	2234.30	5.27%	262.45%	12.08%
Average	3629.60	3816.00	3815.03	2237.15	5.14%	260.67%	11.75%

characteristics (axial compressive strength) [17]. Therefore, twelve cylindrical specimens were produced for each adhesive studied to test the compressive strength at one day and seven days). The casting of two specimens was carried out every 10 min after mixing the two components (resin and hardener) (Fig. 3A) to assess the effect of the compressive strength over time (Fig. 3B), and how long the working life is.

2.4. *Slant shear test on the adhesiveness of the substrate and overlay concrete*

The slant shear test is the most representative test method available for selecting an epoxy resin for a concrete repair [4]. The slant shear test can be used to estimate the suitability of crack repair materials [4,14,18], since it is widely used as a test procedure to determine the bond strength of the repair materials. It is expected that the adhesive failure in the composite cylinder will preferentially occur on the inclined surface to measure the bond strength [6], as shown in Fig. 4 and Fig. 5.

It was used a 59 MPa concrete for the overlay, a 33 MPa, 46 MPa or 59 MPa concrete for the base of the mixed specimens, and six different adhesives were applied in the middle. The ratio between the overlay/base compressive strengths change in the three cases molded, C3/C1 (59/33) = 1,79, C3/C2 (59/46) = 1,28 and C3/C3 (59/59) = 1,00.

2.5. *Characteristic of the surface roughness of the concrete substrate*

In this study, the surface preparation was done by cutting, using a professional industrial mechanical slim steel saw blade with 1000 rpm to reduce the influence of roughness on the ultimate strength and prevent surface damage, obtaining a profile equivalent to CSP-2 [12], considered smooth (grinding) as shown in Fig. 6.

3. Results and discussions

3.1. *Characteristics of the compressive strengths of the base and overlay concrete*

The results of the tests performed on the concrete studied to determine the compressive strength using eight specimens for each concrete and the absorption and porosity tests using five specimens for each concrete are shown in Table 3, which shows that the C1 concrete samples presented higher absorption and higher porosity. For this reason, they had lower compressive strength than the others tested [1].

The absorption and porosity test results were obtained using five specimens for each concrete. First, they were weighed when damped and then put inside the water to measure the hydrostatic weight. Later, they were submerged for 12 h in hot water at 100 °C and weighed in heated condition. Finally, they were dried in the oven until they achieved consistency of weight and then weighed in dry condition. Based on these measurements, the average of absorption and porosity percentages of each concrete were obtained, as shown in Table 4.

Table 5
Results of the average viscosity (cP) of the six epoxy adhesives.

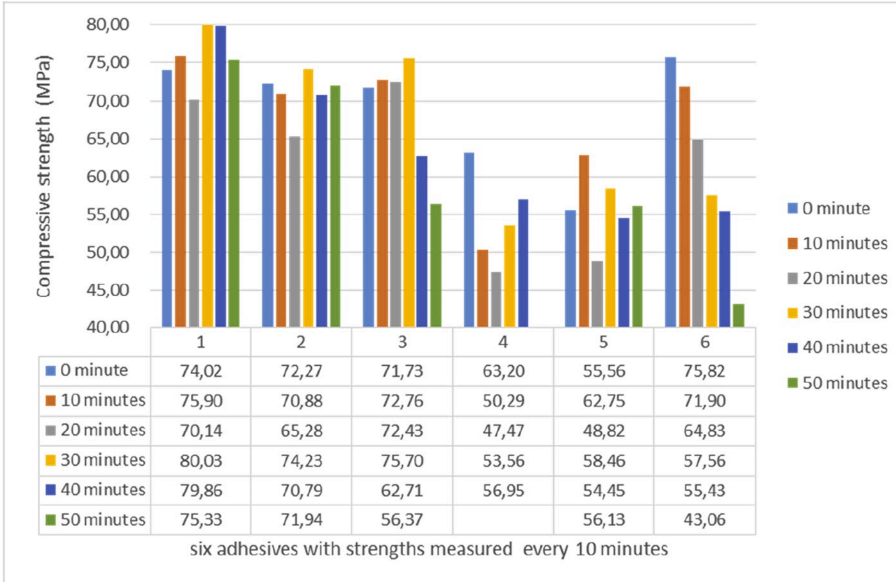
Adhesive	1	2	3	4	5	6
Individual average viscosity (cP)	32,223	22,470	28,490	79,450	84,743	22,166
Adhesives ordered for viscosity	2	6	1	3	4	5
Individual average viscosity (cP)	22,470	22,166	32,223	28,490	79,450	84,743
Grouped average viscosity (cP) 3x	22,300		30,350		82,100	
Grouped average viscosity (cP) 2x	26,300				82,100	

