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Investigations on the ageing of GFRP rebar-concrete bond under sustained load for a high strength concrete

Noémie Delaplanque^{a,b}, Sylvain Chataigner^{a*}, Marc Quiertant^{c,d}, Karim Benzarti^e, Arnaud Rolland^f, Xavier Bourbon^b, Xavier Chapeleau^g, Ludwig Battais^a, Laurent Gaillet^a

^aMAST/SMC, Université Gustave Eiffel, Allée des Ponts et Chaussées, 44344 BOUGUENAI, France

^bAndra, 1-7 Rue Jean Monnet, 92298 CHATENAY-MALABRY, France

^cMAST/EMGCU, Université Gustave Eiffel, 5 Boulevard Descartes, 77454 CHAMPS-SUR-MARNE, France

^dInstitut de Recherche, ESTP, 28 Avenue du Président Wilson, 94230 CACHAN, France

^eNavier, Université Gustave Eiffel, 5 Boulevard Descartes, 77454 CHAMPS-SUR-MARNE, France

^fDTer Ouest, Cerema, 9 Rue Viviani, 44200 NANTES, France

^gCOSYS/SII-I4S, Université Gustave Eiffel, Inria, Allée des Ponts et Chaussées, 44344 BOUGUENAI, France

Abstract

FRP rebars offer notable advantages over steel rebars for internal concrete reinforcement. However, since the technique is relatively recent, further durability investigations are needed to better understand degradation mechanisms and provide optimized safety coefficients. While several researchers have explored the durability of FRP rebars, only few have examined the evolution of the FRP-concrete interfacial bond. This study aims to present investigations into the durability of the bond between GFRP rebars and high-strength concrete. The GFRP-to-concrete bond behaviour was experimentally studied, focusing on the combined effects of thermally accelerated ageing in alkaline environment and sustained loading. First, the pull-out sample geometry and initial characterizations of the interface will be introduced. Then, the ageing protocol will be presented. In this protocol, some pull-out samples were subjected to sustained load in combination with alkaline ageing. The evolution of the residual interfacial properties over ageing is finally presented, allowing for a discussion on the influence of sustained load on the aging process.

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* Corresponding author. Tel.: 0033(0)2 40 84 56 57.

E-mail address: sylvain.chataigner@univ-eiffel.fr

1. Introduction

One of the main advantages of GFRP (Glass Fiber Reinforced Polymer) reinforcing bars (rebars) is their non-corrosive behaviour. However, it is well-known that these rebars may be sensitive to alkaline environment and load, AFGC (2023). Consequently, many researchers have investigated the durability of GFRP rebars in alkaline environment using accelerated ageing protocols under controlled laboratory conditions. These accelerated conditions generally involve immersing the rebars in an alkaline solution at high temperature (up to 60°C), as reported for instance by AFGC (2023), Rolland *et al.* (2021) and D'antino *et al.* (2018). Additionally, other authors, such as D'Antino *et al.* (2019), have also investigated creep mechanisms for such rebars. More recently, the coupling of both load and alkaline environment has also been investigated by Feng *et al.* (2022) and Delaplanque *et al.* (2023a), and it has been demonstrated that this can lead to an acceleration of the damage.

To ensure optimal mechanical performance of the final reinforced concrete element, it is also essential to verify the bond strength between the GFRP rebar and concrete. This is generally assessed through pull-out investigations, Yan *et al.* (2016), or bending tests, Gudonis *et al.* (2014). While bending tests offer a more accurate representation of real on-site bond conditions, they are considerably more complex to execute. Therefore, the existing literature has mostly relied on pull-out investigations to gain insight into the FRP to concrete interface behaviour, Baena *et al.* (2009), Solyom *et al.* (2021). It is worth noting that the existing literature predominantly focuses on normal-strength concrete (compressive strength less than 70 MPa), with limited studies on the bond between FRP rebars and high-strength concrete (compressive strength higher than 70 MPa), Saleh *et al.* (2019).

