Bond behaviour and durability of FRP composites applied externally to masonry structures

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ABSTRACT: The several advantages associated to the use of FRP composites for civil structural applications (mainly reinforced concrete and masonry) has led to a considerable increment in use during the last years. However, the performance of FRP composite strengthening systems when exposed to harsh environmental conditions is a matter of great concern, which justifies the recent research efforts towards the characterization of the deterioration effects. This paper discusses some of the most relevant environmental agents and their effect on the durability of FRP-strengthened concrete and masonry constructions. The results of a comprehensive series of accelerated ageing tests (water immersion and hygrothermal exposure) on external GFRP-strengthened masonry and respective constituent materials recently carried out at University of Minho are presented and discussed in detail.

Keywords: *Bond behaviour, External FRP composites, Durability, Accelerated ageing tests*

1 INTRODUCTION

Among the materials used for rehabilitation or strengthening of existing civil structures, there has been an increasing interest in the use of fiber-reinforced polymer (FRP) composites. FRP composite materials are a very attractive solution due to a series of advantages that include high stiffness and tensile strength properties, low weight, ease of application, adaptability to curved surfaces and corrosion resistance. Yet, it should be realized that the use of FRP is often generally conditioned by strain limitations, due its brittleness.

In general, FRP composite is externally bonded to the substrate through the wet lay-up technique. The reinforcing fibers carry the load along the fibers' orientation and the polymeric resin matrix transfers the loads between fibers and the substrate through adhesion, protects fibers against environmental attack, and controls crack propagation.

Saadatmanesh [1] and Schwegler [2], back in 1994, were the first researchers to analyse the use of FRP for the strengthening of masonry structures. Since then, FRPs have been widely used to strengthen structural masonry components as walls, vaults and arches and to confine columns, including cultural heritage constructions [3]. The most critical aspect controlling the effectiveness of FRP application is debonding of the reinforcing system from the substrate that occurs in a brittle way. Therefore, the success of externally bonded FRP composite systems depends to a great extent on the capacity of the FRP-substrate interface in developing an efficient load transfer mechanism [4].

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Significant progress has been observed in the last years regarding the experimental and numerical characterization of the debonding mechanism in FRP-strengthened masonry elements. However, critical aspects as the role of mortar joints and the three-dimensional nature of the bond behaviour have deserved very few investigation. Recent investigation has demonstrated the great advantages that the use of optical-based measurement techniques can bring to the characterization of the bond behaviour in externally bond FRP masonry systems [5] [6], allowing to overcome most of the disadvantages associated to the use of localized strain gauges.

In external FRP strengthening systems, the most relevant mechanical actions to be considered are actions normal and parallel to the surface of the substrate, which mobilize the tensile bond strength and the shear bond strength, respectively. In the particular case of curved surfaces, both types of actions can occur simultaneously [7]. As for actions normal to the surface, the ASTM C1583 standard method [8] is generally used to estimate the pull-off strength. Regarding actions parallel to the surface, much more frequent in common strengthening applications, specific design rules are still far from general agreement. A comprehensive study on the debonding mechanisms found in FRP-strengthened masonry elements and on the identification of significant parameters for harmonizing laboratory experimental procedures is provide in [9]. It is worth mentioning that the only two guidelines available at international level, CNR-DT 200 [10] and ACI 440.7R-10 [11], provide information about bonding on masonry based on results from reinforced concrete. Furthermore, the ACI 440.7R-10 does not take into account substrate properties, whereas the CNR-DT 200 expresses the reference factor through masonry strength [9].

Presently, the primary issue associated to the use of externally bonded FRP composite systems for strengthening concrete and masonry structures is durability, in particular the aspects connected to fire and environmental agents. While several experimental studies exist on the effects of moisture and temperature exposures on the bond performance of external FRP-strengthened concrete elements, only a few studies have been conducted for FRP-strengthened masonry elements. Furthermore, as the combined effect of different environmental agents accelerates the bond degradation [12], it becomes of major importance to characterize the bond degradation of FRP-strengthened masonry components under simultaneous moisture and temperature (hygrothermal) exposure.

This paper discusses some of the most relevant environmental agents and their effect on the durability of FRP-strengthened constructions, with focus on a comprehensive series of accelerated ageing tests (water immersion and hygrothermal exposure) on external GFRP-strengthened masonry units and respective constituent materials, recently carried out at University of Minho [13].

2 DURABILITY AND DEGRADATION AGENTS

The performance of FRP strengthening systems can be affected by exposure to certain degrading agents. However, the level of deterioration depends on a series of factors, namely type of fibers and resin, manufacturing process and severity of exposure environments. Degradation may be grouped into physical, chemical and mechanical mechanisms. Furthermore, these three fundamental mechanisms may interact with each other, with cumulative or subtractive effects on the material performance [14]. The consideration of FRP-strengthened concrete or masonry structures makes the long-term performance assessment even more difficult due to the interaction between the substrate and the reinforcing system.

It is known that degradation in external FRP strengthening systems occurs due to deterioration in the matrix, deterioration in the fibers or deterioration in the bond at the FRP-substrate interface. Deterioration in the substrate is also susceptible to occur. The most relevant environmental agents concerning the deterioration of external FRP-strengthened structures consist of moisture, thermal cycling, freeze-thaw cycling, creep, fatigue, alkaline environment and ultraviolet light [12]. Each of these environmental agents may significantly affect some materials, while may produce negligible degradation in others. For example, glass and aramid fibers are sensitive to moisture, while carbon fibers are relatively inert to such environment agent.

2.1. Environmental agents

The degradation mechanisms of FRP composites include both physical and chemical related aspects. The physical ageing is referred to reversible changes in material properties mainly dependent on temperature, but these changes can be recovered upon drying. Conversely, chemical ageing occurs for longer exposure periods and generally comprises irreversible degradation of the resin, the fiber and the resin/fiber interface [12].

This section summarizes the most relevant aspects related to deterioration in the material components (fibers and resin) and degradation in the bond between the FRP and the substrate, under moisture and temperature exposures.

Moisture

Significant research work has been developed on the possible effects of moisture on the performance of FRP composites. Typically, the most important effect of moisture is on the strength properties of the composite system [12].

Resins are sensitive to moisture. Degradation of resins due to water includes two mechanisms of different nature. Initially, water penetration causes reversible physical ageing (plasticization), leading to a decrease of the glass transition temperature of the resin (T_g) and of the mechanical properties of the resin [15]. If a long-term exposure to water takes place, irreversible chemical ageing (hydrolysis) and micro-cracking can also occur [12].

Glass and aramid fibers can also experience degradation due to moisture. It was observed that moisture adsorption by the fibers originates a decrease in its surface energy, leading to a reduction of the cohesive strength of the fibers. Furthermore, moisture attack can accelerate the rate of crack growth in glass fibers [16].

Moisture also affects the performance of the fiber-matrix interface by originating a reduction of the interfacial strength parameters, through chemical processes and due to the swelling of the resin caused by moisture sorption [17]. Although carbon fibers are generally considered to be inert to most environmental agents, its inertness does not apply to the fiber-matrix bond and to the matrix itself, both of which can in fact be significantly deteriorated by environmental exposure [12].

When compared to resins, FRP composites are less prone to degradation caused by moisture and temperature because of the existence of fibers. However, the presence of voids and non-uniformities in specimens prepared according to the wet lay-up procedure increases the vulnerability of the composite material to moisture uptake, which may result in its mechanical degradation [18]. Therefore, the degradation caused by moisture to resin, fiber and fiber/matrix interface usually originates important reductions of the mechanical properties of composites. It should be noted that the use of appropriate coatings can result in FRP composites with a significantly enhanced durability under moisture exposure when compared to conventional materials [12].

Thermal cycling

Temperature induces a viscoelastic response to resins, which tend to soften and lose shear capacity with increased temperature exposure. A temperature increase above T_g causes an important reduction of its performance. As an example, the FIB report [19] suggests that T_g should be 20 ºC above the maximum air temperature in shade, with a minimum value of 45 ºC.

A temperature increase below T_g may result in an increase in susceptibility to moisture absorption and also in a post-curing phenomenon (if the temperature is above the ambient curing temperature). Furthermore, long thermal cycling of brittle resins can result in micro-crack formation [12].

In general, fibers are resistant to temperature exposure, therefore any degradation in composite materials due to temperature exposure is essentially due to the degradation in the matrix or in the fiber-matrix interface.

