

Effect of the elevated temperatures on the mechanical behaviour of PBO-FRCM systems

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Abstract – Over the last two decades, fabric reinforced cementitious matrix (FRCM) materials started to be used as a strengthening system in a wide variety of structural applications, especially where their fire-related advantages may offer an alternative to traditional composite materials (e.g. FRP materials). However, there is a major gap in the knowledge of FRCM composites: the lack of information about their mechanical response at elevated temperature. The main objective of this paper is to provide further insights about the influence of elevated temperatures on the mechanical properties of a Polypara-phenylene-benzo-bisthiazole (PBO) FRCM system. Direct tensile (DT) tests and single lap direct shear tests (DS) were performed respectively on PBO FRCM specimens and PBO FRCM-concrete prisms, for temperatures ranging from 20 °C up to 300 °C. Specimens were first heated up to the target temperature, and then loaded up to failure at ambient temperature. The results obtained show that both tensile and bond strength suffer relatively low reductions up to 200 °C. For increasing temperature, the degradation of the mechanical properties was more pronounced: at 300 °C, the reductions of tensile and bond strength were 65% and 40%, respectively.

I. INTRODUCTION

An important topic of civil engineering that has been analysed during recent years concerns the strengthening of structures built with traditional materials, most often reinforced concrete (RC) and masonry. Moreover, the needs of higher speeds of construction and the increase functionality demands combined with the durability problems associated with traditional materials had a stimulating effect in the development of innovative structural solutions using composite materials such as fabric reinforced cementitious matrix (FRCM) [1–3]. These new materials are characterized by a high strength-to-weight ratio, lightness, corrosion resistance and low life cycle costs. Additionally, FRCMs present some properties

that can be useful in a fire scenario; indeed, they show better burn-through resistance than steel, providing a barrier against smoke, flames, toxic fumes, and they are also good isolator, thus allowing to slow down the spread of fire from room to room. Moreover, FRCMs present several fire-related advantages over traditional composite materials (e.g. fibre reinforced polymer (FRP)) such as breathability, non-flammability and incombustibility owing to the inorganic nature of their matrix [4]. However, one of the main drawbacks of using FRCM materials as a strengthening system in degraded concrete or masonry structures is their mechanical behaviour at elevated temperatures. Indeed, the strength, stiffness and bond properties of FRCM materials undergo marked reductions even when heated to moderately elevated temperature (200-300 °C), mainly due to the degradation of the fibre-to-matrix interface [5–10]. Despite the efforts made in the last years to study the mechanical behaviour at elevated temperature of this strengthening system, the understanding of many aspects is still very limited.

In this context, to design FRCM-RC members in structures likely to be submitted to fire, it is of utmost importance to determine: (i) the FRCM mechanical properties and (ii) bond laws at elevated temperatures. The present work presents an experimental investigation about the tensile and bond properties of a PBO (Polypara-phenylene-benzo-bisthiazole) FRCM system. First, mechanical characterization tests were performed on the constituent materials: (i) tensile tests on PBO fibers and (ii) flexural and compressive tests on cement-based matrix prisms. Subsequently, direct tensile (DT) and single lap direct shear (DS) tests were performed respectively on PBO FRCM specimens and PBO FRCM-concrete prisms over a temperature range from 20 °C to 300 °C. Specimens were first heated up to the target temperature and subsequently cooled by a natural process inside a thermal chamber. The aim of this work is to provide further insights about the variation with temperature of the residual mechanical properties of a PBO FRCM system, which is a key information for the design of FRCM-strengthened RC

structures exposed to elevated service temperatures or fire. In addition, the definition of temperature-dependent constitutive relationships and failure criteria can be used in thermo-mechanical simulations of FRCM-concrete members subjected to elevated temperatures.

II. EXPERIMENTAL PREPARATION

The FRCM system studied herein consisted of dry bi-directional PBO fibres (mesh grid of approximately 10×20 mm) embedded in a ready-mix cement-based matrix. The fibre material had a density of 1.56 g/cm^3 , with equivalent thickness in the longitudinal and transverse direction of 0.0455 mm and 0.012 mm , respectively. The mechanical properties of both PBO fibres and inorganic matrix were determined by means of material characterization tests following the recommendations defined in CNR-DT 215 and UNI EN 12190:2000 guidelines. The following material properties are listed in Table 1: matrix compressive strength (f_{cm}); matrix tensile strength (f_{tm}); PBO fibres tensile strength (f_t), PBO fibres elastic modulus (E_f) and PBO fibres failure strain (ϵ_{fu}).