Several studies have investigated the aging behaviour of the interface between FRP reinforcement and concrete. Gravina *et al.* (2020) and Ali *et al.* (2019) have provided comprehensive literature reviews of research works based on pull-out test campaigns, highlighting a significant dispersion in experimental results. This dispersion arises from the variability of the materials and the absence of standard accelerated aging protocols for pull-out specimens. Most authors observed losses of 8 to 15% in the pull-out strength of FRP/concrete specimens after several months of aging in an alkaline solution or in water at 50 or 60°C, Chen *et al.* (2007) and Robert *et al.* (2010). Few researchers reported even larger strength losses of up to 40%, Benmokrane *et al.* (2017), Zheng *et al.* (2020). Under similar conditions, another study observed an initial increase in pull-out strength over the first 4 months of aging, attributed to an improvement in concrete properties associated with the progression of the cement hydration process, followed by a subsequent decrease in strength due to the degradation of the GFRP/concrete interface. Remarkably, after 240 days of exposure, the residual pull-out strength was almost identical to the initial level of the unaged specimens, Rolland *et al.* (2015). To gain deeper understanding of FRP-to-concrete bond ageing, further durability studies are needed.

Similar to the environmental ageing of the FRP rebar, an applied load may also affect the FRP-to-concrete interface. Some authors, like Weber (2008), have investigated the creep behaviour of the interface. However, to the author's knowledge, the combined effects of environmental ageing and sustained load on GFRP/concrete bond performance have not been previously explored.

This paper presents a dedicated study aimed at investigating the durability of GFRP-to-concrete interface under combined environmental/mechanical ageing, utilizing pull-out tests and specific ageing protocols. The concrete under study is high strength concrete with a compressive strength exceeding 80 MPa, for which limited data on the bond properties with FRP rebars are available. The first part of this article will provide a comprehensive description of the materials, samples and initial pull-out investigations. The second part will detail the ageing campaign conducted under accelerated ageing conditions (immersion in alkaline solution at 60°C), both with and without sustained load.

2. Initial characterization of the FRP rebar-to-concrete interface (unaged state).

2.1. Studied materials

This study focuses on FRP rebars comprised of a vinyl ester matrix reinforced with glass fibers (GFRP), which were manufactured through pultrusion. These rebars had a diameter of 10 mm, and their surface was sand-coated as shown in Figure 1. The main properties as supplied by the manufacturer are given in Table 1.

Tensile tests were conducted on these GFRP specimens by Delaplanque *et al.* (2023) in a previous study, yielding an average tensile strength of 1128 MPa and an average tensile modulus of 58 GPa, considering the cross-sectional area specified by the manufacturer. These experimental values significantly exceed the guaranteed levels.

Table 1. Key properties of the GFRP reinforcement supplied by the manufacturer.

Rebars	Nominal diameter (mm)	Effective area (mm ²)	Guaranteed tensile strength (MPa)	Modulus of elasticity in tension (GPa)
GFRP	10	71	900	46

