Adhesion in Interfaces of Building Materials – a Multi-scale Approach
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Effect of Temperature on Systems for the Reinforcement of Concrete

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Abstract

This paper presents an experimental work using prismatic specimens of hydraulic mortar reinforced on the exterior with steel or CFRP plates. The adhesive used was an epoxy. Two series of tests were made. In the first one, the specimens were exposed seven days to temperatures between 20 °C and 250 °C, after which they were subjected to flexure tests made at 20 °C. In the second series, the specimens were exposed 24 hours to temperatures between 20 °C and 60 °C. The exposure to different temperatures was maintained during the flexure tests. In the first series, the efficiency of the reinforcements decreases significantly above 50 °C. In the second series, the significant decrease of the flexure resistance occurred above 40 °C. The simultaneous action of temperature and load leads to a lower thermal resistance than the separate action.

Keywords: Adhesion strength, thermal resistance, epoxies, steel plates, CFRP plates.

1 Introduction

The external reinforcement of concrete structures is applied in order to restore the minimum security conditions. There are many causes for the deterioration of the structures, like: structure age, materials deterioration, exposure to accidental actions, design errors, execution errors, use of bad quality materials and increase of the service load due to a change in the structure utilization.

The external reinforcement of concrete was traditionally done by bonding steel plates. This technique has been used, since 1960. Firstly, the steel plates are bonded to the tension face of reinforced concrete beams [1, 2]. Other applications were developed along the years. Recently, new systems based on bonding composite materials like carbon fibre reinforced polymer (CFRP) plates were used [3]. These composites are in some aspects better than steel. They have low mass, no ability to corrode and more flexibility in application to surfaces of any shape or nature [4, 5].

Epoxies are the oldest and most widely used polymers in repair. They have a lot of advantages when compared with other polymers [6]. One of the advantages is the high adhesion to various materials like mortar [7], concrete [8], masonry units, glass, metals [7] and wood [8]. However, they have some bad properties like thermal behaviour [9].

Compared with other construction materials, epoxies have higher coefficients of thermal expansion [8]. This difference causes stresses at the interface when the temperature increases or decreases. The thermal resistance of epoxies is very low. The decrease of adhesion strength when epoxies are near high temperatures is well known. The problems appear for temperatures near the "Glass Transition Temperature" Tg [10].

An increase in temperature results in a degraded performance of the system (substrate, adhesive and bonded element). High temperatures can occur in many situations l such as a fire or in certain places in some industrial plants and, in some structural elements exposed to the sun, for example in a viaduct or in a building.

In our study, one epoxy was used to bond steel or CFRP plates to hardened mortar. Seven days after bonding, the specimens were exposed at temperatures between 20 and 250 °C. Two series of tests were performed. In the first series, after seven days of exposure to a temperature, the specimens were tested in flexure. During the flexure tests, the temperature was 20 °C. In the second series, after 24 hours of exposure to a temperature, the specimens were tested in flexure. During the flexure tests, the same temperature of the 24 hours exposure was maintained. The results of these tests show the influence of high temperatures on the behaviour of external reinforcement systems.

The study was developed with mortar specimens, in order to have the possibility to make more tests and to evaluate in depth the influence of temperatures. The comparison with concrete structures can always be made. The differences between one mortar and one concrete were not too important in terms of adhesion.

2 Specimens preparation

The mortar specimens were prismatic with 4x4x16 cm3 and were prepared in accordance with the European standard [11]. The specimen preparation was the same for the two different series. Normal Portland cement – CEM I 42,5 [12] was used.

The specimens stayed in the moulds for 24 hours. After that , the specimens were removed from the moulds and maintained 20 days in the water at 20 °C. Before the bond of the external reinforcements, the specimens stayed 7 days at the laboratory room at 20 °C.

The epoxy adhesive used for the bonds was a DGEBA one with the properties shown in Table 1. It is furnished in two parts, one is the resin and other is the hardener. The hardener is an aliphatic polyamine. The proportions of the epoxy adhesive are extremely important. The mixture was made with a spatula till we obtained a homogeneous colour.

Table 1: Properties of the epoxy adhesive.

Identification	Glass transition temperature (°C)	Compressive strength (MPa)	Flexural strength (MPa)	Proportions of the epoxy adhesive parts (by mass)
Epoxy	63	90	45	resin – 44 hardener – 6

As mentioned above, two kinds of bonds were made: hardened mortar/steel plate and hardened mortar/CFRP plate. The steel plates had the dimensions of 40x40x1 mm^3. The CFRP plates had the dimensions of 40x40x1.4 mm3. The two kinds of plates have the same elastic modulus of 200 GPa.

