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ADHESION BETWEEN HIGH-STRENGTH CONCRETE, EPOXY RESIN AND CFRP

José B. AGUIAR
Associate Professor, Dept. of Civil Engineering, University of Minho, Portugal.

Rafal KRZYWOŃ
Assistant Professor, Faculty of Civil Engineering, Silesian University of Technology, Poland

Aires CAMÕES
Assistant Professor, Dept. of Civil Engineering, University of Minho, Portugal.

Marcin GÓRSKI
Assistant Professor, Faculty of Civil Engineering, Silesian University of Technology, Poland

Szymon DAWCZYŃSKI
Assistant Professor, Faculty of Civil Engineering, Silesian University of Technology, Poland

ABSTRACT:
This paper presents a study on the adhesion between high-strength concrete, epoxy resin and CFRP. The adhesion of the high-strength concrete was compared with the same property measured in conventional concrete. Shear tests were made to test adhesion from concretes to epoxy resin. Flexural tests were used to evaluate the adhesion between concretes, epoxy and CFRP. The effect of temperature was also evaluated. For ordinary temperatures (20 ºC) the results showed a better flexural performance of the CFRP reinforced high-strength concrete. However, the adhesion between concrete and epoxy resin was clearly affected with the increase of temperature.

Keywords: HSC, CFRP, epoxy resin, adhesion, temperature, shear strength, flexural behavior

1. INTRODUCTION

Nowadays, there is a growing need for solving problems about degradation of concrete structures. During the period of their life cycle, reinforced concrete structures must present good levels of security, durability and functionality. However several problems on project, construction and use, can put in risk some of these requirements. The civil engineering structural renewal has received considerable attention over the past few years throughout the world. The structures increasing decay is frequently combined with the need for upgrading. In this context it is expected that even high-strength/high-performance concrete structures will need to be strengthened. In situ rehabilitation of reinforced conventional concrete elements using CFRP has proven its effectiveness and is also an efficient and valuable way of reinforcing or rehabilitating high-strength/high-performance concrete structures. The application is simple and quick and has a minimum interference to the architecture. The external strengthening of concrete with CFRP is a technique that has acquired more and more potential. The bond between this type of reinforcement and support is usually made with epoxy adhesives.

In practice, CFRP sheets and strips are being increasingly used in many structural applications due to their excellent mechanical and corrosion resistance characteristics. But the adhesion to high-strength concrete must be better studied and can be affected by both short term and long term environmental exposure. High environmental relative humidity is one of the harmful examples: it may reduce epoxy bond strength below acceptable levels [1].

The systems that use FRP to externally reinforce concrete structures have polymers in two parts, the saturating resin and the adhesive. The glass transition temperature (T_g) is the temperature above which polymers change from relatively hard and elastic to viscous, rubbery materials. Moreover, when the polymer is exposed to high humidity, this temperature (T_g) decreases. Because of this fact, some recommendations have suggested that FRP systems should not be used at temperatures above their T_g and further that the selected materials should have a T_g of at least 20ºC above the maximum expected service temperature.

However, in most of the technical literature, temperature is not considered as a variable. This is not consistent with the importance of the temperature variation on the bond behavior. In fact, the bonding agent deteriorates quicker than concrete, steel or CFRP reinforcement as the temperature increase, and the characteristics of the adhesive affect the strength of the bond [2]. According to Gamage et al [3] both experimental and finite element results show that the epoxy adhesive temperature should not exceed 70 ºC in order to maintain the integrity between the CFRP and concrete at high temperatures.

Surface preparation represents the most critical part of the bonding process [4] and bond failure can also be expected in case of inadequate surface preparation. The behavior of strengthened concrete elements is highly dependent on the proper preparation and profiling of the concrete surface [5]. The soundness of the concrete substrate should be verified. If the deterioration of the concrete has reached a depth that no longer allows shallow surface repair, replacement of the concrete should be considered.

Before the strengthening of a structure there are certain steps that must be taken: substrates should be roughened; laitance, contamination and serious imperfections need to be eliminated; FRP surfaces must be cleaned and; at the time of epoxy application, it must be free of dust, dirt and oil.