Table 1 – FRCM constituent materials: average mechanical properties

FRCM system	f_{cm} [MPa]	f_{tm} [MPa]	f_t [MPa]	E_f [GPa]	ϵ_{fu} [mm/mm]
PBO fibres	-	-	3400.32	211.14	0.0018
Matrix	43.11	6.73	-	-	-

Concerning the PBO FRCM specimens used in the DT tests, they had dimensions of $40 \times 500 \times 6$ mm (width \times length \times thickness). It is worth mentioning that the width of the specimens was defined in order to accommodate four yarns. All the specimens were manufactured using a hand lay-up technique, which consisted of three main steps: initially, the first matrix layer (thickness of approximately 3 mm) was positioned on the plexiglass mould; then, the PBO fibres were slightly pushed inside the first matrix layer and; finally, the second matrix layer (thickness of approximately 3 mm) was positioned on the PBO fibres. The test setup used for the DT tests is illustrated in Figure 1. PVC tabs were bonded at both extremities of the specimens by means of an epoxy adhesive- this procedure aimed at guaranteeing that the load was transferred properly from the testing machine to the specimens. Furthermore, two linear variable displacement transducers (LVDT), with a measurement range of 50 mm, were placed on two opposite sides of the specimens with the objective of measuring the vertical displacements of the FRCM composite (cf. Figure 1). The average values obtained from the two LVDTs were used to compute the axial strain shown ahead in the text (cf. Figure 5). It is worth mentioning that the specimens were tested

under displacement control at a speed of 0.2 mm/min . For each target temperature, at least three tests were carried out.

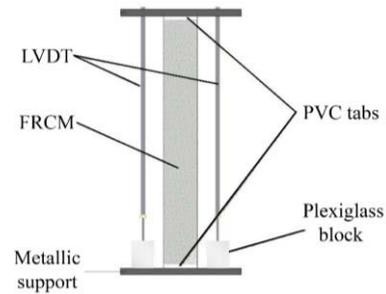


Figure 1 – DT test setup.

Concerning the DS tests, FRCM strips were applied on each side of the concrete prisms (dimensions of $100 \times 200 \times 400$ mm). The PBO mesh (comprising 4 yarns) was positioned between two 3 mm thick layers of cement-based matrix, forming a strengthening system with a total thickness of 6 mm. It is worth mentioning that, prior to the application of the FRCM system, the concrete surface was sandblasted in order to improve the bond between the FRCM and the substrate. Note that the bond length was approximately 300 mm and started at a distance of 30 mm from the loaded-end. Concerning the instrumentation, the slip at the loaded-end was measured using two LVDTs, with a measurement range of 50 mm (cf. Figure 2). The LVDTs reacted off a thin L-shaped aluminium profile that was placed on the bare fibres. In addition, as shown in Figure 2, aluminium tabs were bonded at the loaded-end of the fibres (by means of an epoxy adhesive) before connecting the specimens to the mechanical clamping system of the universal testing machine – this procedure aimed at ensuring a uniform load-distribution among the yarns. All the DS tests were performed until failure under displacement control at a speed of 0.18 mm/min – for each target temperature, at least three DS tests were performed.

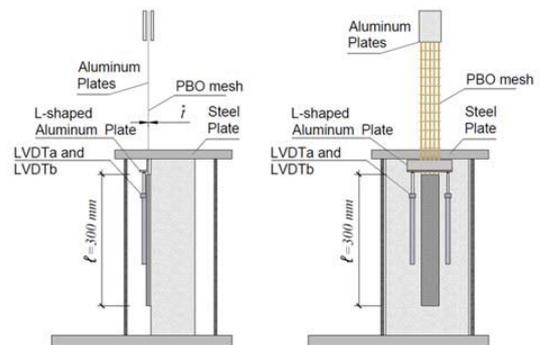


Figure 2 – DS test setup.

Before being tested, all the specimens were subjected to heating-cooling regimes at temperatures ranging from $20 \text{ }^\circ\text{C}$ to $300 \text{ }^\circ\text{C}$ (average heating rate of 2°C/min).



Figure 3 – Heating procedure: placement of the specimens.

The temperature at the mid-depth of the FRMC composite as well as that at the FRMC-to-substrate interface was monitored by means of thermocouples type K, which were installed during the casting. Once the desired temperature at the FRMC/concrete substrate interface was attained, the furnace was switched off and the specimens were left cooling down naturally in the furnace – this procedure aimed at avoiding any thermal shock of the materials. Figure 4 shows, for two representative temperatures (i.e. 100 °C and 200 °C), the temperature vs. time curves of the specimens (measured at the interface FRMC-to-substrate) and the air inside the thermal chamber.