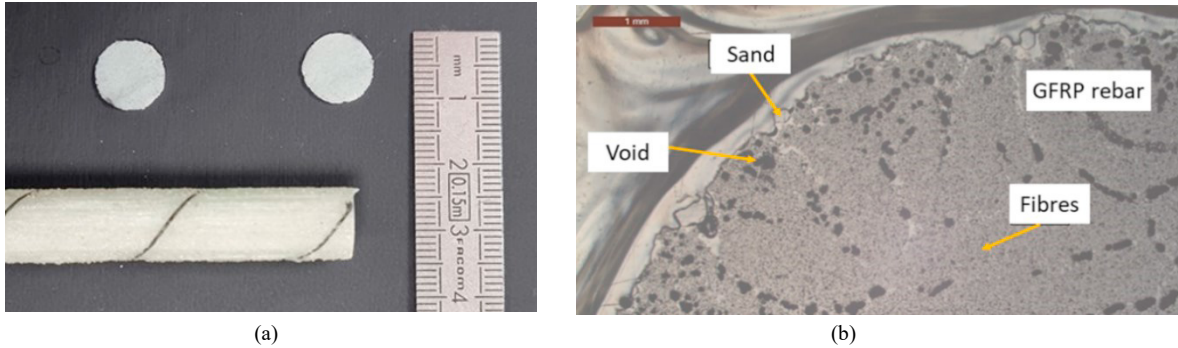


Fig. 1. Photo (a) and microscopic observation (b) of the GFRP rebar studied.

The selected concrete was a high-strength formulation based on a CEM III cement, as outlined in Table 2. The gravel used was sourced from the quarry of Gray (Haute-Saône, France). Following fabrication, the samples were immersed in water for 2 months and then dried in air for 1 month. The extended immersion period of 2 months was chosen to accommodate the slow hydration rate characteristic of CEM III.

Table 2. Composition of the high-strength concrete

Component	Quantity (kg/m ³)
Cement (CEM III-A)	375
Sand 0/4	810
Gravels 4/14	1130
Water	150
Superplasticizer (0.88 %)	3.3

2.2. Sample description

The interface properties were characterized using the pull-out test method as recommended by ACI 440.3R-12 (2012) and AFGC (2023). Cylindrical samples were selected following the approach of Rolland *et al.* (2015). However, to reduce the global volume of the test specimens, we used smaller cylinders of diameter 110 mm. To ensure representative results favouring pull-out failure modes over concrete splitting, internal steel reinforcement was incorporated and a bonded length of 4 times the FRP rebar diameter was adopted due to the high concrete strength. It should be noted that this bonded length is slightly shorter than the traditionally adopted value of 5 or 6 times the FRP rebar diameter.

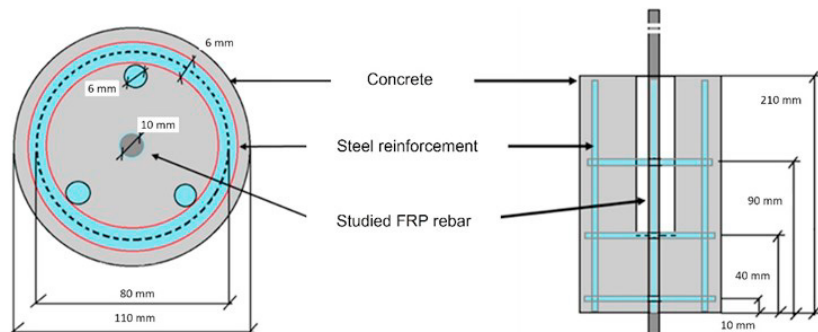


Fig. 2. Scheme of the tested pull-out samples geometry and steel reinforcement details.

Figure 2 illustrates the sample’s geometry. The concrete cylinder is 210 mm high, and the tested rebar is 1 m long. The steel reinforcement was designed according to the recommendations from ISO 10406-1, 2008. A concrete cover of 12 mm and a steel reinforcement ratio of 150 kg/m³ were used to prevent the samples from splitting during the tests.

2.3. Experimental testing procedure

The mechanical tests were conducted on a hydraulic machine at constant displacement rate (0.5 mm/min) until failure. A specific steel frame was used for the tests (Figure 3a). The loaded end of the FRP rebar was blocked with adapted hydraulic grips. During the test, the applied force and the displacements at both the loaded end and the free end of the FRP rebar were measured.