3.2. *Physical characteristics of the epoxy resin adhesives*

Based on the results presented in Table 5, initially, the six adhesives were grouped into three groups with similar average viscosity. Adhesives 2 and 6 had an average viscosity of 22.300 cP, while, in adhesives 1 and 3, the average viscosity was 30.350 cP. In adhesives 4 and 5, it was 82.000 cP. Following this, it was found that the six adhesives can also be grouped in only two groups because four adhesives (1,3,2,6) presented an average viscosity of 26.300 cP. In terms of viscosity, the adhesives tested were classified as Type V, Grade 3 and Class C [16]. [16].

3.3. *Mechanical characteristics of the epoxy resin adhesives*

After determining the viscosity of the adhesives, the specimens were prepared to determine the axial compressive strength. In this study, the molds of the specimens were prepared using a commercial tube with a size of 17 mm diameter by 34 mm height, maintaining the ratio of 2 between the specimen diameter and height. Twelve cylindrical specimens were produced for each one of the adhesives studied, totalizing 72 specimens. The compressive strength was determined at the ages of one day and seven days, and at each age, six specimens were tested for each



	1	2	3	4	5	6
0 minute	74,02	72,27	71,73	63,20	55,56	75,82
10 minutes	75,90	70,88	72,76	50,29	62,75	71,90
20 minutes	70,14	65,28	72,43	47,47	48,82	64,83
30 minutes	80,03	74,23	75,70	53,56	58,46	57,56
40 minutes	79,86	70,79	62,71	56,95	54,45	55,43
50 minutes	75,33	71,94	56,37		56,13	43,06

Fig. 7. Results of the individual strengths of the 6 epoxy adhesives cast in steps of 10 min after mixing and at the age of 7 days.

one of the resins studied.

The preparation of the specimens was performed according to the mixing time of the two components (resin and hardener) of the epoxy adhesives – that is, the 0-min time corresponds to the casting of the specimens at the time the epoxy resin mixture was homogenized. From this moment, specimens were cast every 10 min to assess the effect of the time elapsed between mixing of the two components and bonding of the specimens on the compressive strength after curing, as well as to assess the working life of the adhesive. Fig. 7 presents the individual results of axial compressive strength of the epoxy adhesive samples, determined at the age of seven days in the laboratory with a controlled and constant temperature of 23 °C.

The group of adhesives of higher strength (1, 2 and 3) with an average of 73 MPa is 20% well above the intermediary group (6) of 61 MPa and is 35% higher than the group of lower strength (4 and 5) and an average of 54 MPa. Based on the axial compressive strength of the epoxy adhesives at the age of seven days – the variable being the time elapsed between the mixing of the resin with the hardener and the casting of the specimens – every 10 min, the following observations can be made:

a) Adhesives 1 and 2 presented similar behavior, and high strengths were observed (of the order of 73 MPa) regardless of the mixing time between the resin with the hardener and the casting of the specimens. That is, these adhesives have proved to be adequate until the time of 50 min, showing no loss of performance considering a practical application in situ.
b) Adhesive 3 presented similar behavior to the adhesives 1 and 2 until the time of 30 min. A reduction of the compressive strength of 13% (40 min) and 22% (50 min) in relation to the average strength of this epoxy adhesive was observed for the mixing time of the resin with the hardener and 40- and 50-min casting. This shows that this epoxy adhesive should be applied, preferably, until 30 min after the mixing of the epoxy components to ensure performance.
c) Adhesive 4 showed variable compressive strength between the casting times, and it was not possible to cast specimens at the 50-min time due to the lack of workability of the adhesive. That is, in practice, this adhesive can be used only until 40 min after the mixing of the components and the application, and for minor repairs.

