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Bond strength's degradation of GFRP-concrete elements under aggressive exposure conditions

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HIGHLIGHTS

- The durability of GFRP-concrete bonded specimens was addressed.
- Effects of water and F-T cycles on the strength of bonded joints were studied.
- Artificial ageing protocols were used to simulate long-term degradation of bond.
- Shear strength of adhesive joint decreases significantly with the immersion time.
- Comparison between the artificial ageing and naturel ageing was made.

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ABSTRACT

An experimental study was performed to determine the environmental durability of adhesive bond between Glass Fibre Reinforced Polymer pultruded profile and concrete. The specimens were subjected to two artificial ageing regimes before being tested to failure. Some specimens were exposed to 50 freeze-thaw cycles and other were immersed in water at 45 °C for varying time periods. Furthermore, some specimens were exposed to natural outdoor conditions to up to one year. The water effect on the adhesion of the joints was found to be significant, especially at longer immersion times; the shear strength of push out specimens reduced by 71% after ten months of immersion and the failure mode was shifted from cohesive within concrete to adhesive at the adhesive/concrete interface. The results also show that the ultimate shear strength deteriorated measurably during freeze-thaw cycling, about 56% of reduction was obtained after just 50 cycles, while after one year of outdoor exposure, the shear strength dropped by 27.7% compared to those without ageing. The study suggests that the ageing tests can provide information about the effects of environmental agents in the durability of bonded structures but cannot estimate the real amount of deterioration in real service life of such structures.

1. Introduction

In recent years, structural bonding has become an alternative assembly technique widely used to make hybrid structures which have high mechanical performance in civil engineering. The assembly of materials by bonding has several advantages over other systems such as riveting or welding [1,2]. Bonding prevents any damaging machining process such as drilling, heating and grinding, and allows the construction of lightweight structures where the additional weight due to bonding is very limited compared to the weights of the rivets or of the weld seams.

The current applications of bonding mainly concern the repair and reinforcement of damaged and ageing structures by bonding of composite plates to beams and wrapping concrete columns with composite jackets [3–7]. However, during the last years, association of GFRP (Glass Fibre Reinforced Polymer) pultruded profiles with concrete slabs in hybrid structural elements by an adhesive bonding joint showed great potential in construction area due to its advantages in economic and mechanical terms [8]. GFRP profiles present many advantages including their high strength-to-weight ratio, low self-weight, high durability, corrosion resistance and low production cost [8–13]. Despite their many advantageous properties, they present some disadvantages such as low flexural stiffness, low elasticity to shear moduli ratio and low resistance to concentrated loads [8,10,14,15]. In this way, the combination between GFRP pultruded profiles and concrete slabs allows to overcome these limitations and leads to a new hybrid beam more stiffer and stronger than a GFRP profile or concrete slab alone. This type of bonded hybrid structures has been the focus of numerous studies in the past 15 years [8,13,16]. But, the up to date research

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has focused mostly on the initial mechanical properties and on the instantaneous or short-term behaviour of hybrid beams. The long-term behaviour of these beams when subjected to real weathering was not thoroughly investigated. It seems therefore essential to improve the knowledge on the mechanisms of ageing and durability of these bonded structures to ensure the safety and predict their useful life in real environmental conditions.

Therefore, the experimental study described herein is meant to increase the knowledge and understanding of the effects of different environmental agents such as water, moisture and freeze-thaw cycling on the behaviour, load carrying capacity and bond strength of GFRP-concrete bonded assemblies. The main objective is to determine the suitability and validity of using epoxy resins as assembly technique to bond concrete elements to GFRP profiles in harsh environmental conditions. To this aim, the environmental durability of GFRP-concrete bonded assemblies was evaluated experimentally using different ageing tests (immersion in water at 45 °C for different time spans, exposure to freeze thaw cycles). Mechanical characterizations were carried out on control and exposed specimens of both materials and bonded assembly, in order to evaluate the degradation and damage of the mechanical properties of each material and of the bonded assembly after exposure to different ageing conditions. The performance of the conditioned samples was also compared with that of naturally aged samples (outdoor exposure).

2. Literature review

To date, there have been numerous published studies on the environmental durability of the adhesive bond between FRP (Fibre Reinforced Polymer) and concrete or steel [3,5–7,17–19]. The available studies were performed using small scale specimens subjected to artificial ageing conditions such as single-lap shear or peel, double-lap shear and small-scale beam [3,5–7,17–19]. However, given the vast number of possible combinations between the different environmental conditions, materials type (concrete, steel or GFRP), adhesive formulations and mechanical tests, the mechanism of ageing and the effects of some environmental factors (temperature, humidity, UV…) may possibly not be the same for all bonded assemblies. Moreover, there are no standards specifying the environmental conditions and the ageing tests that can be used to study the durability or to estimate the service life of bonded assemblies under different climates. The ageing tests proposed in the literature were a matter of compromise based on individual judgements that were valid for particular circumstances and applications. Given the numerous differences among these studies, it is difficult to draw general conclusions from them, but some common findings are bold and can be presented as follows.