2. EXPERIMENTAL PROGRAM

To evaluate the adhesion of high-strength concrete to epoxy resin and for the adhesion between concrete, epoxy and CFRP strengthening for reinforced concrete structures, an experimental research program was defined in order to give simple and comparative results.

The adhesion of the high-strength concrete was compared with the same property measured in conventional concrete. Shear tests were made to test adhesion from concretes to epoxy resin. Flexural tests were used to evaluate the adhesion between concretes, epoxy and CFRP. The effect of temperature was also evaluated.

2.1 Materials

Two types of concrete were used: high-strength (HSC) and conventional (CC). The compositions are presented in Table 1.

Table 1 Concrete compositions

Constituents	HSC	CC
Cement (Kg/m^3)	550 (CEM I 52.5 R)	340 (CEM I 42.5 R)
Sand (Kg/m^3)	469	869
Gravel (Kg/m^3)	1158	865
Water (l/m^3)	165	206.4
Superplasticizer (Kg/m^3)	13.75	-

The concretes were produced using CEM I 52.5 R (HSC) or CEM I 42.5 R (CC) portland cement and both were produced with the same natural river sand (maximum aggregate size of 4.76 mm and fineness modulus of 3.21), crushed granite coarse aggregate (maximum aggregate size of 9.53 mm and fineness modulus of 5.82). A copolymer based superplasticizer was also used in the HSC.

High-strength concrete had a water cement ratio of 0.30 and the obtained results of slump test varied between 150 and 180 mm. Conventional concrete was made with a water-cement ratio of 0.60 and slump varied between 80 and 100 mm. At the age of 28 days, the high-strength concrete had an average compressive strength of 90.0 N/mm^2 and the conventional concrete achieved 30.0 N/mm^2.

Cubic specimens with 100 mm edge were moulded in order to evaluate the shear strength of the epoxy adhesive bond between hardened concrete/hardened concrete surfaces. Three plain concrete cubic specimens were bonded together to obtain beam specimens containing two adhesive joints. The adhesive used was an epoxy mortar (Table 2). It was mixed immediately before the application. Resin and hardener were mixed with a ratio of 3:1, respectively. They had different colors, so complete mixing could be evaluated after uniform color had been achieved [6]. This adhesive contained calcareous filler.

Table 2 Epoxy mortar properties

Specific weight (kg/m^3)	1770
Pot-life – 35 ºC (min.)	40
Shrinkage (%)	0.04
Glass transition temperature, T_g (ºC)	62
Static young modulus (N/mm^2)	12800
Thermal expansion coefficient from -10 ºC to 40 ºC ($ºC^{-1}$)	$9x10^{-5}$

To evaluate the flexural behavior, 650x150x100 mm^3 reinforced concrete beams were also produced. The amount of steel reinforcement was the same in HSC and in CC beams and it was designed to avoid shear failures. The flexural reinforcement steel (f_{syd} = 400 N/mm^2) was 6.0 mm diameter and the shear reinforcement steel (f_{syd} = 500 N/mm^2) was 3.0 mm diameter (Figure 1).

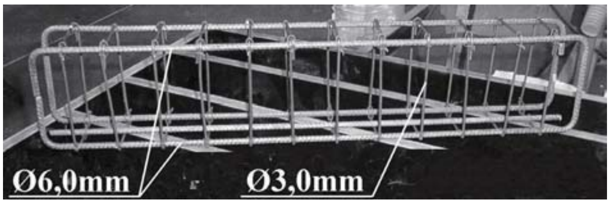

Figure 1 Steel rebars of the flexural beam specimens

The beams were kept in the moulds during the first 24 hours. Afterwards, the specimens were removed and maintained for 20 days in water at a temperature of 20ºC. The CFRP reinforcement was applied to the beams when they were 28 days old. Before the CFRP application, the beams remained for 7 days in air laboratory conditions at a temperature of 20ºC. The CFRP plates have a tensile strength of 2800 N/mm^2 and an elastic modulus of 165000 N/mm^2.