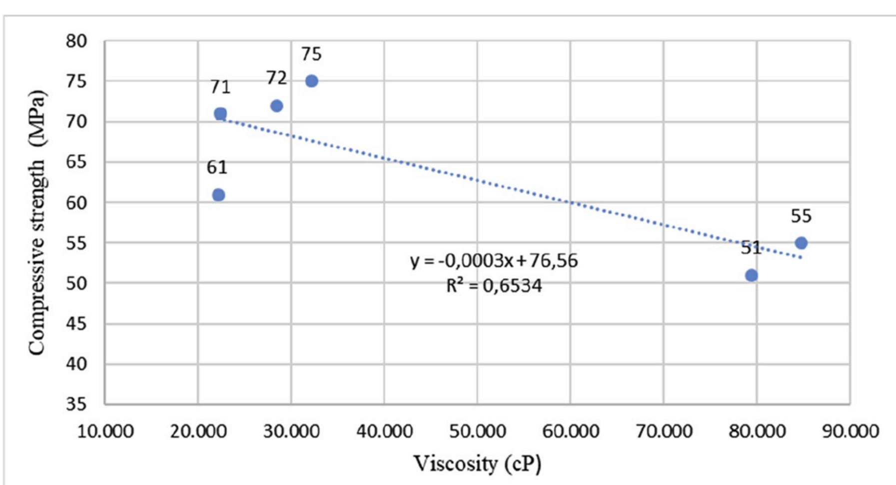


Fig. 8. The relation between the compressive strength and the viscosity of the epoxy adhesives tested.

Table 6
Results of the Ultimate Strength (MPa) of the mixed specimens with adhesives and those without adhesives (reference).

Identification of the specimens	Adhesive strength (MPa)	Adhesive Viscosity (cP)	Overlay Strength (MPa)	Base Strength (MPa)	Ultimate Strength (MPa)	Standart Deviation (MPa)	Variation Coefficient (%)	Reduction Ultimate Strength (MPa)
C1.1:59s-33i	75,62	32223	58,87	33,33	33,23	1,11	3,33	-0,29
C1.2:59s-33i	72,41	22470	58,87	33,33	32,20	2,05	6,36	-3,39
C1.3:59s-33i	72,08	28490	58,87	33,33	30,38	2,82	9,29	-8,87
C1.4:59s-33i	51,93	79450	58,87	33,33	34,60	1,35	3,90	3,81
C1.5:59s-33i	55,85	84700	58,87	33,33	33,80	1,50	4,43	1,41
C1.6:59s-33i	61,20	22166	58,87	33,33	31,00	0,88	2,82	-6,99
C2.1:59s-46i	75,62	32223	58,87	45,78	31,98	1,27	3,98	-30,16
C2.2:59s-46i	72,41	22470	58,87	45,78	37,53	8,67	23,09	-18,01
C2.3:59s-46i	72,08	28490	58,87	45,78	37,40	2,55	6,83	-18,30
C2.4:59s-46i	51,93	79450	58,87	45,78	46,48	1,45	3,12	1,52
C2.5:59s-46i	55,85	84700	58,87	45,78	45,45	1,76	3,87	-0,72
C2.6:59s-46i	61,20	22166	58,87	45,78	46,05	2,19	4,76	0,59
C3.1:59s-59i	75,62	32223	58,87	58,87	40,50	1,70	4,19	-31,20
C3.2:59s-59i	72,41	22470	58,87	58,87	39,83	3,21	8,07	-32,34
C3.3:59s-59i	72,08	28490	58,87	58,87	49,50	2,40	4,86	-15,92
C3.4:59s-59i	51,93	79450	58,87	58,87	51,20	1,50	2,93	-13,03
C3.5:59s-59i	55,85	84700	58,87	58,87	50,60	0,28	0,56	-14,05
C3.6:59s-59i	61,20	22166	58,87	58,87	50,85	1,34	2,64	-13,62
C1.SA:59s-33i	-	-	59	33	37,83	1,19	3,14	13,49
C2.SA:59s-46i	-	-	59	46	48,57	1,89	3,90	6,09
C3.SA:59s-59i	-	-	59	59	44,50	2,50	5,62	-24,41

d) Adhesive 5 exhibited similar behavior to the adhesives 1 and 2, but with lower mechanical performance (average compressive strength of 56 MPa), and it can be used only for minor repairs.
e) Adhesive 6 presented a different behavior from the others, since there was a sharp decline in strength from the mixture of the resin with the hardener. Thus, the application time of this epoxy is crucial for the mechanical performance, and reduction of the compressive strength of 5% (10 min), 14% (20 min) and 24% (30 min) in relation to the initial strength of this epoxy adhesive was observed. This shows that, in general, the adhesives should be applied, preferably, within 10 min.

