Residual Tensile Strength of Textile Reinforced Mortars After Have Been Exposed to Elevated Temperatures

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Abstract. The present paper demonstrates initial results from an ongoing experimental and analytical research programme on masonry structures confined with Textile Reinforced Mortars (TRMs). In the present experimental stage, three series of uniaxial tensile tests were conducted on TRM coupons having variables the types of fibres and the ambient temperature. The purpose of this experimental investigation is to examine the residual strength of Carbon, and Basalt fibre textiles, used for the preparation of TRMs, after having been exposed to elevated temperatures. Within the scope of the experimental programme, TRM coupons and single fibre yarns have been exposed to three different temperatures (100 °C, 200 °C and 300 °C) before tensile testing. Subsequently, parts of all specimens were subjected to Scanning Electron Microscopy (SEM) to assess any changes in the microstructure, both of the mortar and the fibres. Dogbone specimens were used to test the TRMs in tension, while prismatic specimens were used to assess the mortar's flexural tensile and compressive strength. For each temperature group, additional tensile tests were conducted on bare fibre yarns to assess changes in their mechanical properties. A significant decrease in the compressive strength of mortar observed between 20 °C and 100 °C, while there was a tendency for that value to increase gradually from 100 °C to 300 °C.

On the other hand, the flexural strength increased between 20 °C and 100 °C and gradually started to decrease as the temperature rose to 300 °C. Overall, the residual strength of the TRMs, as the results indicated, decreased with temperature. Two main reasons are identified as responsible for that behaviour; loss of bonding between the fibres and the matrix and deterioration of the fibre's and the mortar's original strength. Moreover, changes in the porosity of the mortar and the fibre coating monitored with the use of Scan Electron Microscopy (SEM).

Keywords: TRMs · Elevated temperatures · Tensile tests

1 Introduction

A promising alternative to the Fiber Reinforced Polymer (FRP)-based technique is woven fibres in the form of textiles embedded in inorganic matrices. The cementitious composite system, alternatively known as Textile Reinforced Mortar (TRM) or Fiber Reinforced

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Cementitious Mortar (FRCM), can bypass certain drawbacks of the FRP method, mainly related to their exemplary behaviour when subjected to elevated temperatures. In such cases, when the environmental temperature goes beyond the glass transition threshold (Tg), the organic matrix becomes soft and loses its properties, and therefore the FRP technique becomes inefficient (e.g., rapid deterioration of the FRP-substrate adhesion). TRMs constituted of two components, the open weave fibre fabrics and the inorganic mortars. Usually, those open weave fabrics are made of either Carbon, Basalt or Glass fibres.

Since the beginning of 2000, the number of researchers getting involved with Fiber Reinforced Mortars has increased. Despite the great potential of the TRM strengthening technique, extensive studies (experimental or analytical) on the resistance of strengthened elements exposed to elevated temperatures have been reported. Previous research gave few results on the performance of engineered cementitious composites and TRMs, subjected to elevated temperatures (Zhang et al. 2014; Sahmaran et al. 2010, Kulas et al. 2011; Antons et al. 2012; Ehlig et al. 2009, 2010; Colombo et al. 2011). Trapko (2013) conducted experiments on FRCM-confined reinforced concrete specimens exposed to high temperatures. Michels et al. (2014) conducted tensile tests to carbon FRCM coupons after have been exposed to 300 °C, 500 °C, 700 °C, and 1000 °C for 30 min; a significant drop of the tensile strength for temperatures above 300 °C was recorded. The residual tensile properties of basalt fibres were investigated by Militký et al. 2002 after exposure to 50 °C, 100 °C, 200 °C, and 300 °C. The SEM method observed the morphological and structural changes within the fibres, including a change in the tensile properties. Donnini et al. 2017 conducted uniaxial tensile and double-shear bond tests under high-temperature conditions, ranging from 20 °C to 120 °C, of coated carbon FRCM systems. The results showed that FRCM specimens with coated carbon fabrics were significantly affected by external thermal exposure. As it is evident from the brief literature review, the results on the residual mechanical properties of the TRMs exposed to elevated temperatures are scarce. In the present study, two different fibres are used: carbon and basalt and three target temperatures (100 °C, 200 °C and 300 °C). Initial results from tensile tests on TRM coupons and fibre yarns are presented together with SEM pictures.

