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Accelerated ageing behaviour of the adhesive bond between concrete specimens and CFRP overlays

Karim Benzarti [a,*], Sylvain Chataigner [b], Marc Quiertant [a], Céline Marty [a], Christophe Aubagnac [b]

[a] Université Paris Est, Laboratoire Central des Ponts et Chaussées (LCPC), 58 Bld Lefebvre, 75732 Paris Cedex 15, France
[b] LRPC d'Autun, Boulevard de l'Industrie, BP 141, 71 405 Autun, France

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ABSTRACT

In this paper, the durability of the adhesive bond between concrete and carbon fibre reinforced polymers (CFRP) strengthening systems has been investigated under accelerated ageing conditions, *i.e.*, at 40 °C and 95% relative humidity. Mechanical characterizations were carried-out on control and exposed CFRP strengthened concrete specimens, in order to assess the evolutions of the adhesive bond properties during hydrothermal ageing. Results from different experimental campaigns are presented and reveal significant evolutions (decrease in the adhesive bond strength and/or change in the failure mode) depending on various parameters, such as the surface preparation of concrete, the presence of a carbonated concrete layer, the nature of the CFRP overlay (carbon fibre sheets or pultruded CFRP plates), the ageing behaviour of the bulk epoxy adhesive itself, or the test configuration used to evaluate the adhesive bond strength (pull-off or shear loading test). Moisture diffusion from the superficial layer of concrete (*i.e.*, diffusion of interstitial pore solution) towards the adhesive joint is suspected to be a key factor driving the degradation process during hydrothermal ageing.

1. Introduction

Externally bonded composites systems are commonly used worldwide for the strengthening of civil structures [1–3]. In France, for instance, carbon fibre reinforced polymers (CFRP) are increasingly being considered for the rehabilitation and upgrading of deteriorating or under-strength infrastructures [4]. If the technique effectiveness has been clearly demonstrated and is now accepted by all stakeholders in the construction sector, the long term durability of the adhesive bond between the FRP and concrete is still a crucial issue [5]. Environmental factors, such as moisture and temperature cycles, exposure to marine or other aggressive environments, may indeed affect the integrity of both the interfacial bonds (substrate/polymer interactions) and the polymer material itself (adhesive joint in the case of bonded composite plates, or polymer matrix in the case of laminates made from impregnated fabrics according to the wet lay-up process), leading to a decrease in the overall performances of the composite overlay. At the moment, such long term effects are taken into account in the design guidelines either by introducing semi-empirical safety coefficients on tensile properties of FRP reinforcements and shear characteristics of bonded interfaces [6,7], or through reliability-based approaches [8].

In the last decade, many researches were undertaken on the durability of ambient temperature cured resins used in construction [9,10], FRP reinforcements [11,12], and concrete/concrete or FRP/concrete bonded interfaces [13–23]. In these studies, property evolutions of specimens exposed to various accelerated ageing conditions were assessed, especially under freeze–thaw or dry-heat cycles, immersion in salt or alkali solutions, salt fog spray, or under fixed hydrothermal environments; although these environments were not representative of the actual in-service conditions, they allowed to investigate the effects of selected or coupled parameters. As regards the bonded interfaces, substantial decreases in bond strength over ageing time (up to 40–50% loss in some cases) were observed under wet environments [13–15,18–23], which was usually attributed to extensive moisture plasticization of the low T_g polymer adhesive and to additional breakage of interfacial bonds.

However, a broad range of FRP and adhesive systems was used by the different authors as well as various bond test methods (pull-off, beam test, single or double-lap-joint shear tests, slant shear, etc.) which makes it difficult to compare the relative intensities of the property evolutions. It was shown indeed, by Momayez et al. [24] and Aiello and Leone [25], that the measured bond strength between the concrete substrate and repair materials is highly dependent on the test method, due to large variations in the stress field at the bonded interface; measured values were found to be up to 8 times larger from one method to the other

* Corresponding author. Tel.: +33 1 40 43 52 51; fax: +33 1 40 43 65 14.
E-mail addresses: benzarti@lcpc.fr, Karim.Benzarti@lcpc.fr (K. Benzarti).

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[24]. The selection of the test methods is therefore a key issue with regard to the pertinence of durability studies.

If the pull-off test is easy to carry-out and is widely applied for quality control on working site, it is also known to be affected by small misalignment between the specimen and the loading axis [24,26]; stress concentrations due to partial coring of the test zone can also result in erroneous results and large scatters [26]. According to Aiello and Leone [25], the single lap shear test represents a good alternative to more complicated methods and could also be used for characterizations in the field.

The present experimental approach aims at providing new insights or at least confirmation of previous trends regarding the hydrothermal ageing behaviour of FRP strengthened concrete specimens, and the influence of selected parameters. The influence of the test method is also investigated as explained in the next section.