2.2 Bond Procedures

After 28 days, the bonding was carried out. Two types of bond were made: hardened concrete/hardened concrete and CFRP/hardened concrete. To prepare the surface of the hardened concrete, a diamond disc, an abrasive disc, air spurts and a soft brush were used. These resources were important in order to remove laitance, oils and dust. At the same time they gave roughness to the extremely smooth surface. The CFRP was cleaned immediately before the application of epoxy adhesive, with the volatile product indicated by the supplier.

It is important to spread the adhesive immediately after mixing, to dissipate the heat and extend its usable life. The adhesive was applied both on the concrete and the CFRP surfaces [7]. This procedure reduced the risk of forming voids when pressing the CFRP plate against the concrete surface. The producer recommends a joint of 0.5 to 2 mm thickness.

The specimens subjected to shear strength tests were plain concrete beams made of three bonded concrete cubes with two adhesive joints (Figure 2) and the specimens subjected to flexural tests were reinforced concrete beams strengthened with CFRP (Figure 3). They were maintained in laboratory air conditions (20ºC) for 7 days after the bonding process. Afterwards, they were exposed to the degradation process

Figure 2 Shear test: hardened concrete/hardened concrete bonded by epoxy mortar

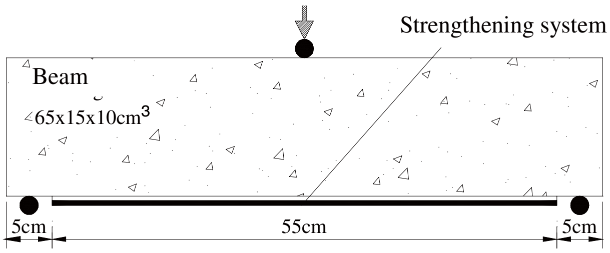

Figure 3 Flexural test: reinforced concrete beam strengthened with CFRP

2.3 Thermal Degradation Procedures

In order to evaluate the effect of high temperatures in the performance of the adhesive used, a thermal degradation program was established. The glass transition temperature of the adhesive, an epoxy mortar, was of 62ºC, so, one of the temperatures of the thermal exposure was 60ºC. It would be equally important to exceed significantly that temperature and know the behavior at lower temperatures, such as in the laboratory environment and between that and the glass transition temperature.

The thermal exposures were based on previous work and on an European standard [8]. The program of degradation is presented in Figure 4. The time of each cycle was 6 hours at each temperature. The number of cycles was 50.

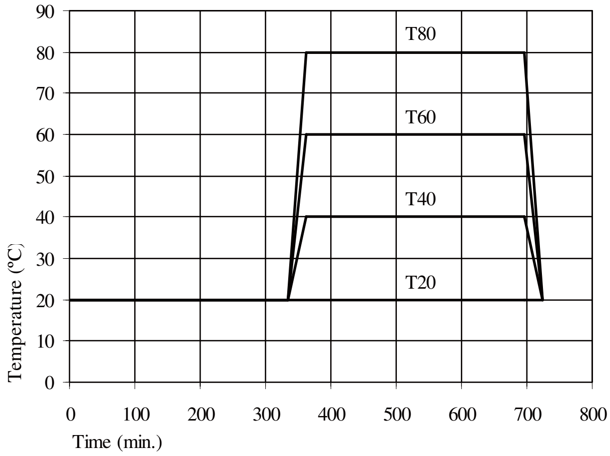

Figure 4 Variations of temperature during the thermal degradation

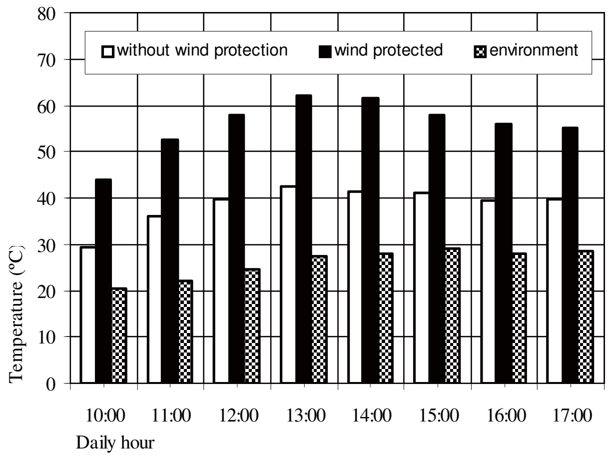

Figure 5 Variations of temperatures in the adhesive during a spring day in May

2.4 Measurement of Surface Temperature

To verify the real temperature due to solar exposure that can affect the surface of the adhesive, some measurements were made. A thermocouple was installed in a CFRP strengthened beam into the epoxy adhesive layer, and the temperatures were recorded during a spring day in May. Beams were subjected to two different kinds of exposure conditions: protected and unprotected from wind action. In Figure 5 one can see the results obtained.