In order to obtain good bonding it is necessary to take special care with the preparation of the surfaces [8, 13]. To prepare the surface of the hardened mortar, it was used an abrasive disc, air spurt and a soft brush. The steel plates and the CFRP pates were cleaned immediately before the application of the epoxy adhesive. The steel plates were cleaned with air spurt and alcohol. The CFRP plates were cleaned with the volatile product indicated by the supplier. After the preparation of the surfaces, the epoxy was applied to the specimens and to the plates with the care necessary to obtain a good soaking. The surfaces were maintained in horizontal position during the application of the adhesive. After the time indicated by the manufacturer, the plates were bonded to the mortar specimens (Fig. 1). The reinforced specimens were maintained in the laboratory room during seven days, before the exposure to the different temperatures.

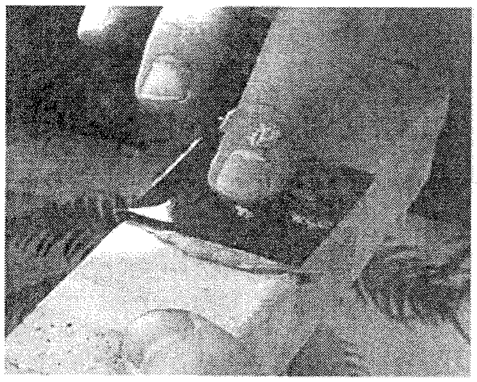

Figure 1: Bonding a CFRP plate to a mortar specimen.

3 Tests and results

Series nº 1

The reinforced specimens were maintained at a fixed temperature for seven days. The temperatures used were 20, 50, 100, 150, 200 and 250 °C. The adhesion strength was determined with three-point flexure tests, at room temperature.

After the flexure tests, the failure load and the failure mode were recorded. The reinforced specimens experienced mortar failure (Fig. 2 and 3) or adhesive failure (Fig. 4). The results of the tests are presented in Fig. 5. The adhesion strength indicated at each temperature is the mean of the flexural strength of five specimens. The specimens with steel reinforcement presented mortar failures, except the 200 °C specimens. Only the 250 °C CFRP specimens presented adhesive failures. The flexural strength of the mortar without reinforcement was 7,59 MPa, at 28 days.

With the results obtained (Fig. 5), the variation of adhesion strength, f_a, can be related with temperature, T, by the following equations:

$$f_{aCFRP} = -5x10^{-5}T^2 - 0{,}0015T + 10{,}405 \quad (3.1)$$

$$f_{aSTEEL} = -2x10^{-5}T^2 - 0{,}005T + 8{,}644 \quad (3.2)$$

Equations (3.1) and (3.2) are valid only for T in °C and for f_a in MPa. The R^2 is 0,98 for the CFRP specimens and 0,86 for the steel specimens.

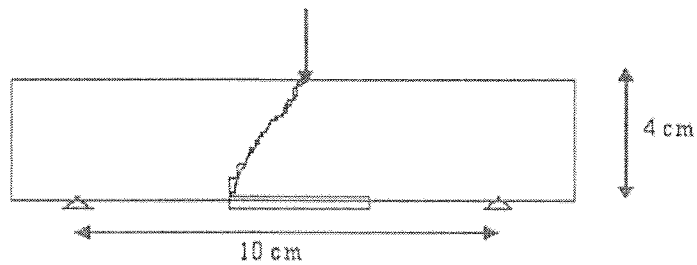

Figure 2: Mortar failure

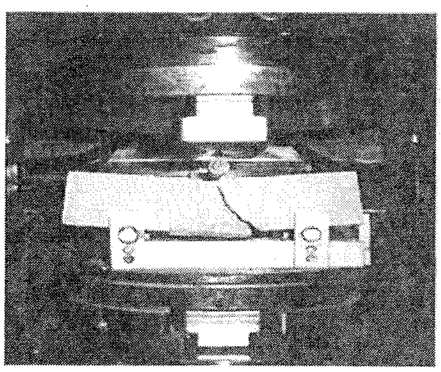

Figure 3: Mortar failure of a specimen

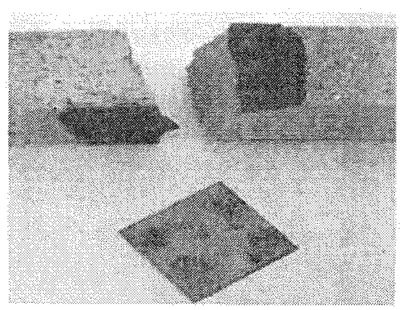

Figure 4: Adhesive failure of a specimen

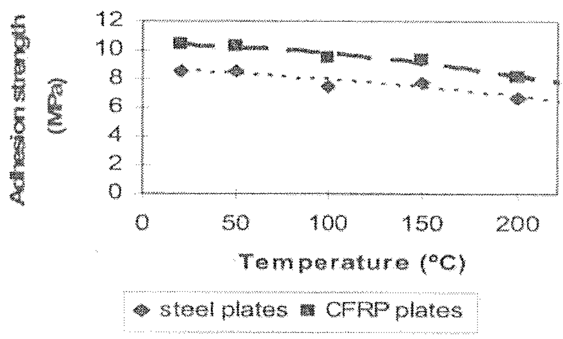

Figure 5: Variation of adhesion strength with temperature (Series n° 1)

Series n° 2

The reinforced specimens were maintained at a fixed temperature during 24 hours. The temperatures used were 20, 40 and 60 °C. The adhesion strength was determined with three-point flexure tests, maintaining the mentioned temperatures.