Thermal incompatibility in FRP composites and FRP-strengthened elements is an important issue to be considered in the presence of thermal cycling [12]. The thermal incompatibility is due to the considerable difference in thermal expansion between the fibers and the polymer matrix, and/or between the reinforcing system and the substrate [13]. Such large differences produce thermal stresses at the fiber-matrix and matrix-substrate interfaces. In this way, thermal cycling can be the source of severe bond degradation in FRP-strengthened elements [20].

Freeze-thaw cycling

Freezing and thawing exposures generally do not affect fibers, but resin and fiber-resin interface can be affected [21]. Freeze exposure causes embrittlement of the resin, resulting in increased strength and stiffness, but decreases damage tolerance. De-icing salt in wet conditions with subsequent freeze-thaw cycling can lead to the occurrence of micro-cracks and progressive degradation due to crystal formation and increased salt concentration, in addition to effects of moisture included swelling and drying [21]. Freeze-thaw cycling can originate micro-cracking growth in the presence of previous moisture degradation [12]. Also, experimental results seem to indicate that the combined effect of moisture, sustained loading and freeze-thaw cycling accelerates the bond degradation.

2.2. Environmental durability studies

The evaluation of the factors affecting the long-term performance of external FRP-strengthened structures is generally done resorting to accelerated ageing tests. Although suitable in-situ tests take long time to be effective, there's a recognized need to establish a reliable correspondence between laboratorial accelerated ageing tests and real time ageing tests.

This section provides an overview of the most relevant experimental results on environmental durability studies of concrete and masonry components strengthened with FRP, based on thermal and moisture exposure conditions.

Moisture

During the 1990s several experiments to assess moisture effects on FRP composites were carried out. Chajes et al. [22] tested GFRP- and CFRP-bonded concrete specimens under wet-dry cycling, for which a 36% and 19% decrease in ultimate strength was observed, respectively, after 100 cycles. Toutanji and Gomez [23] observed a strength reduction up to 33% on specimens made of various epoxy and FRP systems after exposure to 300 wet-dry cycles. Karbhari and Zhao [24] measured a reduction in bending capacity of GFRP- and CFRP-strengthened beams of about 40% after 120 days of moisture exposure.

More recently, Grace and Singh [25] tested 78 large-scale strengthened concrete beams using CFRP plates and fabrics and observed that moisture affects the bond between FRP and concrete to a great extent. Tuakta and Buyukozturk [26] studied the effect of variable moisture conditions on the fracture toughness of CFRP-bonded concrete specimens. A significant reduction of bond strength was observed during a first period of water immersion (70% degradation after 8 weeks). Moreover, it was concluded that the bond degradation was not reversible upon drying during the wet-dry cycles.

As for masonry, very few studies are available. Briccoli Bati and Rotunno [27] and Aiello and Sciolti [28] observed a significant reduction in bond strength of CFRP-strengthened masonry specimens after exposure to different wet-dry cycles and distinct durations. Sciolti et al. [29] obtained a reduction in bond strength of CFRP-strengthened weak stones of about 26% after 25 weeks of water immersion.

Although the use of different specimens, exposure conditions and testing procedures, researchers found that generally exposure to moisture can be the cause of important strength degradation of FRP-strengthened elements.

Thermal and freeze-thaw cycling

As for moisture exposure, a series of experiments were developed during the 1990s to characterize the effects of thermal and freeze-thaw cycling on the structural performance of FRP-strengthened concrete elements. Chajes et al. [22] tested concrete beams reinforced with glass fiber and carbon fiber composites subjected to freeze-thaw and wet-dry cycles. They observed strength losses after 100 freeze–thaw cycles of 27% and 21% for the glass and carbon fiber composites, respectively. They also observed that wet-dry cycles caused more strength degradation than freeze–thaw exposures. Karbhari and Zhao [24] tested CFRP- and GFRP-strengthened concrete beams submitted to freeze-thaw cycles ranging from -15.5 °C to +23 °C. A 7.5% decrease in flexural failure load and a more brittle failure mode was observed after exposure to 127 cycles. Green et al. [30] tested the effect of freeze-thaw cycling on the bond between CFRP sheets and concrete. A moderate

level of degradation in the FRP-concrete bond was found after 300 freeze-thaw cycles. Authors also reported that the failure mode shifted from the substrate region to the adhesive region as the number of cycles increased. Other studies have also shown that freeze-thaw cycling exposure did not cause significant reduction in the bond strength of FRP-strengthened concrete beams.

More recently, Subramaniam et al. [31] studied the effect of freeze-thaw cycling on the performance of FRP-strengthened concrete elements. Authors observed that 300 cycles of freeze-thaw ranging from -18 °C to +5 °C originated a 17% decrease in the ultimate load and 35% decrease in the interface fracture energy. Colombi et al. [32] analysed the bond behaviour of CFRP-strengthened concrete elements under freeze-thaw cycling from -18 ºC to +4°C. After exposure to 100 and 200 cycles, they observed moderate reductions on load capacity, not much influenced by the number of cycles.

Studies about the effects of temperature exposure on the behaviour of external FRP-strengthened masonry are practically absent from literature. Briccoli Bati and Rotunno [27] studied the performance of FRP-strengthened masonry elements exposed to freeze-thaw cycling between 8 °C and +50 °C. They observed a progressive decrease in shear strength with increasing cycles, with a 50% decrease for 96 cycles. Desiderio and Feo [33] investigated the behaviour of CFRP-bonded masonry specimens to freeze-thaw cycling between -18 °C and +30 °C. They observed a decrease in bond strength and ultimate load after exposure to 105 cycles. They also reported that the governing failure mode shifted from cohesive (failure in the masonry region) to adhesive (failure in FRP-masonry interface).

From the available studies, and in spite of the use of different test procedures and observation of different degradation trends, it can be commonly assumed that temperature exposure reduces the bond performance of externally bonded FRP systems to a certain degree.

3   DEGRADATION INDUCED BY WATER IMMERSION

The effect of moisture on the bond behaviour of FRP-strengthened masonry bricks was investigated trough a laboratorial campaign carried out at UMinho. The degradation of bond was characterized by performing conventional pull-off and shear bond tests after different periods of water immersion. Specimens from all components were also submitted to water immersion to detect possible degradation in their mechanical properties.

3.1. Materials

Specimens from brick, primer, epoxy resin and glass fibers were tested to characterize their properties prior to any damage induced by continued water immersion. Hand-made solid clay bricks, used in previous experimental works and here termed as type 1, were employed as representative of ancient bricks [34] [4].

Primer and epoxy resin specimens were cured for a period of 60 days at room temperature. Previous studies have shown that undercure has an important impact on increase the moisture susceptibility of ambient-temperature cured epoxy resins [29]. The glass transition temperature of the epoxy resin T_g was characterized following the differential scanning calorimetry (DSC) method. Thermal scans were performed between 5 °C and 200 °C with a heating rate of 10 °C/min. Further details in terms of specimens' size, testing procedures and relevant standards used are provided in [35].

Table 1 summarizes the main results, in terms of average values of five specimens and respective coefficients of variation (CoV). Details in terms of specimens' size, testing procedures and relevant standards applicable are given in [13]. Brick specimens present relatively high CoVs (around 20%), mainly because bricks were hand-made and traditionally fired. The results found for primer, resin and GFRP coupons are in agreement with those found in literature. The CoV values found are relatively low except for the GFRP coupons (around 15%) due to the manufacture process.

Water absorption tests based on the gravimetric sorption method were also carried out on all materials according to ASTM D570-98(2010)e1 [36]. Brick specimens absorbed 10% mass of water upon saturation while epoxy resin and GFRP coupons absorbed 1.6% and 3.7%, respectively. The equilibrium moisture content of the GFRP coupons is higher than of the epoxy resin due to the imperfect interfaces that are in contact with water in the composite specimens [37].

The water absorption rate and the amount of water absorbed till saturation in epoxy resins vary with several parameters as curing conditions and environment conditions (temperature, humidity, etc.) [37]. A wide range of values can be found in literature. In [38] the water content ranged from 0.42% to 1.88%, while in [37] a water content ranging from 4.7% to 8.7% was observed at saturation.

Table 1. Properties of the materials.