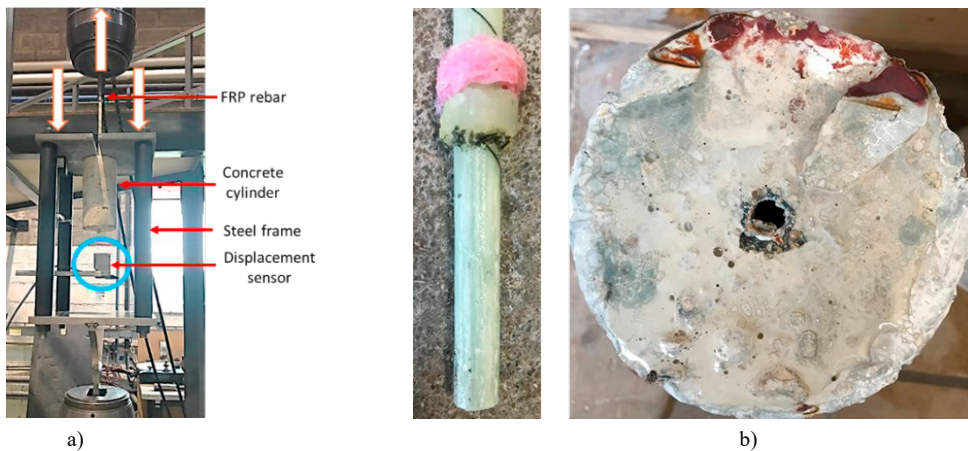


Fig. 3. Pictures of the pull-out test setup (a), and the pull-out specimens after failure.

2.4. Initial characteristics before ageing

Three samples were tested to determine the initial characteristics of the interface. The typical pull-out failure mode is shown in Figure 3b. The average shear stress at the interface was determined and is plotted against the applied displacement at the loaded end and the measured displacement at the free edge in Figures 4a and 4b, respectively.

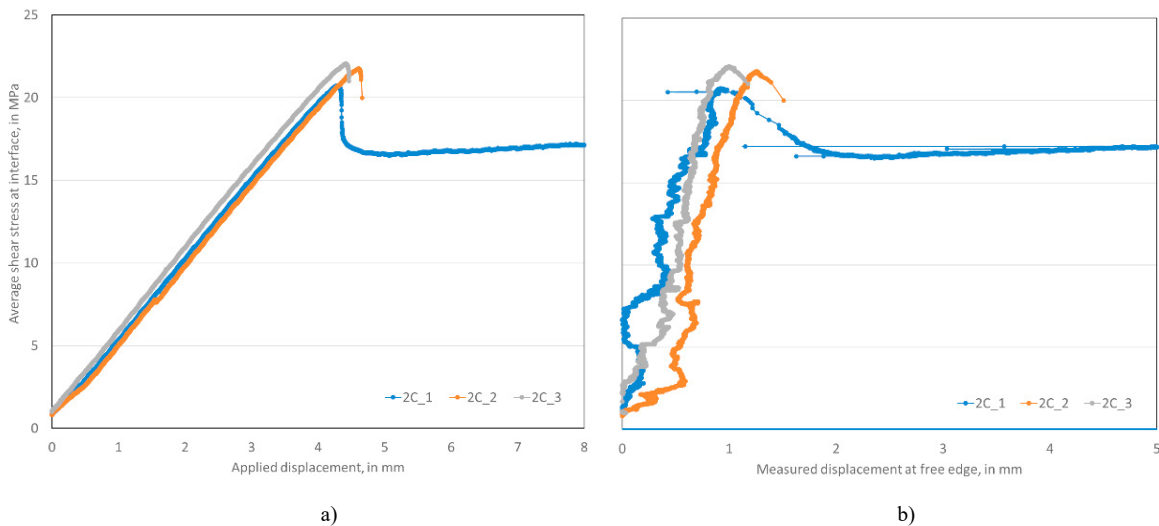


Fig. 4. Average shear stress at the interface vs. applied displacement (a) and measured displacement at free edge (b) for the three initial samples

It can be observed that the average shear stress reaches a maximum before stabilizing at a plateau. This maximum value, referred to as the interface shear strength, averaged 21.5 MPa with a rather low dispersion of 0.6 MPa. This is significantly higher than the minimum resistance of 7.5 MPa required by AFGC (2023), and comparable to the shear strengths obtained for FRP/high-strength concrete interface by Saleh (2019). This corresponds to an applied stress level in the rebar of 344 MPa, which is approximately 30% of the tensile strength determined for the same rebars.