The results of the tests are presented in Fig. 6. The adhesion strength indicated at each temperature is the mean of the flexural strength of five specimens. The flexural strength is given by the maximum tension strength in the specimen. So, the adhesion strength is considered this tension strength developed at the specimen. The specimens with steel reinforcement presented mortar failures for the 20 °C test. The tests at 40 and 60 °C with steel reinforced specimens presented mixed adhesive/mortar failures. At 40°C the predominance was for the mortar failures (60 %). At 60 °C the predominance was for the adhesive failures (60%). All the CFRP specimens presented mortar failures. The flexural strength of the mortar without reinforcement was 7,54 MPa, at 28 days.

With the results obtained (Fig. 6), the variation of adhesion strength, f_a, can be related with temperature, T, by the following equations:

$$f_{aCFRP} = 0,0009\ T^2 - 0,0272\ T + 9,82 \quad (3.3)$$

$$f_{aSTEEL} = 0,0008\ T^2 - 0,022\ T + 9,17 \quad (3.4)$$

Equations (3.3) and (3.4) are valid only for T in °C and for f_a in MPa.

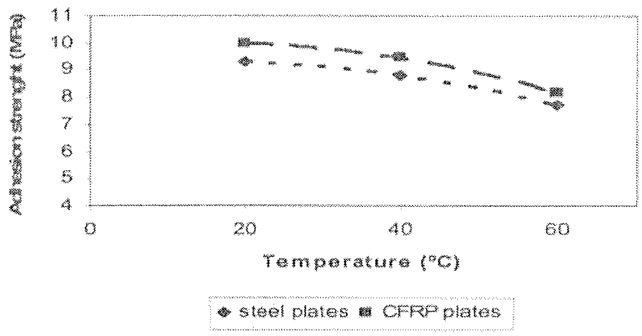

Figure 6: Variation of adhesion strength with temperature (Series n° 2)

4 Analysis of the results

Adhesion strength always decreases with temperature. For the first series, the decrease is more important after 50 °C. For the second series, the decrease is more important after 40 °C. This can occur because the glass transition temperature of the epoxy is 63 °C and the thermal resistance of the polymer is usually situated between 10 and 20 °C below this value. The difference of behaviour between the two series can be observed in Figure 7. In the second series the decrease of adhesion strength is more accentuated. This occurred because in this series the specimens were subjected to load and high temperature at the same time.

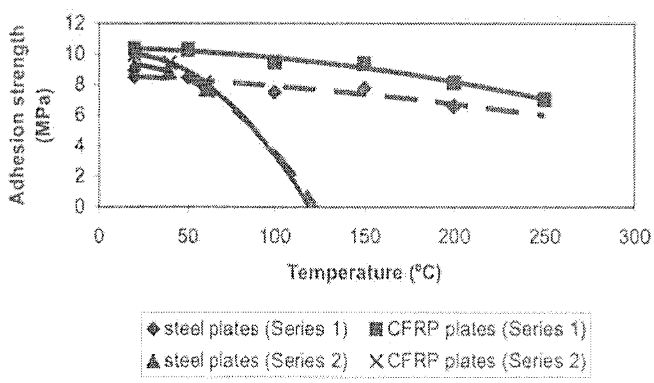

Figure 7: Variation of adhesion strength with temperature

The fact that the mortar failures were maintained, while adhesion strength decreases, could be explained by concentration of stresses, near the joint. The great difference between the coefficients of thermal expansion of the epoxy and the hydraulic mortar could be the cause of the concentration of stresses.

5 Conclusions

The external reinforcements can improve the mechanical resistance of a structural element. With the reinforcements used in this study, it was possible that the flexural resistance increased 37 %. The load capacity of the reinforced specimens decreases with the increase of temperature.

The thermal resistance of the tested external reinforcements can be considered between 40 and 50 °C. For temperatures above these values the efficiency of the reinforcements decreases significantly, even if failures continue to be mortar failures. The concentration of stresses near the joint can explain this behaviour.

The tests with the simultaneous action of load and temperature lead to a lower thermal resistance. The thermal resistance determined is not very high. Therefore, the use of reinforced systems bonded with epoxies is not recommended, without a protection system. The behaviour will be critical near furnaces, boilers or chimneys and during a fire.

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