Material	Average value	CoV (%)
Solid clay brick type 1		
Compressive strength (f_{cb}; MPa)	8.0	11
Flexural tensile strength (f_{tb}; MPa)	1.5	25
Primer		
Tensile strength (f_{tp}; MPa)	55.3	11
Young's modulus (E_p; GPa)	2.9	6
Epoxy resin		
Tensile strength (f_{tr}; MPa)	53.8	10
Young's modulus (E_r; GPa)	2.5	10
Glass transition temperature (T_g; ºC) (4 specimens only)	70.0	3
GFRP coupons		
Tensile strength (f_{tf}; MPa)	1250.0	15
Young's modulus (E_f; GPa)	79.2	7
Ultimate strain (ε_f; %)	3.0	20

3.2. Pull-off and shear bond testing

Both pull-off and shear bond specimens were prepared by gluing unidirectional GFRP sheets on single bricks with dimensions of 200x100x55 mm^3 using an epoxy resin and following the wet lay-up procedure. Bricks were previously dried, cleaned and a primer was applied to the brick's surface for preparation of the substrate.

For the pull-off specimens GFRP sheets were applied over a 180x80 mm^2 area of the brick surface as illustrated in Figure 1. For the shear bond tests, GFRP sheets with 50 mm width were applied on the brick with a 150 mm bonded length and leaving a 40 mm unbounded part at the loaded end, see Figure 2.

The pull-off tests were performed in accordance to ASTM C1583 [8]. A 50 mm diameter partial core was drilled on the test zone with an approximate depth of 5 mm, see Figure 1(b). Then, aluminium disks were firmly glued on the GFRP surface and pulled at a rate of 20 kPa/s. The shear bond tests were carried out under displacement control at a rate of 5 µm/sec, see Figure 2(b). Both the resulting force and the relative slip between the GFRP and the brick, measured with LVDTs placed at the free and loaded ends, were recorded.
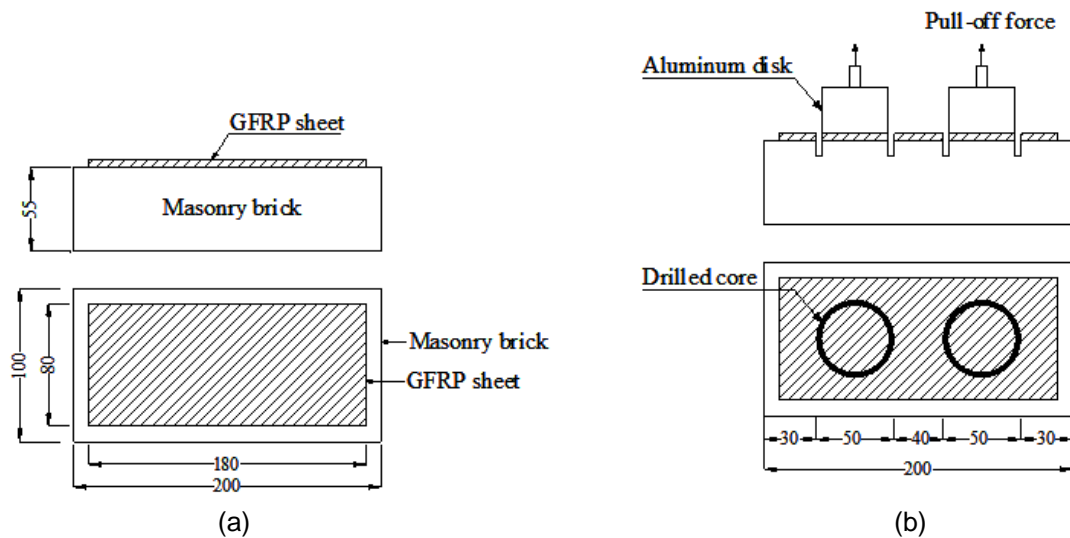
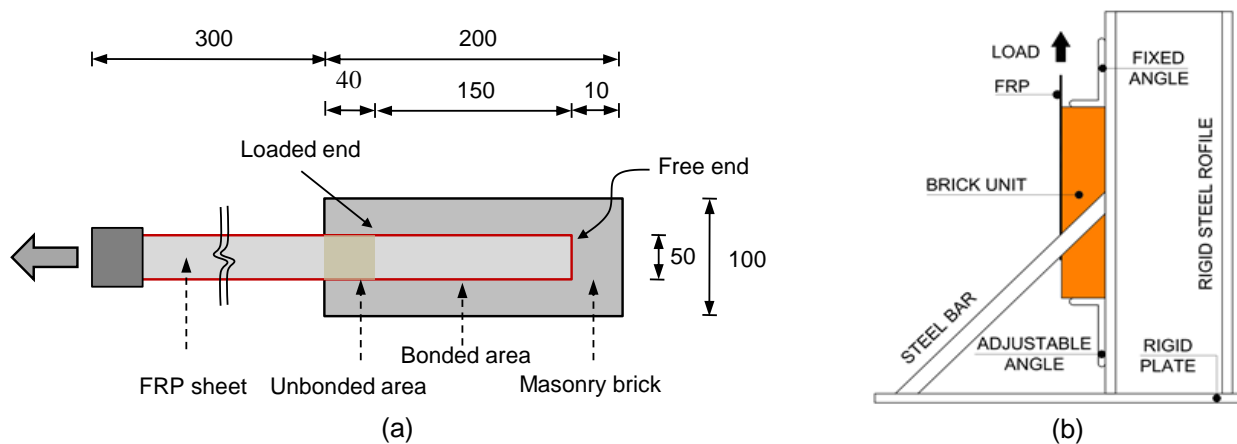**Figure 1.** Pull-off tests: (a) geometry of the specimens; (b) test setup (dimensions in mm).

Figure 2. Shear bond tests (single-lap shear bond): (a) geometry of the specimens (dimensions in mm); (b) scheme of the test setup.

3.3. Water immersion

Specimens for both pull-off and shear bond tests were immersed in deionized water at a constant temperature of 23 ºC in a water tub up to 24 weeks. The key purpose was to characterize the effect of continuous exposure to moisture on the bond behaviour. Post-ageing tests were performed every four weeks of immersion, both for mechanical characterization of material components and bond behaviour of FRP-strengthened bricks. Five specimens from each type were tested in each exposure period.

3.4. Post-ageing tests on components

The effect of water immersion on the mechanical properties was investigated by performing compressive tests on brick samples and tensile tests on epoxy resin and GFRP coupon specimens. The variation of the brick compressive strength is illustrated in Figure 3. A reduction up to 25% of the compressive strength after 24 weeks of immersion was found, probably due to chemical reactions of water with brick constituents, promoted by the dissolving effect of water or by insufficient firing temperature [39]. Insufficient firing temperature in clay bricks can originate a low degree of vitrification and a high moisture expansion coefficient [40]. The water may react with the remaining clay inside the brick leading to micro-cracking, expansion and strength degradation.
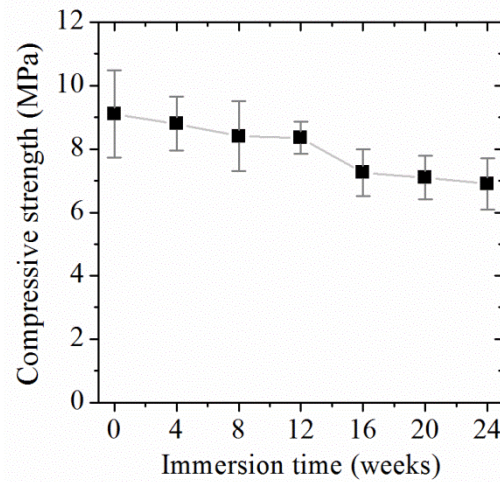
Figure 3. Variation of the brick compressive strength.

The variation of the Young's modulus and tensile strength of epoxy resin specimens is presented in Figure 4. An important reduction of both parameters was observed. The Young's modulus and tensile strength decreased by 40% and 25% after 24 weeks, respectively, corresponding to 1.2% of water absorption. Although the Young's modulus degradation seems to stop after 12 weeks of immersion, the tensile strength decreases in a relatively continuous way during the entire period of exposure. Other studies have shown that the degradation of epoxy resins due to water absorption varies with the type of epoxy resin, e.g. see [37] [41]. While Sciolti et al. [37] reported a 45% reduction of Young's modulus and 32% reduction of tensile strength for 4% water absorption, Tuakta and Büyüköztürk [41] reported a 7% reduction of Young's modulus and 22% reduction of tensile strength in epoxy resin for 1.2% mass water absorption.