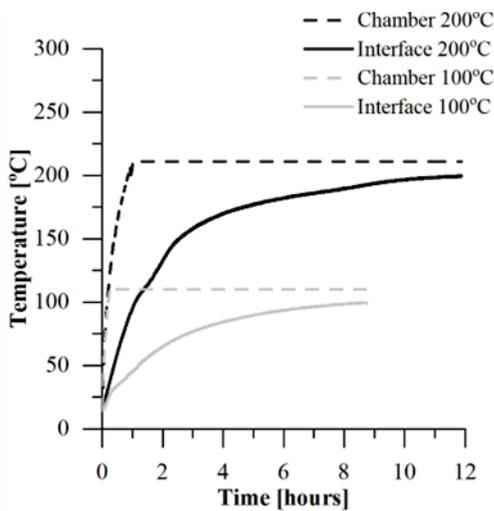


Figure 4 – Temperature vs. time curves of the specimens and the air inside the furnace.

III. EXPERIMENTAL RESULTS

The results obtained from the experimental tests confirmed that both tensile and bond properties undergo significant reductions even at moderately elevated temperatures; moreover, it was possible to quantify such degradation. Figure 5 presents the tensile stress vs. axial strain curves of one representative PBO FRMC specimens for each temperature tested. It is worth mentioning that the tensile stress was computed as the ratio between the applied load and the cross-sectional area of the fibres (width × longitudinal thickness). In this context, the width and the thickness of the PBO reinforcement were taken as 40 mm and 0.0455 mm; respectively. As shown in Figure 5, for the range of temperature considered in this study, all the PBO FRMC composites presented the typical strain-hardening behaviour characterised by three different stages: I stage - uncracked, II stage - crack development and III stage - cracked. The average values of the cracking stress (i.e. stress at the end of stage I), σ_{cr} ; tensile strength (i.e. peak stress), σ_u ; and corresponding failure strain ϵ_u are listed in Table 2. In addition, Figure 6 shows the normalised tensile properties reductions with temperature.

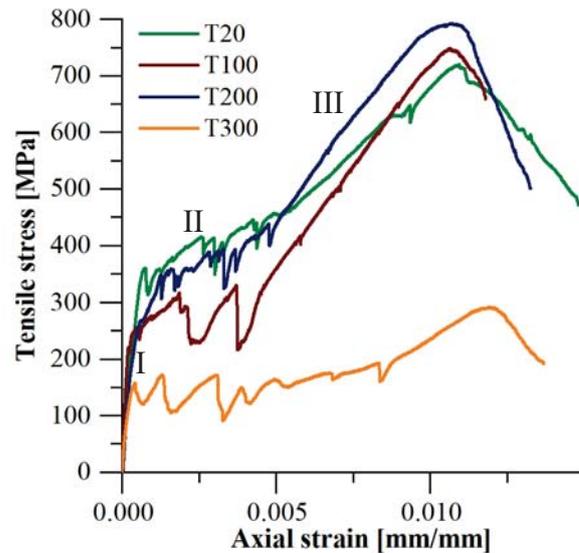


Figure 5 - Representative tensile stress vs. axial strain curves for all temperatures tested.

As shown in Table 2 and Figure 6, the thermal treatment did not have a significant influence on the tensile strength of the PBO FRMC composite at 100 °C and 200 °C, for which the retained values were about 95% and 99%.

Table 2 - Results of tensile tests on PBO-FRMC composites (average ± standard deviation).

T [°C]	σ_{cr} [MPa]	σ_u [MPa]	ϵ_u [mm/mm]
20	396.3±63.1	743.3±110.0	0.013±0.002
100	348.4±43.2	704.3±76.9	0.010±0.001
200	257.3±13.58	738.6±12.5	0.011±0.001
300	128.3±34.3	261.2±55.43	0.011±0.001