Lower compressive strength was observed in adhesives 4 and 5, and this should be related to the chemical composition of the product. The results are consistent with the studies conducted [19], which evaluated epoxy adhesives and concluded that most products have application time of 15–30 min at 25 °C, making it essential to mix only the amount that can be properly used in that period, so the adhesive can maintain its physical and mechanical characteristics. Studies have found that the progress of curing is determined by time, temperature and composition [20]. The effects of these parameters on the properties of the materials can be worrying. The variables mentioned influence the resin properties in the fluid state. Similarly, it was found that a fast heating rate can assure a sufficiently low viscosity for the resin to flow, but it causes a fast gel effect, shortening the application time [21].

Fig. 8 correlates the average compressive strength with respect to the viscosity of the epoxy adhesives. It is observed that there is an inverse relationship between the compressive strength in relation to the viscosity of the six adhesives studied – that is, the highest viscosity group (average of 80.000 cP) showed the lowest compressive strength (around 50 MPa). The lowest viscosity group (between 20.000 and 30.000 cP) presented the highest compressive strength values (between 61 MPa and 75 MPa), which shows a strong inverse correlation between viscosity and compressive strength with correlation (R2) of 0,65. However, influence of the adhesive strength on the ultimate strength was not observed.

3.4. Ultimate strength of the mixed specimens subjected to the slant shear test

Table 6 shows the ultimate strength results of the mixed specimens subjected to the slant shear test at an angle of 45° with the application of the epoxy resin layer of the six adhesives studied, compressive strength and viscosity of the adhesives studied, the compressive strength of the base and overlay concrete, the ultimate strength and the percentage of reduction of the ultimate strength of the mixed specimens. It's important to mention that the working life of adhesives was observed previously. In the end, the results of the mixed specimens without adhesive application were presented.

A reduction up to 18% was considered acceptable, which is compatible with research [3] that established a reduction of 15% as an acceptable limit. As shown in Table 5, with the application of epoxy adhesive at the joint of the mixed specimens with base concrete strength of 33 MPa, all specimens had acceptable ultimate strength, with maximum reduction of −8,87%. In relation to the mixed specimens with a strength of 46 MPa, the ultimate strength decreased to an unacceptable level (−18,01% and −30,16%) in the first three adhesives (C2.1, C2.2 and C2.3). In the mixed specimens with a strength of 59 MPa, the ultimate strength decreased to an unacceptable level (−31,20% and −32, 34%) in the two first adhesives (C3.1 and C3.2).

In the specimens without epoxy adhesive application at the joint of the mixed specimens with base concrete strength of 33 MPa and 46 MPa, all the specimens had ultimate strength with an increase of +13,49% and +6,09% respectively. On the other hand, the ultimate strength decreased to an unacceptable level (−24,41%) in the mixed specimens with a strength of 59 MPa. The results are consistent with other studies that found similar differences in the adhesiveness of mixed specimens bonded with epoxy adhesive [2,13]. The results of the mixed specimens

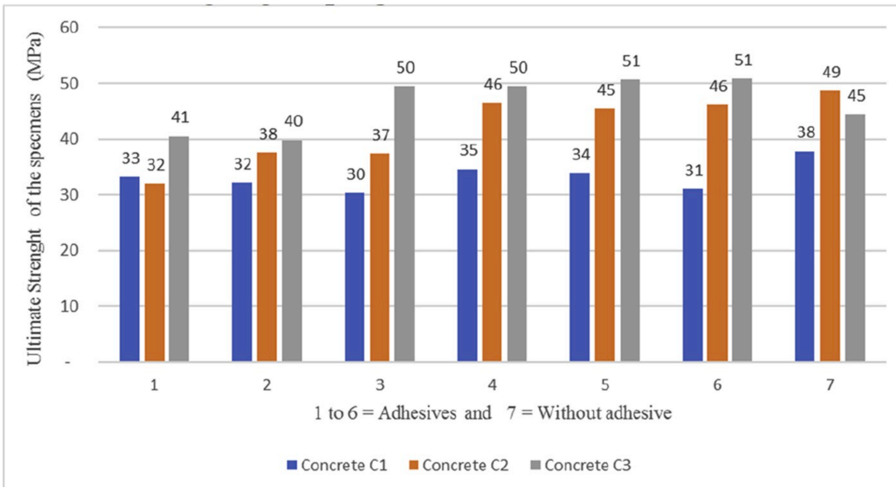


Fig. 9. Ultimate strength grouping the 6 adhesives with concrete C1, C2 and C3.