The reduction of the Young's modulus and tensile strength is due to the plasticization and possibly hydrolysis of epoxy resin [42]. The water absorbed by the resin acts as a plasticizer, which usually reduces the T_g and mechanical properties. The decrease of T_g reflects the degree of plasticization and occurrence of water/resin interactions [43], nevertheless this decrease can be partially regained upon drying [44]. For long exposure periods, the possibility of resin degradation increases because hydrolytic reactions may also occur and these can affect the resin performance in a serious way [43].
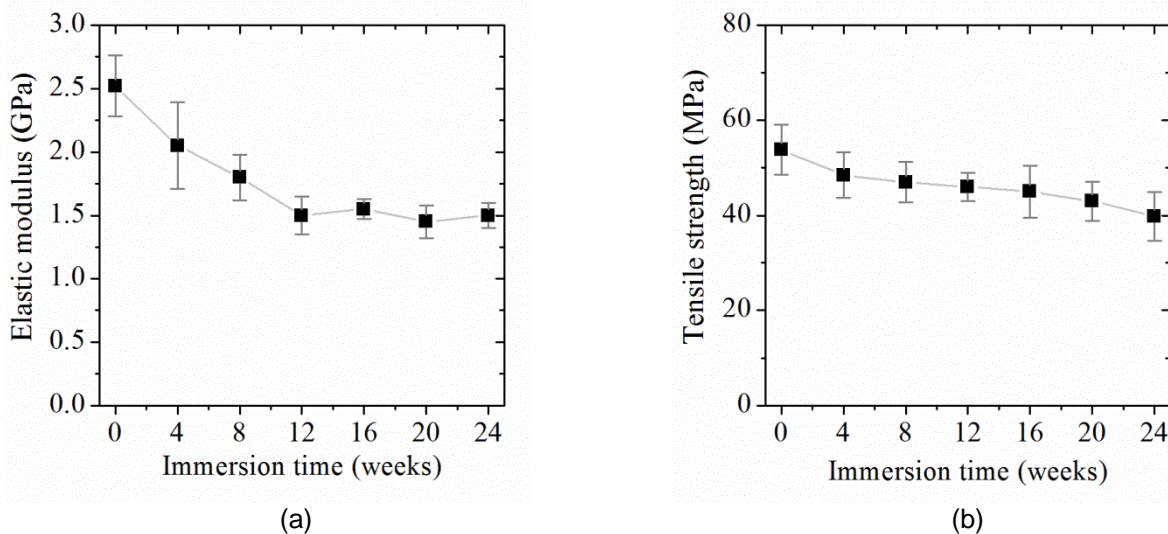

(a)

(b)

Figure 4. Variation of the properties of epoxy resin: (a) Young's modulus; (b) tensile strength.

The variation of the Young's modulus and tensile strength of GFRP coupons is depicted in Figure 5. As in wet lay-up procedures the specimens' thickness may vary, the results were normalized to the specimens' thickness according to ASTM standards [45]. As for the epoxy resin, Young's modulus and tensile strength values decreased significantly. The Young's modulus reduction stabilized at 16 weeks of immersion with a 38% degradation. The tensile strength decreased about 40% after 24 weeks of exposure corresponding to 3.7% water uptake. A similar severe reduction of mechanical properties of GFRP (tensile strength degradation of 50%) has been reported in [46]. The formation of air bubbles and non-uniformities in the specimens prepared following the wet lay-up procedure increases the vulnerability of the composite material to moisture uptake [18]. Therefore, the degradation of mechanical properties of GFRP coupons reported in this paper can be attributed to the water effect on the epoxy and epoxy-fiber interface. Additionally, the water can cause attack fibers, which results in corrosion and bond degradation at the epoxy/fiber interface [47].

As GFRP coupons were cured for 2 months before water immersion, it is considered that polymerization of the resin has fully occurred and, therefore, the results present solely the strength degradation due to water immersion, without any beneficial effect due to post-curing.
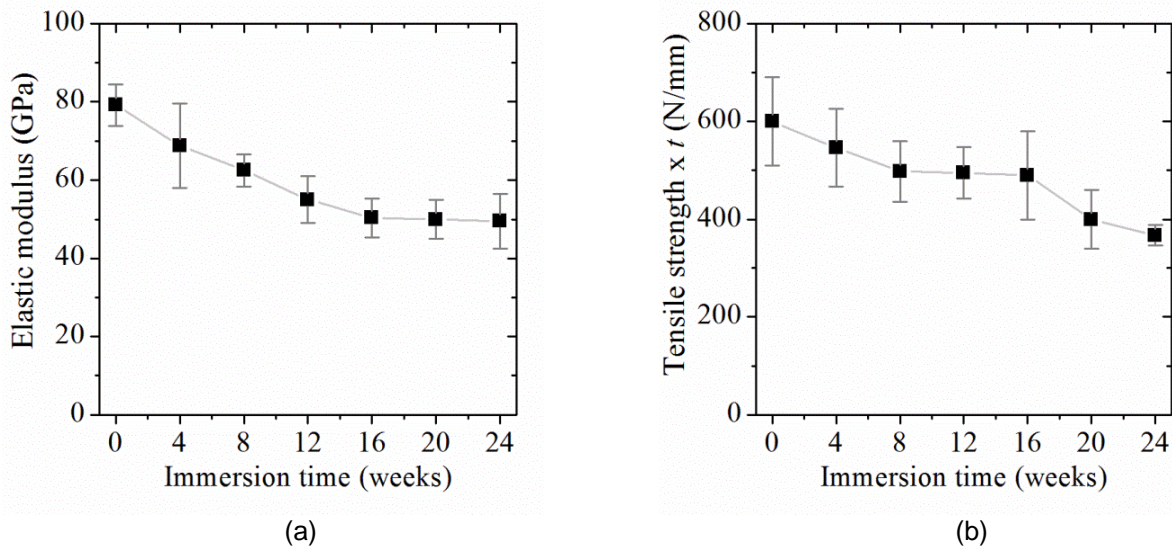

Figure 5.   Variation of the properties of GFRP coupons: (a) Young's modulus; (b) tensile strength.

3.5. Post-ageing tests on pull-off specimens

Figure 6 illustrates the variation of the average pull-off strength as a function of the immersion time. A huge and progressive reduction of the bond strength can be deduced from the tests, with a 56% reduction after 24 weeks of immersion. The scatter found in the results is somehow common for this type of test [48]. The failure mode remained cohesive in all immersion periods with a reduction of the thickness of the detached brick layer until reaching the primer impregnated layer of the brick.

3.6. Post-ageing tests on shear bond specimens

Figure 7 illustrates the load-slip curves, in terms of envelope average values, for three different immersion periods. The increase in exposure time lead to a reduction of bond stiffness and bond strength and to a less brittle behaviour. In fact, the average ultimate slip recorded at the loaded end for specimens tested at 24 weeks immersion (1.4 mm) double the value corresponding to the case of specimens tested without any immersion (0.6 mm). Finally, an apparent increase of the effective bonded length due to water immersion seems to take place [35].

Figure 8 presents the variation of the average values of the bond stiffness and debonding force with the immersion time. The bond stiffness, defined as the initial slope of the load-slip curves, has decreased considerably in the first 8 weeks (around 60%). Afterwards, the rate of bond stiffness degradation is much lower, reaching 80% reduction at 24 weeks. This reduction in the bond stiffness can be attributed to the stiffness reduction in epoxy resin, GFRP, and FRP-brick bond. In comparison, it

was observed that the stiffness remained practically unaffected by water immersion in CFRP-strengthened calcernite stones [29] and concrete specimens strengthened with CFRP laminates [49].
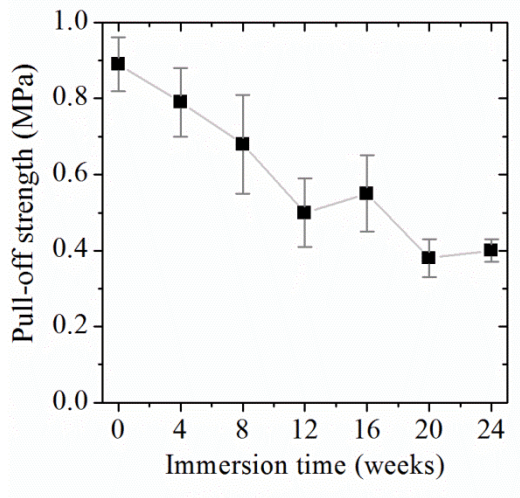