The concrete compressive strength was characterized through tests on three concrete cylinders cast at the same time as the pull-out samples and subjected to similar curing conditions and history. An average compressive strength of 99.9 MPa was obtained with a dispersion of 1.78 MPa.

3. Investigations on the durability of the GFRP-to-concrete bond

3.1. Ageing protocols

To investigate the durability of the GFRP-to-concrete interface, two different ageing protocols were adopted, based on those developed by Delaplanque *et al.* (2023a) for FRP bar durability. Both ageing protocols were conducted in an alkaline solution to increase the mobility of alkaline ions. The selected solution consisted of 0.1 mol/L (4 g/L) of sodium hydroxide (NaOH) and 0.5 mol/L (28 g/L) of potassium hydroxide (KOH), with a pH between 12 and 13 as described by Rolland *et al.* (2015). To further accelerate the degradation mechanisms, the solution was heated at 60°C. Higher temperatures were avoided to stay significantly below the glass transition temperature of the FRP rebar, preventing extensive rebar creep. Additionally, this precaution helped avoid inducing premature concrete phenomena that would not be representative of real ageing situations.

Some samples were not submitted to any load during ageing (named VSC), while others were submitted to 40% of the initial bond strength (named VAC), which corresponds to a tensile stress of 138 MPa in the GFRP rebar. This stress level is 12% of the experimental tensile strength, and 15% of the guaranteed tensile strength. The unloaded samples (VSC) were simply disposed in heating tanks in a vertical position, immersed in the same alkaline solution. The solution level was monitored throughout the ageing process to ensure that at least 40 mm of the concrete cylinder (corresponding to the bonded length) remained in the solution.

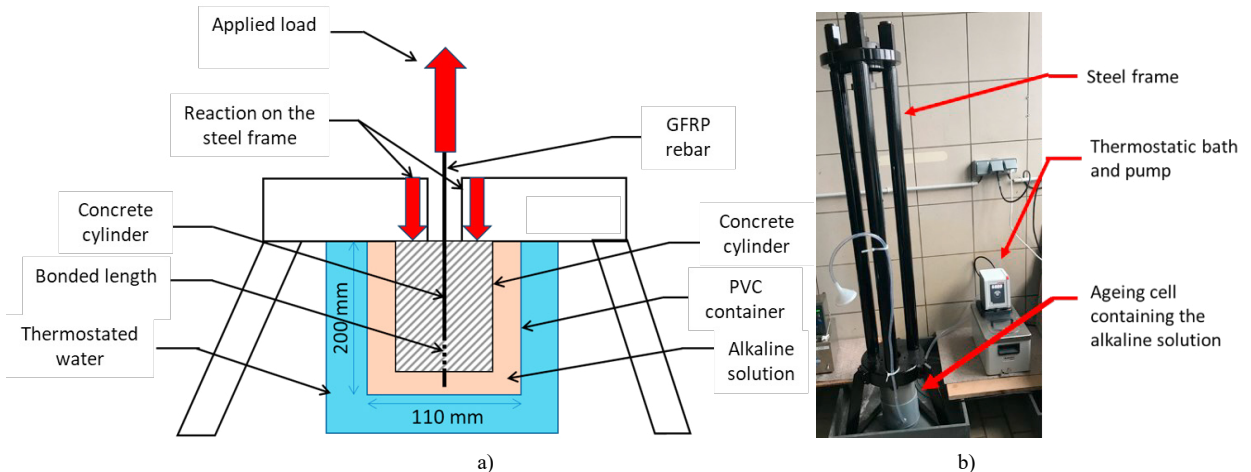


Fig. 5. Scheme of the ageing protocol under load (a) and picture of the steel frame used (b)

For the loaded samples (VAC), a specific experimental protocol was developed. Dedicated steel frames were employed to maintain a constant displacement at the top of the pull-out samples, as depicted in Figure 5. This was achieved using a hydraulic jack and specific anchorage systems. To ensure that the load did not deviate more than 5% from the initially applied load due to relaxation phenomena, it was continuously monitored with an annular load sensor. During the ageing process, it is worth noting that significantly more relaxation was observed in the pull-out samples compared to GFRP tensile samples, at similar load levels. This observation suggests that the interface itself and/or the concrete play a significant role in the overall relaxation phenomenon.