2. Objectives and outlines of the experimental program

In the present paper, the main results of two distinct experimental campaigns devoted to accelerated ageing of FRP strengthened concrete specimens are presented. Constant hydrothermal ageing conditions were intentionally chosen, *i.e.*, a temperature of 40 °C and a relative humidity of at least 95%, in order to avoid complex coupling effects induced by either hydro/thermal cycling or specific aggressive environments (salt fog, salt or alkaline solutions). Those exposure conditions were not supposed to be representative of the in-service ageing environment, but were mainly intended to study moisture effects on the properties of the concrete/FRP bonded interfaces. The chosen temperature of 40 °C allowed to accelerate both the post-curing process of the epoxy adhesive system and the water sorption kinetics (in comparison to the same processes at room temperature), while remaining just below the usual glass transition temperature range of ambient curing epoxies used in construction.

A first set of experiments was concerned with hydrothermal ageing of FRP strengthened concrete slabs and the assessment of adhesive bond property evolutions by means of pull-off tests. Ageing behaviours (over a period of 20 months) of several model concrete/composite interfaces were compared and analysed, in order to get information:

– regarding the influence of various parameters on the bond durability, such as the concrete surface preparation, a superficial carbonation of the concrete substrate or the nature of the FRP system,
– on mechanisms responsible for the property evolutions of concrete/FRP bonded interfaces under wet environments.

In the second experimental campaign, accelerated ageing behaviours of both FRP strengthened concrete blocks and the constitutive materials taken separately (concrete, bulk epoxy adhesive and composite element) were investigated over a period of 13 months. Adhesive bond properties were assessed by means of two different techniques, *i.e.*, the pull-off method and the single-lap-joint shear test, in order to get comparative data. The "sensitivity" of the two test methods was discussed in the light of apparent property evolutions of both the bonded interfaces and the separate constituents. As regards the shear tests, changes in the load transfer mechanism induced by humid ageing at the bonded interface were also investigated.

For both experimental campaigns, the interval period between two test sessions was adjusted according to the observed evolutions of mechanical properties (see details in Table 4). The final periods of exposure (20 and 13 months, respectively) were dependant on the number of ageing specimens which could be stored in the climatic chambers, hence on the size of the test specimens.

3. Durability of concrete/composite interfaces: first experimental study based on pull-off characterizations

3.1. Preparation of the test specimens

In the framework of a first experimental campaign, specific test specimens based on FRP reinforced concrete slabs, and providing various model bonded interfaces were prepared. The preparation steps were as follows:

– concrete slabs of dimensions $30 \times 30 \times 5$ cm^3 were cast from a Portland cement (CEM I 52.5 PMES from Lafarge, Le Havre, France) and silico-calcareous aggregates (0/4 and 5/20 mm), with a conventional water-to-cement ratio of 0.5. These specimens were then immersed in water for a maturation period of 28 days. The resulting material exhibited an average compressive strength of 35 ± 2 MPa, as determined by compression tests (EN 12390-3 European standard) on cylindrical 16×32 cm samples casted with the same concrete (three repeated tests).
– these mature concrete slabs were then divided into two series which were subjected to specific surface preparations commonly used on working sites. Half of the specimens was sand-blasted using a manual equipment, whereas the other half was ground with a rotary diamond bur tool. For both preparation methods, a 1–2 mm thick layer was removed from the concrete surfaces; however grinding led visually to a much smoother surface finish than sand-blasting. Machined surfaces were then carefully vacuum cleaned in order to remove dust particles.
– for each of the previous series, half of the specimens was also subjected to a carbonation process: slabs were stored for 1 month under controlled air/CO_2 atmosphere at 20 °C and 65% relative humidity, in order to form a carbonated surface layer of thickness 10 mm,
– all abovementioned slabs were finally strengthened by two types of commercially available FRP systems: for each type of prepared concrete surface, half of the available specimens was reinforced using the wet lay-up process based on carbon fibre sheet (CFS), and the remaining half by pultruded unidirectional CFRP plates of thickness 1.2 mm and width 50 mm (Fig. 1a and b, respectively). A single composite layer was used in the two cases. Bonding was achieved at room temperature using two bi-component epoxy formulations, denoted A and B, which are prescribed for the CFS and CFRP plate systems, respectively. Implementation was carried-out by experienced staff from FRP supplier companies.

Characteristics of the various materials used in the preparation of the FRP strengthened slabs of series A and B (concrete, commercial adhesives, composites reinforcements) are summarized in Tables 1–3.

Finally, eight types of concrete/composite bonded interfaces were obtained, as listed below:

– sand-blasted concrete/CFS,
– sand-blasted concrete/CFRP plate,
– ground concrete/CFS,
– ground concrete/CFRP plate,
– sand-blasted and carbonated concrete/CFS,
– sand-blasted and carbonated concrete/CFRP plate,
– ground and carbonated concrete/CFS,
– ground and carbonated concrete/CFRP plate.