Figure 6.   Variation of the pull-off strength.
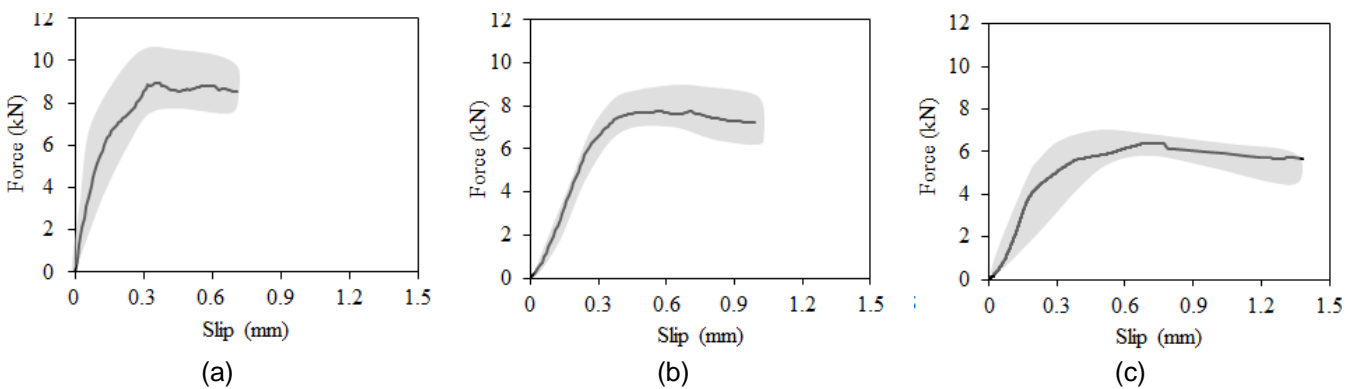

| (a) | (b) | (c) |

Figure 7.   Envelope and average load-slip curves from single-lap shear tests: (a) prior to immersion; (b) 12 weeks of immersion; (c) 24 weeks of immersion.
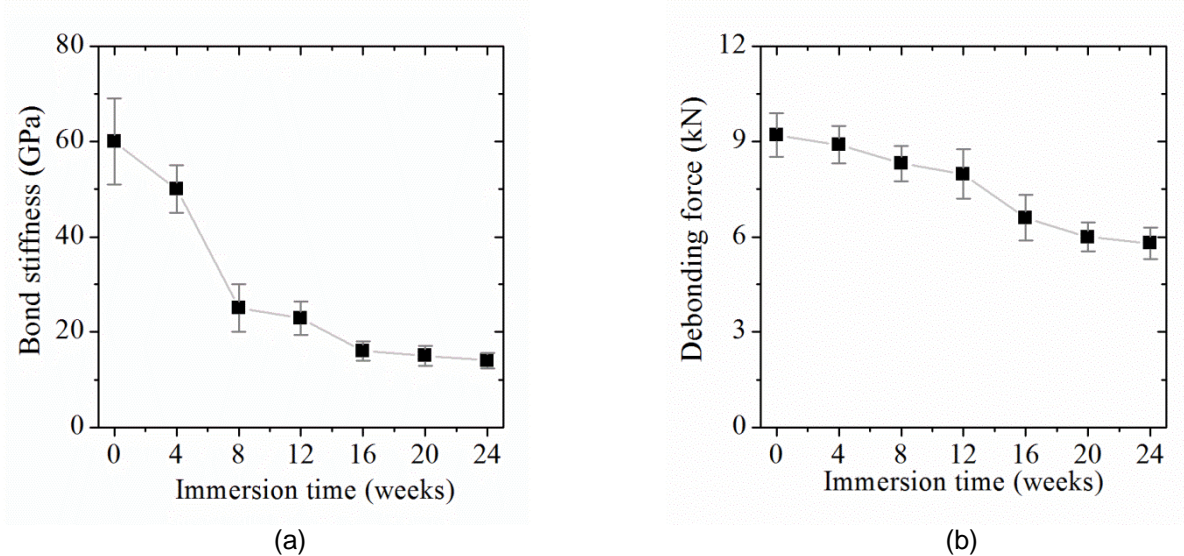

| (a) | (b) |

Figure 8.   Variation of bond parameters: (a) bond stiffness; (b) debonding force.

It is possible to observe that the bond strength decreased slightly in the first 12 weeks of immersion (about 16%). Then, the degradation rate increased reaching 35% reduction of bond strength after 20 weeks of exposure. Figure 8(b) suggests that the degradation is less dependent on time after 20 weeks of immersion and the bond strength might have reached its residual value. Nevertheless, a longer immersion time is necessary to investigate this apparent trend. A similar residual bond strength has been reported by Sciolti *et al.* [29] after 8 weeks of immersion for CFRP strengthened calcernite stones.

In general terms, it seems that the degradation rate diminishes with exposure for both bond stiffness and bond strength. This phenomenon is an evidence that most probably a thermodynamic balance has been attained, as reported also in [41] [49].

Considering debonding as a local failure involving crack propagation, a fracture mechanics approach seems more appropriate than a conventional strength-based approach [41]. Taking the fracture energy G_f as the preferred degradation parameter, its value for each immersion period can be computed according to CNR-DT 200 [10] as:

$$G_f = \frac{P_{max}^2}{b_f^2 \left(2\, E_f\, t_f\right)} \qquad (1)$$

where P_{max} is the bond resistance, b_f and t_f are the GFRP width and thickness, respectively, and E_f is the GFRP Young's modulus.

Figure 9 presents the average fracture energy associated to each immersion period. In the first 12 weeks of immersion there is no reduction of the interfacial fracture energy. However, a significant reduction degradation occurs between the 12th week and the 20th week. After 20 weeks of immersion, the fracture energy value apparently reached a residual value with 40% reduction when compared to its initial value. A similar degradation trend is also reported in [49]. The dominant failure mode observed was mainly a cohesive one, with a progressive reduction of the thickness of the detached brick layer with immersion time, up to a thin layer equal to the primer impregnated thickness.
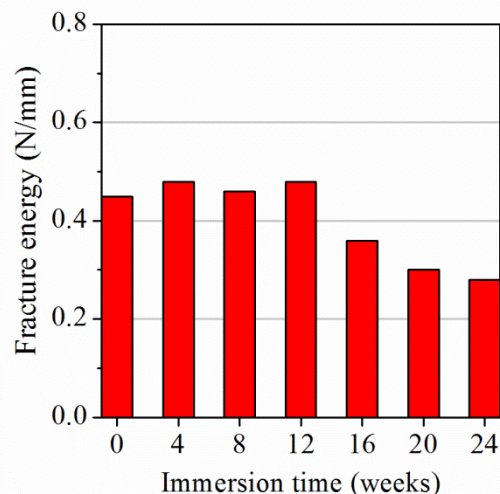

Figure 9.   Variation of the interfacial fracture energy.

4   DEGRADATION INDUCED BY HIGROTHERMAL CONDITIONS

Aiming at getting insight into the bond degradation evolution of externally reinforced masonry with FRP subject to combined moisture and temperature cycles, an experimental campaign was carried out at University of Minho on FRP-strengthened masonry units subjected to accelerated ageing tests. The degradation of bond was quantitatively assessed by performing conventional single-lap shear tests. As no correlation was found between the pull-off and the shear bond tests subjected to water immersion tests, pull-off tests were not performed in specimens exposed to hygrothermal conditions.

Specimens of all components were also submitted to accelerated ageing tests in order to identify possible changes in their mechanical properties. Two distinct hygrothermal conditiões were considered in this research aiming at clarifying the possible coupled effect of exposure to temperature cycling and moisture.

4.1. Materials

All materials employed, namely brick, primer, epoxy resin and glass fibers were initially tested in order to determine their relevant mechanical properties.

As a different type of brick (type 2) was used here, its average properties and respective CoVs are listed in Table 2. The results regarding primer, epoxy resin and glass fiber coupons were already presented in Table 1. The brick presents moderate mechanical properties and the CoV value is relatively low.

Table 2. Properties of the brick type 2.

Material	Average value	CoV (%)
Solid clay brick type 2		
Compressive strength (f_{cb}; MPa)	14.2	4
Flexural tensile strength (f_{tb}; MPa)	1.6	12

4.2. Bond testing

Specimens were prepared by gluing unidirectional GFRP sheets of dimensions 490x50x0.17 mm^3 on solid clay bricks with dimensions of 200x100x50 mm^3 using an epoxy resin and following the wet lay-up procedure. The preparation of the specimens and the set-up used to perform the single-lap shear tests are described in section 3.2.