As can be seen observing Figure 5, solar exposure can imply adhesive temperatures that can attain high values, higher than 60 ºC during a warm and windy spring day of May. Moreover, this shows that the chosen thermal temperatures up to 60 ºC may reflect real solar exposure conditions.

2.5 Compressive Shear Tests

After thermal cycle exposure of 25 days, the shear test specimens (hardened concrete/hardened concrete) were subjected to compressive shear tests (Figure 6). The shear tests were made using a constant loading rate of 20 kN/min. The test was carried out with the beam at the maximum temperature of the thermal cycle.

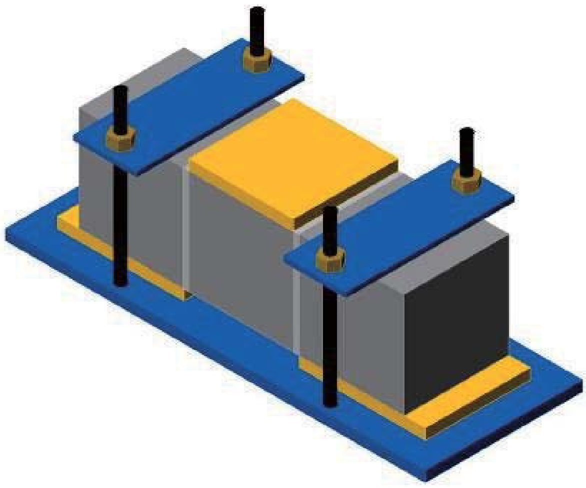

Figure 6 Schematic of the compressive shear test

2.6 Three-Point Bending Tests

The strengthened beams were subjected to three-point bending tests, after the thermal cycle exposure. The load test was carried out using a servo controlled system guaranteeing a mid span deflection increase at a constant rate of 10 μm/s (Figure 7). The test was carried out with the beams at the maximum temperature of the thermal cycle.

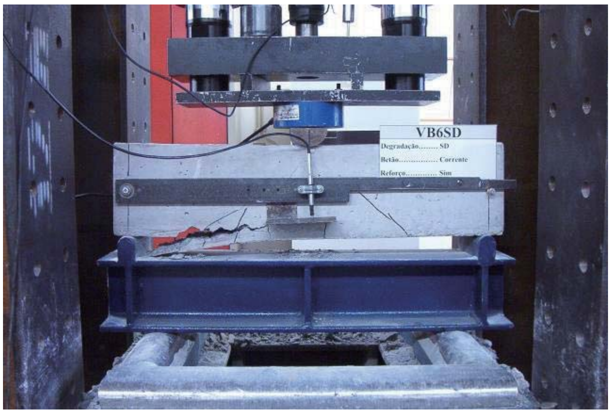

Figure 7 Three-point bending test

3. RESULTS

3.1 Compressive Shear Strength

The evaluation of the compressive shear strength test results was made by recording the failure load and through the visual analysis of the behaviors of the beams during and after the load test.

Figure 8 represents the obtained shear strength average curves after the thermal exposure; the corresponding failure types are presented in Table 3. Figures 9 and 10 present the two different failure types observed in the specimens subjected to compressive shear tests.