Similar to the unloaded samples, the concrete part of the loaded sample was immersed in the alkaline solution maintained at 60°C thanks to a circulating surrounding water heater using a thermostatic bath. Throughout the aging process, it was ensured that the solution level remained above the bonded length of the FRP rebar, i.e., 40 mm. The maximum ageing duration was 90 days, and for each series of pull-out samples, concrete cylinders were cast and exposed to similar ageing conditions (excluding load), enabling determination of the concrete compressive strength. To enhance the robustness of the study, samples and measurements were triplicated.

3.2. Results

The results obtained for the average shear strength τ_{\max} and concrete compressive strength f_c are gathered in Table 3. No change in the failure mode was observed, and the force-displacement curves remained consistent with the initial investigations. To facilitate result interpretations, a normalized shear resistance was also determined ($\tau_{\max}/f_c^{1/2}$), following the strategy outlined by Baena *et al.* (2009) and Saleh *et al.* (2019). Sample names correspond to: xC the number of the concrete casting, VAC the samples aged under load, and VSC the samples aged without load.

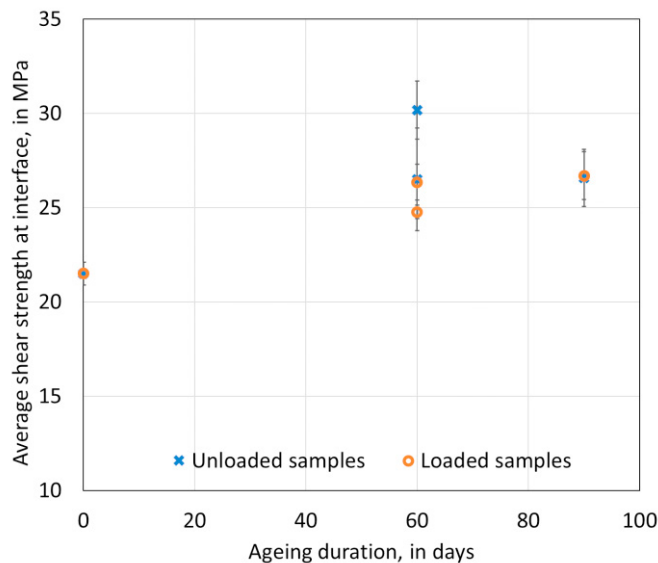


Fig. 6. Evolution of the average shear strength of the interface during ageing with and without load

The obtained shear strengths closely align with those reported by Saleh *et al.* (2019) who determined bond strengths in high-strength concrete ranging between 20 and 30 MPa for a bonded length of 5 times the rebar diameter. A slight increase in average shear strength was observed after ageing for both conditions, with or without load. It is important to note that there was no significant difference between loaded and unloaded samples across the studied durations (60 and 90 days) in Figure 5.

To evaluate the variability of the raw concrete, two batch of samples were used, labelled ‘2C-1, 2, 3’ and ‘2C-Bis-1, 2, 3’. A slight difference in concrete compressive strength was observed between the two batches indicating an additional effect of ageing conditions on properties evolution, although the shear strength in both cases showed less variation. When studying the normalized shear resistance in Table 3, a slight increase was observed after 60 days of ageing compared to the initial value (around 20% increase), with no further clear evolution between 60 and 90 days. This increase in normalized shear resistance could primarily be ascribed to the progression of the cement hydration process and subsequent improvement in mechanical properties at the GFRP/concrete interface during exposure (including a possible confinement effect of the rebar). Furthermore, the post-curing of the GFRP rebar at 60°C may also contribute to this trend. In a previous study, Delaplanque *et al.* (2023a) noted that this batch of GFRP rebars is initially partially cured, with the crosslinking process advancing steadily during immersion in the alkaline solution at 60°C.