Moisture diffusion, which can take the form of humidity, liquid water or de-icing salt solutions, is one of the main factors that affect bonded elements durability and therefore shorten their useful life [6,17,20–22]. It was shown that, in an aqueous environment, the diffusion of moisture into a bulk adhesive leads to physical and chemical deterioration of the adhesive such as plasticisation, swelling and hydrolysis process causing a reduction in the adhesive's mechanical properties [17,23–27]. On the other hand, the glass transition temperature of adhesive is either improved [17] or even reduced [17,21,28] by the hydrothermal ageing procedures that employ wet-dry cycles and immersion tests. Concerning the bonded interfaces, damage and strength degradation caused by the ingress of water (even small amounts) into the interfacial region between substrate and adhesive was often found to be significantly larger than that of the bulk adhesive [20,26,27,29]. Furthermore, there were also significant changes in failure modes recorded in the literature, where the cohesive failure within the adhesive or substrate shifted to adhesive or/and cohesive failure near or at the interface substrate/epoxy [3,4,6,21,30]. This decrease in bond strength was explained by the moisture diffusion into the adhesive layer of bonded joints through micro-cracks near to the interface between substrate and epoxy, capillary processes via gaps formed in the joint during the bonding process or through the porous substrate such as concrete. Once moisture inside, the water molecules accumulate in the pores and voids at the interface and into the adhesive layer. In this way, water molecules may degrade the adhesive in a reversible manner by plasticisation and swelling, or in an irreversible manner by hydrolysis and cracking. Moreover, it was also found that the presence of water at the interface led to the development of osmotic pressure at the bonded interface. This osmotic pressure can cause a large debonding zone and weaken the intermolecular adhesion bonds (chemical bonds) at the substrate/adhesive interface [26,27,31].

In what concerns the effects of curing conditions on the thermal and mechanical properties of epoxy adhesives and their durability, researchers have carried out extensive studies aimed at investigating the behaviour and the properties of cold-curing or low-temperature adhesives, generally used in civil engineering applications, under different curing and ageing conditions. It was shown that the physical and mechanical properties of epoxy resins strongly depend on the cure conditions, such as time and temperature of cure [32–35]. Unless the cure process is completed by post cure the glass transition temperature and modulus will be lower than predicted [32–35]. In fact, the low curing temperatures considerably decelerate the curing process and consequently the rate of development of thermal and mechanical properties of adhesive, whereas the elevated curing temperatures (post-cure) increase the cross-linking density of adhesive and help to achieve higher level of properties [32,34,36]. Moreover, the influence of curing conditions on the strength development of adhesively bonded joints has also been studied by several authors [33,36]. The results obtained from the mentioned studies showed that the strength of an adhesive joint depends on cure time and temperature. As both time and temperature increase, the epoxy bond strength increases [33,36]. However, the results of artificial ageing (immersion in water or salt water at different temperature levels) and natural ageing (outdoor exposure) tests performed on epoxy adhesive specimens cured under different conditions (cold, or hot/post-cured), obtained in different studies [37–39], showed that the environmental agents such as water, moisture and UV radiation, affect the mechanical behaviour of the adhesives and produce Tg reductions. The variation of properties was attributed to plasticization effects due to water uptake during outdoor ageing or immersion test [37–39].

Another very important factor that can alter the performance of bonded joints is the thermal cycles exposure such as freeze–thaw cycling. Due to the fact that the bonded elements may be exposed to cold climate in some regions, a large number of studies have focused on this issue [3,6,7,19,40]. A wide variety of FRP materials were used in these studies, as well as various types of adhesives. In addition, the mechanical properties of concrete substrates differed significantly in these studies. Each of the studies used a different type of freeze-thaw cycling procedure repeated for a different number of cycles. However, it has been seen that the frost-induced damage under cyclic F–T load has two main consequences in some cases: degradation of bond strength [3,6,7,12,19] and changes in failure mode [7]. A common conclusion can be drawn from these studies is that the freeze-thaw cycles alter the mechanical properties of bonded joints. The decrease in the ultimate strength was explained by the internal cracking of concrete near to the free surfaces (in contact with air) and by the weakening of the concrete surfaces which lead to the degradation of concrete properties [6,7,41].