4.3. Hygrothermal exposure

The combined thermal and moisture conditions consisted in exposing specimens to two different hygrothermal conditions inside a climatic chamber. The main purpose was to characterize the effects of hygrothermal conditions on the bond behaviour. Figure 10 illustrates the time variation of temperature within both exposures. The relative humidity was kept at a constant value of 90% in both exposures.

In the first exposure (HT), specimens were submitted to 6 hours temperature cycles from +10 °C to +50 °C. Within each cycle, the temperature was kept constant at +10 °C for 2 h, subsequently increased to +50 °C in 1 h, followed constant temperature of +50 °C during 2 h. Subsequently, the temperature was decreased back to +10 °C in 1 h resulting in a 6 h cycle of exposure. The +50 °C temperature is considered relatively high to accelerate the degradation phenomenon, but far enough from T_g (70 °C). Taking into account that environmental conditions can lead to a reduction of the glass transition temperature in epoxy resins, the maximum temperature set in the thermal cycles should prevent reaching T_g during the tests [12]. The specimens were subjected to 225 cycles during this exposure.

Within the second exposure (FT), temperature cycles ranged from -10 °C to +30 °C. Conversely, here the objective was to investigate the effect of freeze-thaw conditions on the bond behaviour while keeping unchanged all the other potential influencing parameters regarding exposure HT. Therefore, similar temperature rates were adopted leading to a 20 °C decrement of the maximum and minimum temperatures. Specimens were subjected to 300 cycles during this exposure.

Post-ageing tests were performed every two weeks of environmental exposure (about 60 cycles), both for mechanical characterization of all material components and bond behaviour of FRP-strengthened bricks. Five specimens were tested for each exposure period.
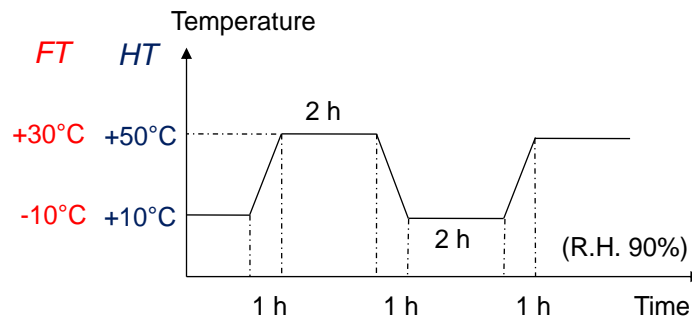
Figure 10. Conditioned hygrothermal cycles adopted.

4.4. Post-ageing tests on components

The effect of the accelerated ageing tests was assessed by performing axial compression tests on brick samples and direct tensile tests on epoxy resin and GFRP coupon specimens. The variation of the brick compressive strength in all post-ageing tests was found to be negligible in both exposure conditions, with a CoV up to 10%. This result shows that the brick used exhibits a good resistance against the two environmental exposures considered.

As for the epoxy resin, the Young's modulus exhibited negligible changes in both exposures. However, some degradation occurred in the tensile strength. In HT exposure, a 20% reduction of tensile strength was observed after 225 cycles, see Figure 11(a), while for FT exposure a better durability performance was found, with only 8% reduction of tensile strength after 300 cycles, see Figure 11(b). Given these results, it is advised to perform more exposure cycles in order to get a better insight into this phenomenon. It is worth to mention that low CoVs were found for the tests of both exposures (up to 13%).

The reduction of the tensile strength of the epoxy resin specimens could have been originated by different degradation mechanisms. The water absorbed by the epoxy resin acts as a plasticizer, and the result of plasticization is usually the reduction of T_g and of the mechanical properties of the epoxy resin [43]. The apparent increase in the degradation rate after 150 cycles for the HT exposure can be due to the fact that hydrolytic reactions may occur for long exposure periods, which can strongly affect the properties of the resin [43]. In turn, exposure to high temperatures below T_g results in an increment of the moisture diffusion coefficient and epoxy post-curing [47]. While the former lead to a higher moisture uptake and consequently to mechanical degradation, the latter can cause an improvement in the mechanical properties of the resin.
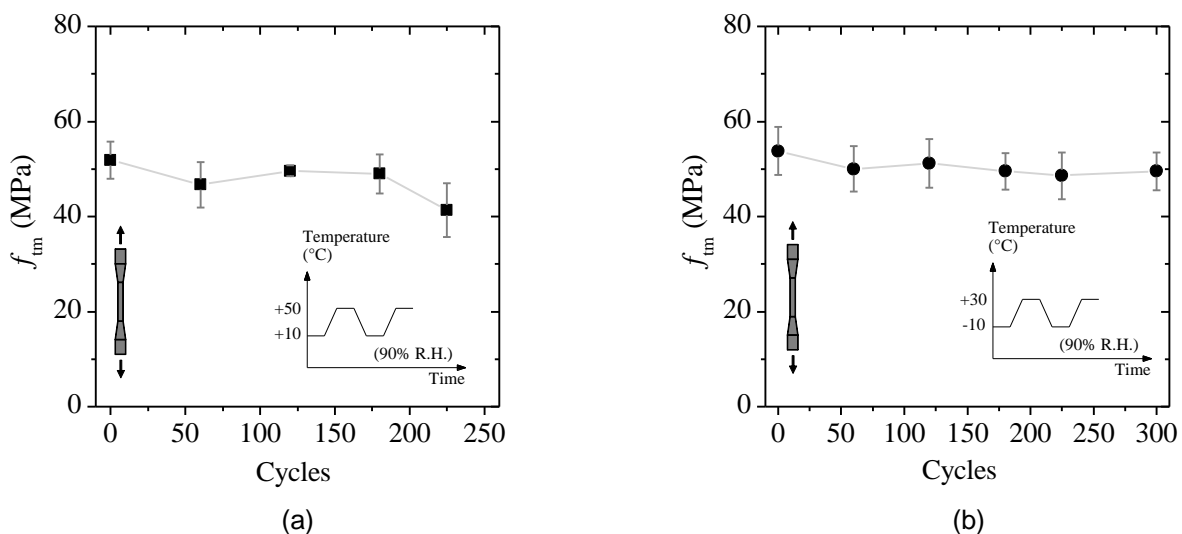

(a)

(b)

Figure 11. Variation of the tensile strength of epoxy resin: (a) HT exposure; (b) FT exposure.

As for the GFRP coupons, both hygrothermal exposures caused some degradation, but a higher degradation was observed in specimens exposed to HT conditions. The results regarding the Young's modulus and the tensile strength are illustrated in Figure 12 and Figure 13, respectively. Also here, results were normalized to the specimens' thickness according to ASTM D7565 [45]. The Young's modulus of the GFRP coupons decreased 23% and 18% under the HT and FT exposures, respectively. In a similar way, the tensile strength of the GFRP coupons decreased 22% and 10% under the HT and FT exposures, respectively. The CoVs of the experimental results in both exposures were kept under 12%.
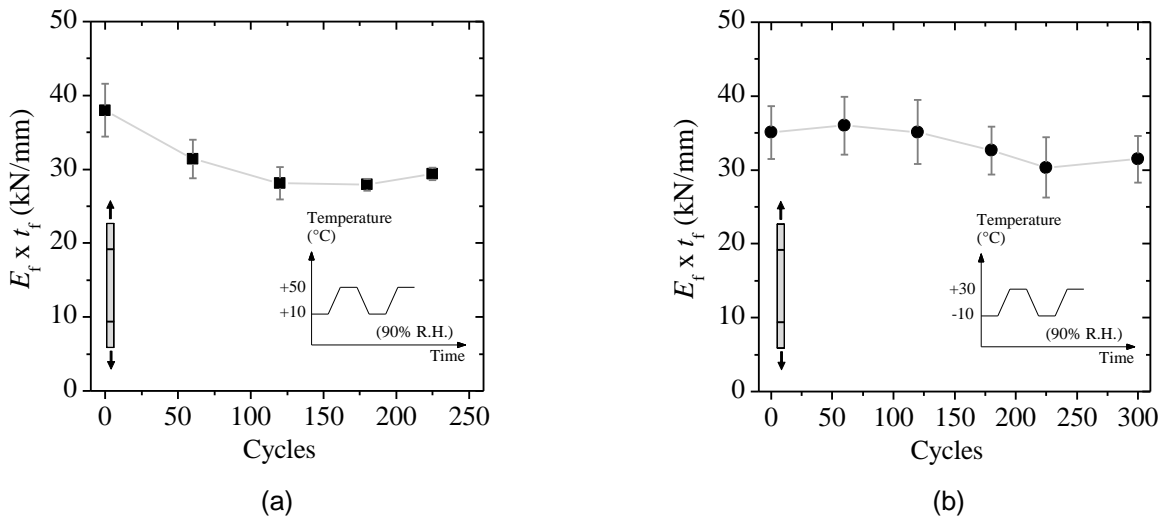