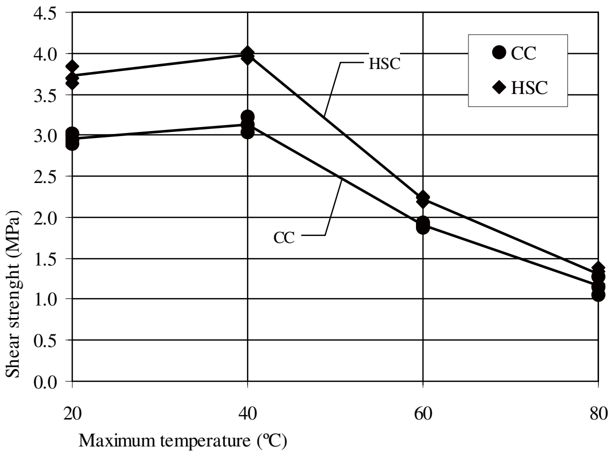

Figure 8 Variation of shear strength with temperature and with the type of concrete

Table 3 Shear strength failure types

Thermal degradation	Failure type	
	CC	HSC
T20	Substrate	Substrate
T40	Substrate	Substrate
T60	Adhesive	Adhesive
T80	Adhesive	Adhesive

Figure 9 Substrate failure

Figure 10 Adhesive failure

3.2 Three-Point Flexural Behavior

The evaluation of the flexural behavior of the tested beams involved the numerical obtained results and the visual analysis of the specimens during and after the test.

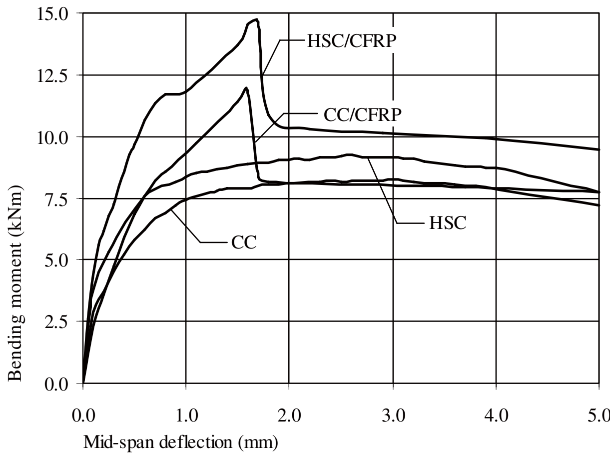

Figure 11 Variation of the bending moments with mid span deflection, type of concrete and CFRP reinforcement (T20)

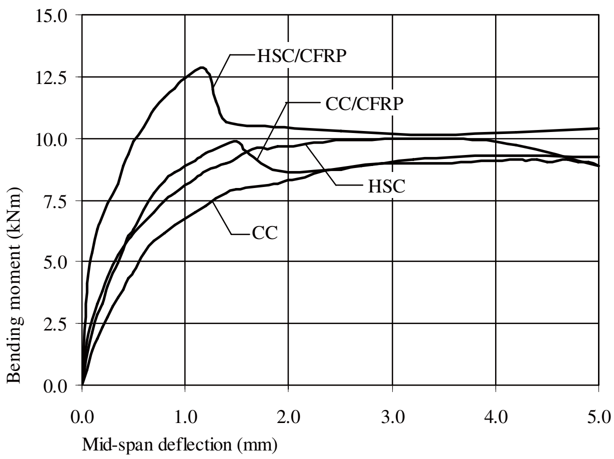

Figure 12 Variation of the bending moments with mid span deflection, type of concrete and CFRP reinforcement (T40)

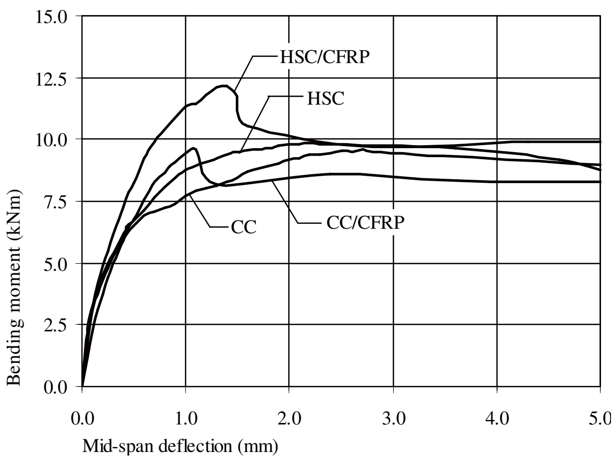

Figure 13 Variation of the bending moments with mid span deflection, type of concrete and CFRP reinforcement (T60)