a) The average ultimate strength in concrete C1 (33 MPa) was approximately equivalent to and even greater than the strength of the base, as occurred with adhesives 1, 4 and 5. Adhesives 2, 3 and 6 did not achieve the same level but were similar, and were 2%, 8% and 6% below the strength of the base.
b) By increasing the compressive strength of the C2 concrete (46 MPa), there was an increase of the average ultimate strength, which was also equivalent to the base strength, as with adhesives 4, 5 and 6. In adhesives 1, 2 and 3, the ultimate strength was, respectively, 31%, 18% and 19% lower than the compressive strength of the base concrete.
c) This behavior was not reported for concrete C3 (59 MPa), since the ultimate strength reached a level 13% below the compressive strength of the concrete base of the mixed specimens, and adhesives 3, 4, 5 and 6 achieved a compressive strength of only 50–51 MPa. Adhesives 1 and 2 reached only 31% and 33% below the compressive strength.
d) After being cut and bonded with an epoxy adhesive application, the integral specimens with high strength concrete (59 MPa) were found to have a compressive strength reduction (at minimum) of 13% versus a 25% reduction of the specimens without epoxy adhesive. The results are consistent with other studies [3], whose concrete structures bonded with epoxy adhesive had a compressive strength reduction of 8% versus 41% when the structures did not receive epoxy adhesive.
e) In the mixed specimens without adhesive, it was observed brittle and violent ruptures of the mixed specimens tested, and a different behavior was reported in the specimens with adhesives, proving the importance of the use of adhesive, which reduces the variability of the results and the brittle rupture.
f) The use of epoxy adhesives in repairs of concrete with strength between 33 and 46 MPa proved to be effective in preventing the occurrence of brittle and violent ruptures.
g) Further studies are necessary on the concrete with a strength of the order of 60 MPa. In addition, the process should be validated with analysis of the characteristics of the adhesive type chosen (compressive strength and viscosity), the maximum time of adhesive application, preferably in the first 10 min, observance of the surface preparation using a minimum CSP of 3 (greater than the one tested) and the use of concrete with a maximum w/c ratio of 0,4.

shown in Table 6 and Fig. 9 demonstrate that the six epoxy adhesives studied produced different ultimate strength for the same compressive strengths of the base and overlay concrete.

3.5. Variation in the adhesiveness of the substrate and overlay concrete

The results showed that in the C1 and C2 concrete with an adhesive application, 50% of the specimens reached ultimate strength equivalent to the compressive strength of the base concrete. On the other hand, in the C3 concrete, 67% of the adhesives reached ultimate strength of the order of 50 MPa and 33% of the order of 40 MPa and are in accordance with the literature that the application of the epoxy adhesive improves the bond strength [4] in some situations. It has been observed that, when an epoxy resin is applied, the importance of the surface roughness of the substrate decreases because the epoxy adhesive layer eliminates the roughness differences between the substrate surfaces. This fact is in line with other studies [4].

Based on the data from Table 6, the ANOVA test[1] [22] was carried out to analyze the data variance, having as group variable the six epoxy adhesives in the concrete C1, C2 and C3 and the ultimate strength. The following values were found: C1 ($F_{calculated} = 3,40$, $F_{critical} = 2,81$ and Significance-P = 0,026,034), C2 ($F_{calc} = 10,12$, $F_{crit} = 2,90$ and P% = 0, 000217), and C3 ($F_{calc} = 17,88$, $F_{crit} = 3,48$ and P% = 0,000195). Considering that all the $F_{calculated} > F_{critical}$ and all the P% < 0,05 (5%), proves that the values of the adhesive groups are significant and that the adhesives are different or produce different results among them, at a 5% significance level. Results of the ANOVA analysis with different epoxy adhesives confirm that there are significant differences among the six adhesives studied and present variations within the same concrete group in relation to the ultimate strength for the mixed specimens.

The results show that the adhesives applied have different bond properties. Without the application of adhesives, results of the mixed specimens C1 and C2 are consistent with previous studies, which found that appropriate adhesion can be obtained without the use of adhesives by diligent labor involving the preparation of the substrate surface, consolidation and proper curing [6,14].