(a)

(b)

Figure 12. Variation of the Young's modulus of GFRP coupons: (a) HT exposure; (b) FT exposure.
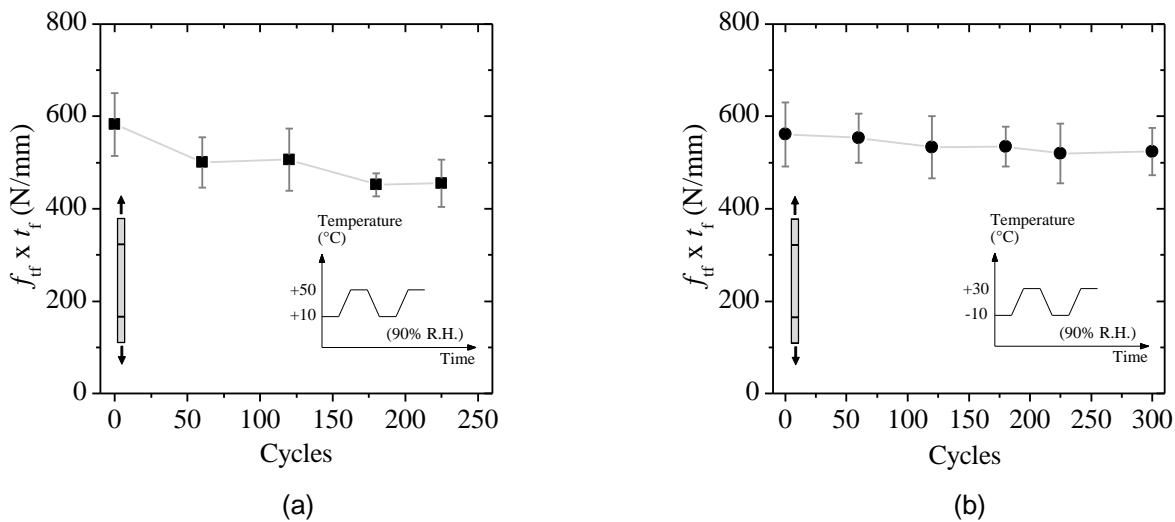

(a)

(b)

Figure 13. Variation of the tensile strength of GFRP coupons: (a) HT exposure; (b) FT exposure.

Also in this case, the degradation observed experimentally can be attributed to different degrading mechanisms. GFRP coupons absorb moisture when exposed to moisture conditions, which causes degradation in the epoxy resin properties, as discussed above. Additionally, the water attacks the glass fibers degrading their mechanical properties. Under this scenario, the fiber-epoxy interface may also be degraded due to the degradation of fibers and epoxy resin and also the produced osmotic pressure at the interface [12]. On the other hand, the cyclic temperature may causes micro-cracking due to differences between the thermal expansion coefficients of glass fibers and epoxy resin [50] [51]. Finally, the 50°C temperature in the HT exposure may lead to post-curing of the epoxy resin and increase the moisture absorption coefficient, as referred to above.

4.5. Post-ageing tests on FRP-strengthened specimens

The bond degradation evaluation was investigated following both qualitative and quantitative approaches. Initially, specimens were inspected visually in order to detect the existence of any visible damage or delamination in the interfacial region. Progressive FRP delamination was observed in some specimens with the increasing number of exposure cycles. The reduction of the bonded area (normalized by the initial bonded area) with exposure time is illustrated in Figure 14. Each point represents the average value of five inspected specimens. Delamination was generally larger in specimens subjected to HT cycles.

Delamination observed in the FRP-strengthened specimens subjected to higrothermal cycles is most probably due to the thermal incompatibility between the composite material and the brick. The thermal expansion coefficient of clay bricks is in the order of 5×10-6 /°C [52]. The thermal expansion coefficient of E-glass fibers is similar to the one from bricks, while for epoxy resin it is in the range of 30~54×10-6 /°C [10]. This large difference of thermal expansion coefficients between the epoxy resin and the glass fibers and bricks induces thermal strains at the brick-resin and fiber-resin interfaces. This effect is further amplified by cycling leading to thermal fatigue that may cause FRP delamination from the brick surface during exposures. On the other hand, it has been shown that the thermal expansion coefficient of epoxy resins is much lower at low (and negative) temperatures [53]. Therefore, it is expected that the interfacial strains produced by thermal incompatibility would be lower for the FT exposure. This fact explains the smaller delaminated areas observed in specimens exposed to the FT conditions.

For a better detection and precise quantification of the delamination area, infrared thermography technique was also used. The technique employed and the results obtained are discussed in [54]. Further details regarding the qualitative approach are provided elsewhere [13].
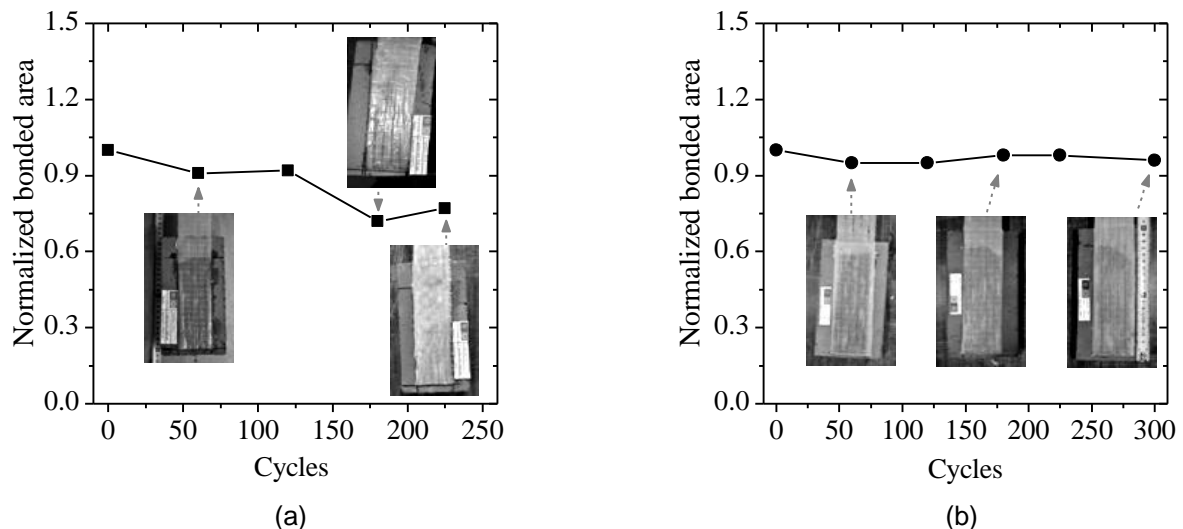

(a) (b)

Figure 14. Reduction of the bonded area induced by higrothermal exposure: (a) HT exposure; (b) FT exposure.

In the second phase, the bond behaviour degradation was assessed by performing conventional single-lap shear tests on five specimens for each exposure period. As done for the materials, tests were performed every two weeks of environmental exposure.