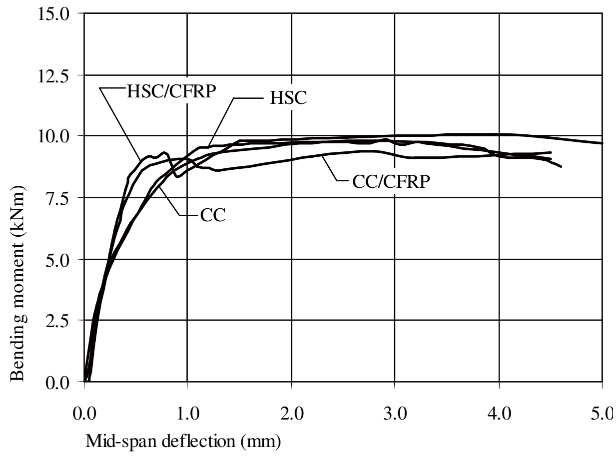

Figure 14 Variation of the bending moments with mid span deflection, type of concrete and CFRP reinforcement (T80)

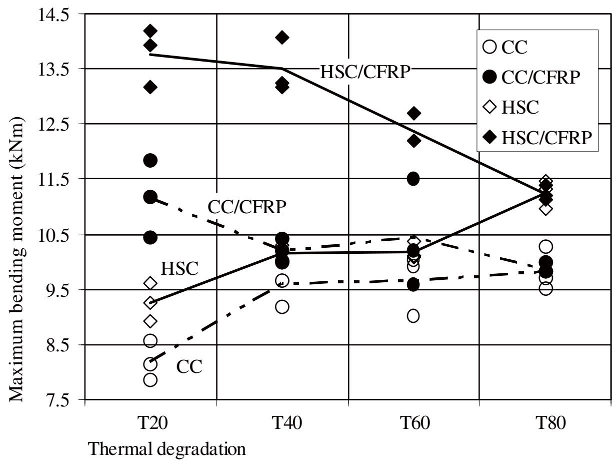

Figure 15 Evolution of maximum bending moments with temperature, type of concrete and CFRP reinforcement

Figures 11 to 14 represent the average curves of bending moment vs. mid span deflection after each type of thermal exposure. Figure 15 shows the evolution of the maximum resisting bending moment for the different degradations.

Beams without CFRP strengthening made with high-strength and conventional concrete are referred as HSC and CC respectively. The abbreviation HSC/CFRP and CC/CFRP represents correspondingly the CFRP strengthened high-strength and conventional reinforced concrete beams.

Table 4 Flexural strength failure types

Thermal degradation	Failure type			
	CC	CC/CFRP	HSC	HSC/CFRP
T20	Flexural	Delam.	Flexural	Delam.
T40	Flexural	Delam.	Flexural	Delam.
T60	Flexural	Delam. and Deb.	Flexural	Delam. and Deb.
T80	Flexural	Deb.	Flexural	Deb.

The failure types observed in the flexural tests are presented in Table 4. From Figures 16 to 18, one can observe the different failure type that occurred: flexural failure (flexural), delamination of the concrete cover (delam.) and CFRP debonding (deb.).

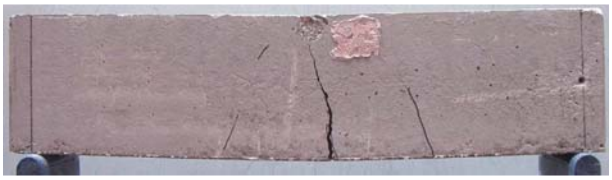

Figure 16 Flexural failure

Figure 17 Delamination of the concrete cover

Figure 18 CFRP debonding

4. ANALYSIS OF RESULTS

4.1 Compressive Shear Tests

The analysis of Figure 8 shows that between 20 ºC and 40 ºC the epoxy resin maintained all of its properties and also that the concrete shear strength slightly increased. This increase was due to concrete strength gain with temperature and didn’t reflect the strength in the adhesive because failure occurred in concrete (even in the high-strength one), i.e., the shear strength of the epoxy adhesive was greater than the values obtained. With exposure to 60 ºC (near the T_g) the failures became predominantly adhesive and the failure stress decreased significantly. For high-strength concrete the shear strength after exposure to 60 ºC was 56 % of that obtained after 40 ºC. With conventional concrete the behavior was similar: the shear strength value after exposure to 60 ºC was 61 % of that obtained after 40 ºC.