2 Experimental Programme

2.1 Materials

The materials used for the present study were two different types of fibres, namely, carbon, and basalt and one type of mortar served as the cementitious matrix. The carbon and basalt, and fibres were in the form of bi-directional textiles (0o/90o), each having the same architecture but different grid dimensions; 30 × 30, and 25 × 25 respectively. Note that the fibres in all three different textile products were coated. In the case of the cementitious matrix, a commercial polymer-modified mortar used containing microfibers as well. Tensile, compressive, and three-point bending tests performed to determine the tensile strength of the fibres, the compressive, and the flexural tensile strength of the mortar. The tests for the mortar followed EN 1015-11 (1993), whilst in the case of the fibre rovings, the ASTM D3039 standard (1996) was followed. In calculating the roving's tensile strength, the area Af used based on the weight of the textiles and the respective density of the fibres. The average values together with the standard deviations of the properties above are presented in Table 1 and Table 2.

Table 1. Mortar properties

Property	f_u (MPa)	$\overline{f_u}(MPa)$	s^2
Mortar flexural Strength	7.70	7.54	0.023
	7.40		
	7.53		
Mortar compressive strength	31.90	34.23	2.90
	32.45		
	35.00		
	34.65		
	36.36		
	35.00		

Table 2. Textile properties

Fiber type	Area Weight [gr/m^2]	A_f [mm^2] per roving	σf [MPa] (CoV)	ε_f [%] (CoV)
Carbon fiber roving	220	1.83	135.22 (0.35)	1.21 (0.42)
Basalt Fiber roving	170	0.80	536.42 (0.26)	1.13 (0.096)

3 Specimens, Test Set-Up and Instrumentation

To assess the residual mechanical properties and the mechanical behaviour of the TRMs, when subjected to elevated temperatures, composite coupons and fibre rovings were used. Three target temperatures investigated, namely, 100 °C, 200 °C and 300 °C and each one had three different types of TRM specimens and rovings. The types of coupons and the rovings corresponding to the different types of fibres. Three coupons and three rovings for each type of fibres were prepared to achieve a certain level of repeatability for each temperature level. An additional group of specimens tested without being exposed to elevated temperatures and used as reference.

In the experimental procedure, dog bone type specimens were used to test the tensile strength of the TRMs following the dimensions suggested in De Santis et al. (2017) (Fig. 1). All coupons were cast in wooden moulds comprised of a single layer of textiles embedded in cementitious mortar. Each specimen included at least two rovings; two for the Carbon, three for the Basalt and four for the Glass textiles. Moreover, in the shoulders of the dog bone specimens, the textiles were fixed using an epoxy paste between two orthogonal aluminium plates having dimensions 13 * 5.5 * 0.2 cm.

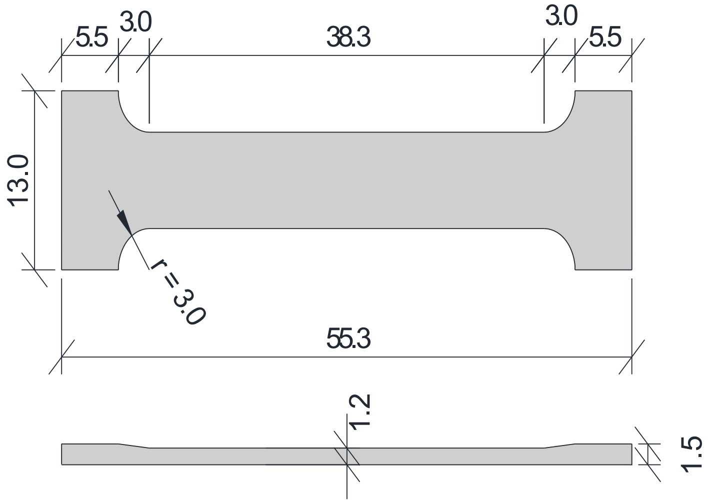


Fig. 1. Typical dimensions of the TRM coupons (all dimensions in cm)