The effect of the two hygrothermal exposures on the debonding force is depicted in Figure 15. The debonding force progressively decreased with the number of exposure cycles, but at different rates. The debonding force decreased 17% and 45% after 120 and 225 cycles of HT exposure, respectively. As for the FT exposure, it decreased 4% and 14% after 120 and 300 cycles, respectively. A direct comparison between the results normalized with respect to the initial force clarifies that the HT exposure induces a higher degradation in the FRP-strengthened specimens tested in this study, see Figure 16.
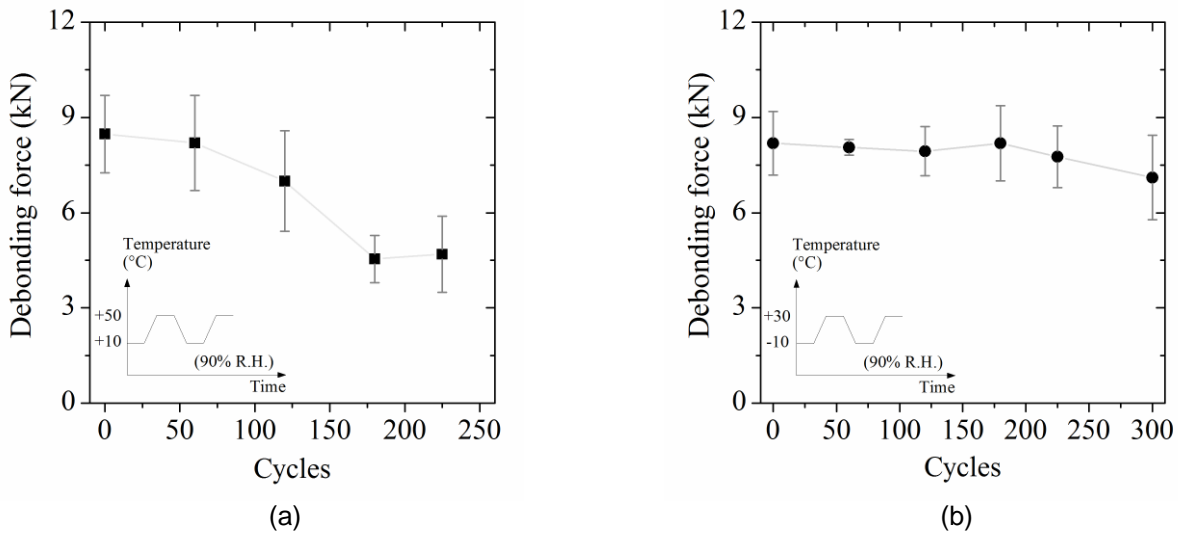
Figure 15. Variation of the debonding force: (a) HT exposure; (b) FT exposure.
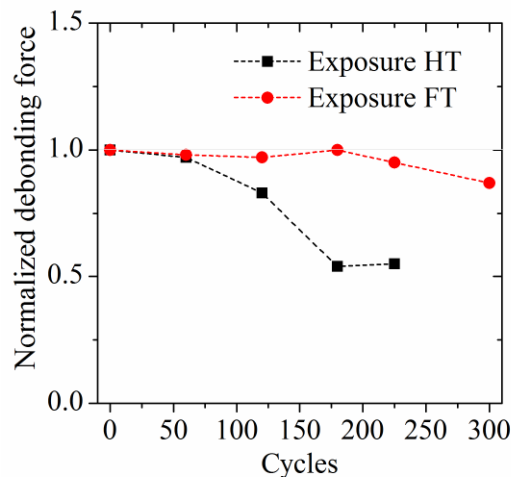

Figure 16. Comparison of the debonding force recorded for the HT and FT exposures.

The debonding process observed in the experiments varied from a brittle to a progressive and less brittle mode. Three different failure modes were identified and classified as follows:

- cohesive: failure within a thick layer of brick
- interfacial cohesive: failure within a superficial layer of brick
- adhesive: failure at the FRP/brick interface

More precisely, the increase of the number of exposure cycles causes larger bond degradation and changes the dominant failure mode from cohesive to adhesive in both hygrothermal exposures. Similar results regarding changes in the debonding process have been also reported in literature for specimens exposed to freeze-thaw and wet-dry cycles, e.g. [55] [56].

The measurement of the area in correspondence to each failure mode in each specimen and for each exposure period, after the debonding tests, allows to estimate the relative contribution of each failure mode in the debonding behaviour. This result is illustrated in Figure 17. As realized during the tests, the contribution of the cohesive failure mode reduces as the exposure time increases, being progressively substituted by adhesive failure.
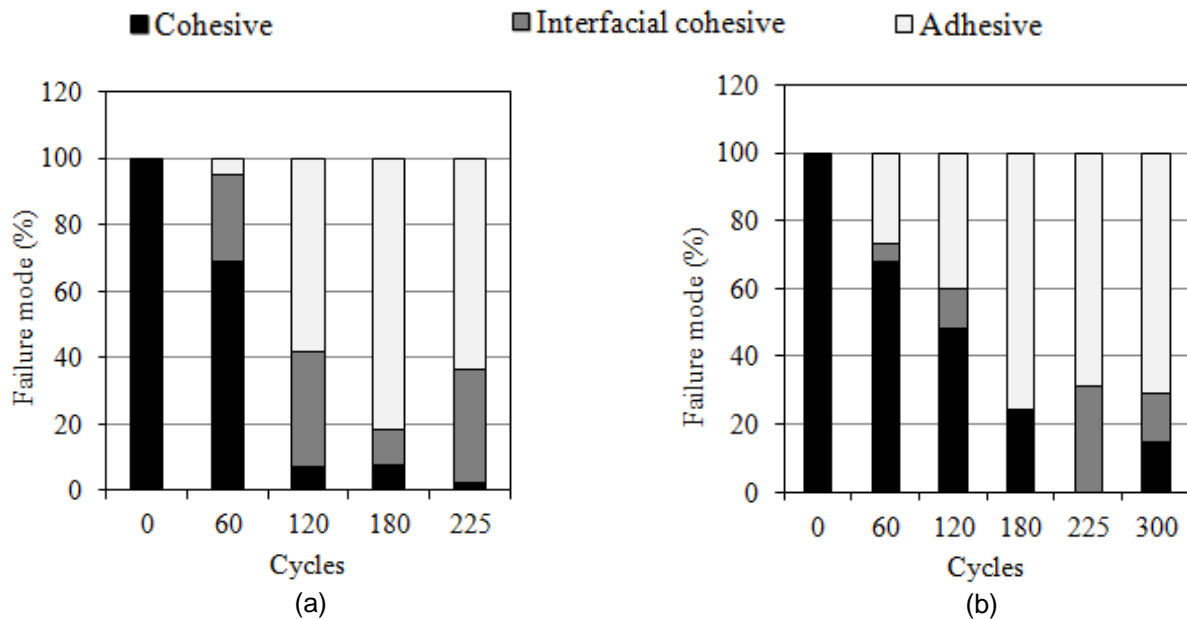
Figure 17. Contribution of each failure mode for the debonding behaviour: (a) HT exposure; (b) FT exposure.

5 CONCLUSIONS AND RESEARCH NEEDS

The paper provided an overview on some of the most relevant environmental agents and their effects on the durability of external FRP-strengthened concrete and masonry structures. The results of a comprehensive series of water immersion tests and hygrothermal tests on GFRP-strengthened masonry recently carried out at University of Minho were presented and discussed.

As for the ageing tests about the effect of water immersion on the bond performance of GFRP-strengthened masonry bricks, the following conclusions could be derived:

- GFRP coupons suffered a strength reduction higher than bricks and epoxy resin due to the reduction in the mechanical properties of epoxy resin and the degradation of the fiber-resin interface.
- The final pull-off strength decreased considerably, but these results showed a different degradation trend when compared to results from shear bond tests. A cohesive failure mode was found in all tests, but the fracture surface moved progressively from the brick to the brick-primer interface.
- Shear bond tests showed an increase in displacement capacity (slip) prior to failure with immersion time, while the bond strength and stiffness decreased. Also here, the fracture surface was inside the brick, but moving towards the brick-primer interface with time.
- Possible degradation trends were identified, although some trends did not seem completely consistent, therefore water immersion tests for longer periods are necessary to clearly identify trends and possible residual values.

With regard to the accelerated ageing tests on the combined effect of thermal cycling and moisture, the results obtained show that:

- The hygrothermal exposures caused some degradation to epoxy resin and GFRP coupons, but not to bricks. In particular, the HT exposure caused generally higher degradations in components.

- Reinforcement delamination was observed at the GFRP-brick interface after exposure to combined thermal cycling and moisture. The detached areas increased with the number of cycles. The detachment was larger in specimens exposed to HT conditions.
- A progressive degradation of bond strength was observed in both exposure types, but more severe in the specimens subjected to HT cycles.
- The failure mode changed progressively from cohesive (in the brick) to adhesive (at the GFRP-brick interface) with exposure time, for both exposures.
- The interfacial degradation can be attributed to the thermal incompatibility inside the composite system and at the GFRP-brick interface.

From the conclusions listed above and considering the gaps in knowledge identified in literature, a few significant research needs are proposed here:
- Development of standardized accelerated environmental test procedures (and connection with results from real time tests).
- Expansion of real time durability tests.
- Definition of accurate environmental reduction factors for design purposes.
- Validation of reliable in-situ monitoring techniques and procedures to assess degradation levels.

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