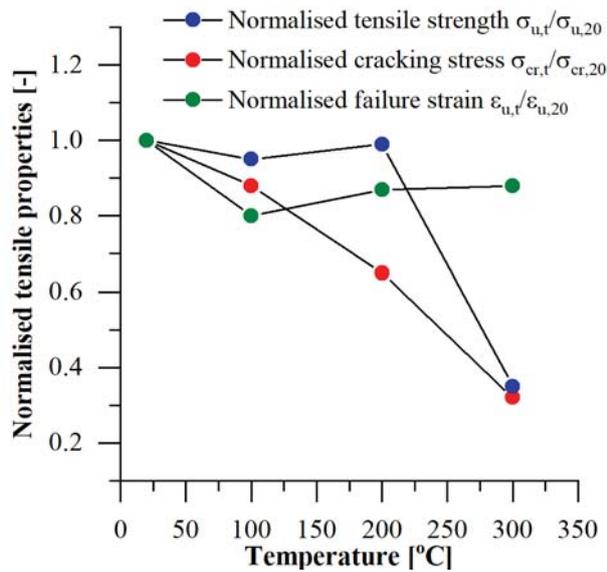


Figure 6 – Normalised tensile properties vs. temperature.

These results could be associated to the interlocking mechanism between the PBO fibres and cementitious matrix caused by the thermal shrinkage of the matrix, which may lead to an improved bond between the fibres and the matrix; and consequently, to a better load-bearing capacity. On the other hand, drastic reductions of tensile strength were observed at higher temperatures – decreases of approximately 40% (compared to ambient temperature values) were obtained at 300 °C. The latter result suggests that for such range of temperature, the degradation of the fibre-to-matrix bond causes a reduction of the composite action (i.e. fibres/matrix interface) and; as a consequence, the tensile strength decreases. From the results obtained it can be also seen that increasing temperature does not affect significantly the failure strain: all specimens failed at an average axial strain of approximately 0.011 mm/mm, regardless of the test temperature. This result suggests that for the specific material studied herein, the failure load is governed by the critical strain rather than the load-bearing capacity of the fibres. Regarding the failure mode, all the specimens failed due to the slippage of the fibres within the matrix. From Figure 10 it can be seen that increasing the temperature caused a progressive increase of the number of cracks; again, this should be due to the improved fibre-to-matrix bond which improve the load-bearing capacity of the composite. However, at 300 °C, the dehydration of the main hydrates in the cement-based mortar caused a significant reduction of the number of cracks [11], which also resulted in a loss of tensile strength.



Figure 7 – Typical failure modes of the DT specimens for each temperature tested.

With respect to the bond tests, they provided a better understanding about the influence of elevated temperatures on the bond properties of PBO FRCC-concrete prisms. As for the tensile stress, the bond stress was calculated by dividing the applied load by the cross-sectional area of the fibres.

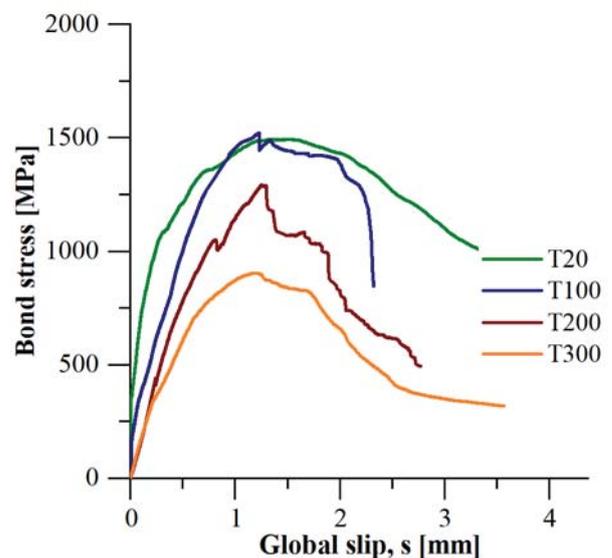


Figure 8 - Representative bond stress vs. slip curves for all temperatures tested.

Overall, the bond strength retention at 100 °C, 200 °C and 300 °C were 105%, 90% and 60%, respectively, highlighting a non-monotonic variation of this property with increasing temperature. The relatively good bond strength retention observed up to 200 °C may be explained by the fact that some matrix micro cracks close after the occurrence of the thermal shrinkage, thus leading to an

overall improvement of the bond strength. On the other hand, the marked bond strength reductions observed at temperatures above 200 °C should be associated to the chemical degradation of the matrix, dehydration, and changes in the interphase morphology [8].

Table 3 - Results of DS tests (average ± standard deviation).