Based on these results, longer exposure duration may be necessary to fully assess the consequences of interface degradation.

Table 3. Ultimate interfacial shear strength, concrete compressive strength and normalized shear resistance, for various ageing durations

Sample	Ageing days in alkaline env. in days	Average shear strength, in MPa	Average shear strength τ_{max} , in MPa	Standard deviation on shear strength in MPa	Concrete compressive strength $f'c$, in MPa	Standard deviation on concrete compressive strength, in MPa	Normalized shear resistance, $\tau_{max}/\sqrt{f'c}$
2C_1	0	20.70	21.50	0.60	99.90	1.78	2.15
2C_2	0	21.80					
2C_3	0	22.10					
2C_2VAC_1	60	24.27	24.77	0.36	80.44	1.41	2.76
2C_2VAC_2	60	25.13					
2C_2VAC_3	60	24.90					
2C_2VSC_1	60	31.88	30.17	1.54	78.98	4.57	3.39
2C_2VSC_2	60	28.15					
2C_2VSC_3	60	30.49					
2C_2VAC_Bis_1	60	26.96	26.35	0.95	99.14	11.9	2.65
2C_2VAC_Bis_2	60	27.08					
2C_2VAC_Bis_3	60	25.00					
2C_2VSC_Bis_1	60	30.29	26.49	2.72	99.14	11.9	2.66
2C_2VSC_Bis_2	60	24.07					
2C_2VSC_Bis_3	60	25.11					
4C_3VAC_1	90	26.82	26.69	1.27	107.86	7.5	2.57
4C_3VAC_2	90	28.19					
4C_3VAC_3	90	25.07					
4C_3VSC_1	90	28.38	26.57	1.52	107.86	7.5	2.56
4C_3VSC_2	90	24.67					
4C_3VSC_3	90	26.66					

4. Conclusion

In this study, specific pull-out sample geometry was adopted to accommodate the high strength concrete, and using 110 mm diameter concrete cylinders was necessary due to geometrical constraints. This allowed us to investigate the GFRP-to-concrete interface and obtain an initial shear strength value of 21.5 MPa, consistent with values reported in the literature, such as in Saleh *et al.* (2019). The observed interfacial behaviour exhibited a plateau value, indicating good softening properties of the interface without further concrete damage (cracking).

Following this initial characterization, investigations were conducted under accelerated ageing conditions (alkaline solution and 60°C), to study potential degradation of the GFRP/concrete interface with or without applying a combined tensile load on the GFRP. For ageing under applied load, a specific setup was developed, enabling the application of a load level corresponding to 40% of the initial interfacial shear strength. This value may be subject to adjustment in future investigations to accelerate or enhance the studied phenomena.

Regarding ageing without load, a slight improvement in the interface shear strength was observed, partly attributable to concrete curing. Nevertheless, when considering normalized shear resistance values, a 20% improvement was still observed after 60 days of ageing. Both a confinement effect of the bar and the post-curing process of the GFRP at 60°C may contribute to this trend.

In the case of ageing under load, no significant difference was noticed in terms of residual shear strength compared to samples aged without loads. Overall, no degradation of the interface attributable to the ageing process was detected throughout this tests campaign.

In future investigations, it would be valuable to analyse the interface behavior more locally, for instance through local strain monitoring with distributed optical fiber sensors, as proposed by Rolland *et al.* (2020). However, it is crucial to ensure that ageing does not affect the monitoring sensors, a topic that is currently under investigations, Delaplanque *et al.* (2023b).

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