3.6. Influence of the viscosity of the adhesives on the adhesiveness of the substrate and overlay concrete

The results from Table 5 and Fig. 8 show two adhesive viscosity levels. In the concrete C1, C2 and C3 studied, the results of the ultimate strength of the mixed specimens tended to be greater when using adhesives with higher viscosity, and in some C1 and C2 samples, the compressive strength was even exceeded. There are few samples in which adhesive with lower viscosity reached high ultimate strength. In concrete C3 (59 MPa), the difference is clear, since the ultimate strength results are more homogeneous in the adhesives of the highest level when compared to the adhesives of the lowest level. The same behavior repeats in concrete C2 (46 MPa). In concrete C1 (33 MPa), of lower strength, the viscosity variation showed little influence on the ultimate strength and is only a trend.

[1] Analysis of Variance (ANOVA) is a statistical method used to test differences between two or more means.

4. Conclusions

It was concluded that the epoxy adhesives used are effective to regain the concrete monolithic properties, and the ultimate strength variations (bond strength) can be due to the intrinsic factors of the adhesives studied, like the differences of the viscosities and compressive strengths, the casting and curing process, the time elapsed between mixing of the components and the application of the adhesive and their working life. This also can be due to the intrinsic factors of the concretes, like the variations of the casting process of the strengthening concrete (mixed specimens).

The results of the ultimate strength, bond strength and rupture mode analysis of the specimens repaired indicate that, when working with concrete in the order of 33 MPa and 46 MPa (C1 and C2) in the base and of 59 MPa (C3) in the overlay, the average ultimate strength occurs in the level near the lowest compressive strength of the specimen, and it occurs as a monolithic rupture. For the specimens repaired with base and overlay concrete of 59 MPa (C3), the average ultimate strength was 14% below the compressive strength of this concrete, and a predominance of monolithic rupture was observed, although there were cases of adhesive rupture. In addition, when the compressive strength of the base concrete increase, the mode of failure can change from monolithic to adhesive, and the ultimate strength increase when the compressive strength of the base concrete increase. Thus, the results showed that adhesive rupture can occur in the equivalence of strengths in the base and in the overlay. For this reason, it is recommended to use new concrete of greater compressive strength for the repair. Finally, it is possible to conclude that the adhesives are different because they produce different ultimate strengths for the same concrete combination.

Specimens were bonded without adhesive (SA) to control the process of bond strength, using concrete of 59 MPa (C3) for the overlay. At the bond with base concrete of 59 MPa (C3), 100% of adhesive rupture occurred. With concrete of 46 MPa (C2), 50% of adhesive rupture and 50% monolithic rupture occurred, and with concrete of 33 MPa (C1), 25% of adhesive rupture and 75% of monolithic rupture occurred. In conducting the tests in this group, many brittle and violent ruptures were observed. A distinct behavior was observed in the specimens with adhesive, proving the importance of the use of adhesive to decrease the variability of the results and prevent brittle ruptures.

According to the ANOVA statistical analysis, the results obtained with mixed specimens bonded with adhesives of different viscosities and compression strengths showed no significant ultimate strength variation between them in concretes of 33 MPa (C1). However, the result variations of the ultimate strength between the adhesives tested with the increase of compression strength for concrete of 46 MPa (C2) and concrete of 59 MPa (C3) were significant and presented greater ultimate strength when using adhesives with higher viscosity. It was highlighted that in concrete of 59 MPa (C3) the ultimate strength was more homogeneous.

This study has shown that the use of epoxy adhesive in concrete repairs of normal compressive strength (between 33 and 46 MPa) is effective for most of the epoxy adhesives studied. On the other hand, further studies are necessary on concrete of high compressive strength (in the order of 60 MPa), as adhesive rupture can occur, indicating that, in this case, mechanical adhesion is more important than in the concretes of normal compressive strength. Thus, the adhesion process needs to be validated. It is recommended to analyze the characteristics of the type of the adhesives chosen (compressive strength and viscosity), the maximum time of application of the adhesives, preferably in the first 10 or 15 min, the influence of roughness on the adhesion with surface preparation with "concrete surface profile" (CSP) being at least greater than the one tested (CSP = 2), and the use of concrete with a maximum w/c ratio of 0,4.

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