T [°C]	τ_m [MPa]	s_m [mm]
20	1426.8±170.4	0.9±0.5
100	1511.8±51.8	1.3±0.2
200	1290.8±20.6	1.2±0.2
300	891.2±28.9	1.0±0.2

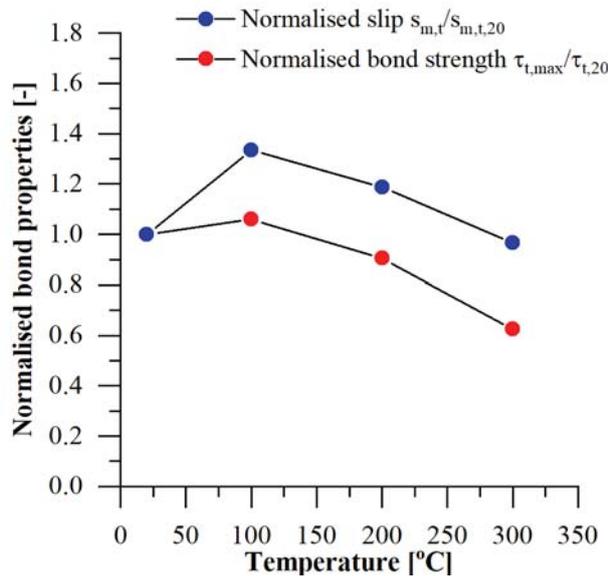


Figure 9 – Normalised bond properties vs. temperature.

Concerning the slip at the maximum bond stress (s_m), higher values were found for temperatures below 200 °C (compared to what obtained at ambient temperature): this result points out that the slippage of the PBO fibres within the matrix increases with increasing temperatures. However, this variation trend was not confirmed at higher temperatures; in fact, all specimens tested at 300 °C (except one) exhibited values of s_m lower than those observed at 100 °C and 200 °C - this result mostly stems from differences in the failure mechanisms among the specimens. Indeed, it is worth mentioning that the collapse of the specimens tested up to 200 °C was triggered by the slippage of the fibres within the matrix (cf. Figure 10a), whereas at 300 °C, the specimens failed due to premature rupture of the bare fibres (cf. Figure 10b).

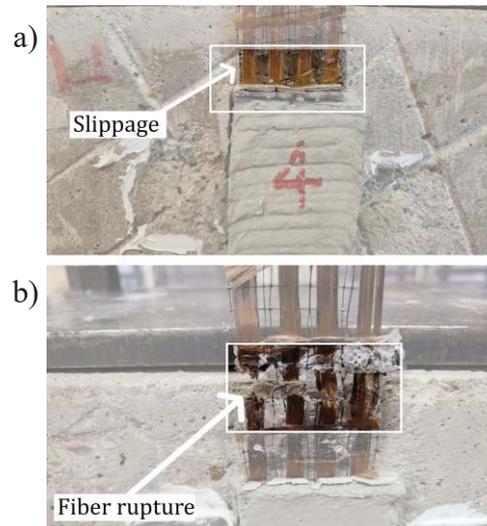


Figure 10 – Failure modes observed in the DS tests: (a) specimens tested in the range 20-200 °C and (b) specimens tested at 300 °C.

IV. CONCLUSIONS

This paper presented an experimental investigation which aimed at providing a better understanding about the variation with temperature of the tensile and bond properties of FRCM composites. Tests were performed at room temperature on specimens that were previously thermally conditioned over a temperature range from 20 °C to 300 °C. From the results obtained the following conclusions can be drawn:

The tensile strength of PBO FRCM materials exhibits a marked degradation at 300 °C, with retained values of approximately 35%. On the other hand, the variation with temperature was less pronounced at moderately elevated temperature: in the range 100-200 °C, the reductions of tensile strength were almost null. The latter result can be associated to the improved bond fibre-to-matrix bond, which increases the load-bearing capacity of the composite.

The failure strain of the PBO FRCM specimens remained approximately the same, regardless of the test temperature. This result suggests that for the specific material studied herein, the ultimate tensile load is more dependant on the failure mechanisms experienced by the specimen than on the load-bearing capacity of the PBO fibres. Note that for all the PBO FRCM specimens tested, the failure mode comprised the slippage of the fibres from the matrix.

The bond strength also exhibits a significant reduction with increasing temperature due to thermophysical and thermochemical changes in the composite material,

presenting residual values of approximately 60% at 300 °C. As for the tensile tests, the bond strength at 100 °C did not present significant changes, with a retention of 105%.

Two types of failure modes were observed in the DS tests. For temperature ranging from 20 °C to 200 °C, the collapse was always triggered by the slippage of the fibres inside the matrix, while for higher temperatures the specimens failed in a brittle manner due to the rupture of the PBO fibres.

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