With exposure to 80 ºC (above the T_g) the failures all became adhesive ones and the failure stress continued to decrease. Compared to that obtained after 40ºC, the shear strength loss due to the 80 ºC thermal exposure was about 70% for the two concretes tested.

When the concrete resistance was mobilized the high-strength concrete displayed a higher shear resistance than the conventional concrete, as would be expected. The difference before the thermal degradation occurred (20 ºC and 40 ºC) was about 0.8 MPa. After the thermal degradation occurred (60 ºC and 80 ºC), the observed values were no longer related to the strength of the concrete but to the strength of the adhesive joint and, as expected, the values obtained for specimens of HSC and conventional concrete were similar.

4.2 Three-Point Bending tests

As expected, the increase in the severity of the thermal exposure decreased the CFRP reinforcement efficiency. When the glass transition temperature of the adhesive was nearly attained (exposition T60) or exceeded (expositions T80), CFRP started to debond both in HSC and CC reinforced concrete.

With the temperature increase, the bending moment vs. deformation curves (Fig. 11 to 14) of the strengthened beams became closer to the curves for the beams without CFRP reinforcement. The maximum bending moment increases associated with the presence of CFRP diminished significantly when the temperature was increased. For T20, the CFRP strengthening gains (measured by maximum bending moments) were about 50% and 35% for HSC and CC, respectively. For T60 this was reduced to only about 20% (HSC) and 10% (CC) and for T80 exposure there was no apparent advantage in using CFRP reinforcement because the maximum bending moments of concrete beams with or without CFRP laminates were similar both for HSC and for CC.

In the series without degradation (T20) and degradation T40, the beams without reinforcement displayed flexural failure (Figure 16), while the CFRP strengthened beams exhibited delaminations caused by failure of the cover concrete (Figure 17).

When the aggressiveness of the thermal exposition was near the adhesive T_g (T60), some debonding in the extremities of the CFRP reinforcement was noted. In these situations, particularly for the HSC/CFRP beams, debonding occurred at the concrete/adhesive interfaces (Figure 18). In the most severe exposure (T80) and with HSC/CFRP beams, complete debonding of the CFRP reinforcement was observed.

5. CONCLUSIONS

Based on the results obtained, it seems that, for ordinary temperatures (20 ºC) the CFRP reinforcement is more efficient for HSC than for conventional concrete. The CFRP strengthening gains (measured by maximum bending moments) were about 50% and 35% for HSC and CC, respectively.

However, the study carried out here shows that, the adhesion between high-strength concrete, epoxy resin and CFRP is substantially affected by temperature increase. The epoxy adhesive used to form the bond between CFRP and concrete was shown to be very sensitive to temperature variations. This effect was noticed both for CFRP reinforced HSC and for conventional one.

From the shear strength test results, a rapid loss of resistance was apparent when cyclic thermal degradation increased to or above a temperature of 60 Cº. The flexural load capacity of the CFRP reinforced beams decreased with the increase of temperature and the efficiency of the CFRP strengthening tended to vanish.

So, based on the results obtained, it is possible to conclude that the epoxy adhesive bond properties deteriorate rapidly with exposure to high temperatures. This seems to be highly important, because even in solar exposure of a concrete element, it is possible to have temperatures high enough to cause some problems. Therefore, the use of reinforced systems bonded with epoxies in warm locations needs to be carried out in a very careful way. It is recommended to select epoxies with an elevated T_g at least 20ºC above the maximum environmental temperature or to considerer the application of protective insulation systems.

It is important to note that this study involved only the effect of temperature and load acting simultaneously, but there are other degradation agents to consider. At the same time then, one must also take into account the effects of relative humidity, substrate moisture, substrate surface contamination by chlorides in marine location, or chemically aggressive environments.

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