After demoulding, the coupons were kept in a humidity chamber (22 °C, and RH ≈ 80%) for twenty-one days and subsequently kept in environmental conditions until twenty-eight days. Subsequently, all coupons but the reference were placed in heating chambers and heated for eight hours up to the target temperature (Fig. 2). The chambers provided air heating conditions at a rate of 30 °C per hour. After that stage, the specimens left to cool off for twenty-four hours inside the heating chambers and then tested in tension. The installation of the coupons was made using bolted steel grips clamped by the machine wedges (Fig. 3). The tensile tests on the coupons were conducted using a UTM testing machine with a load capacity of 300 kN. The tensile tests were subjected to a displacement control mode at a rate of 0.05 mm/min until the first crack and changed to 0.5 mm/min up to failure. In the absence of an adequate external LVDT, the machine's stroke was used at a gauge length of 39 cm to determine the strain development on the specimens (Fig. 3). For each triad of coupons, a corresponding triad of rovings, taken from the same textile, was used. The rovings, having a length of 500 mm, were heated following the same procedure, whereas the tensile testing conducted using a 100 kN UTM in a displacement control mode at a rate of 0.5 mm/min. To prevent the fibres from slip two rectangular aluminium tabs, two at each end, were used before those were directly clamped to the wedges. The tabs were glued with epoxy raisin and had an edge of 5 cm to match the machine wedge length. The code used for the coupons' notation was RC_T_X, where RC = denotes the type of fibre used for the coupon, T = the target temperature and X = serial number.

Fig. 2. TRM coupons inside the heating chamber.

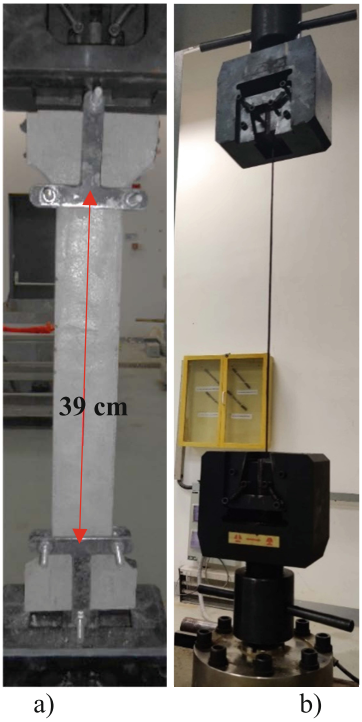


Fig. 3. Installation of a) the TRM coupon and b) the fiber roving onto the testing machine.

In rovings, the coding was similar but the RR symbol used instead (R = denotes the type of fibres, and R stands for 'roving'). After the tests, samples were taken from the coupons and the rovings to assess changes in the microstructural properties through SEM and TGA inspections.

4 Results and Discussion

In Tables 3 and 4, the mortar and the yarns' results for all the target temperatures are presented.

Table 3. Mortar properties after exposure to high temperatures

Temperature	Flexural strength [MPa]	Compressive strength [MPa]
100 °C	8.95	20.34
200 °C	7.09	21.42
300 °C	5.03	22.66

Table 4. Fiber properties after exposure to high temperatures

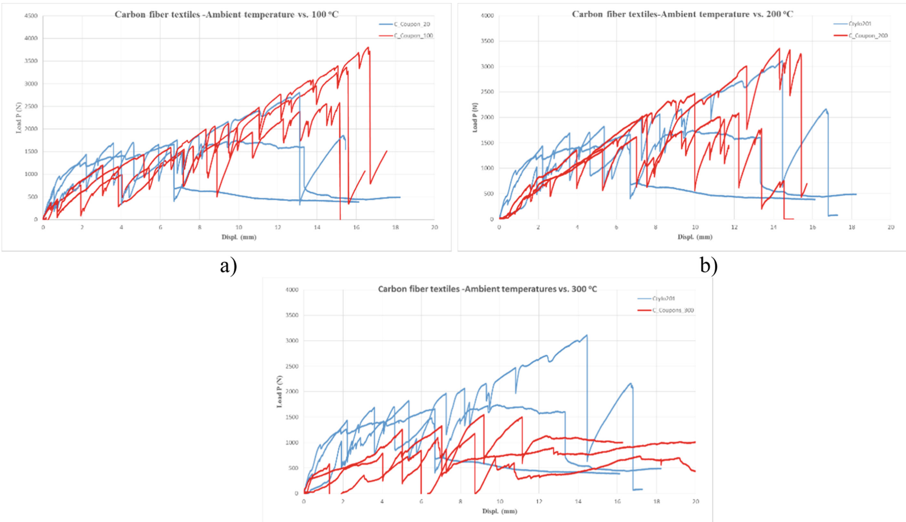
Temperature	Carbon fiber		Basalt fiber	
	Tensile Strength f_u [MPa] *(CoV)*	Ultimate strain ε_u [%] *(CoV)*	Tensile Strength f_u [MPa] *(CoV)*	Ultimate strain ε_u [%] *(CoV)*
20 °C	1676.50 (0.008)	–	1438.33 (0.25)	–
100 °C	719 *(0.206)*	1.74 *(0.086)*	672.37 *(0.163)*	1.20 *(0.137)*
200 °C	906.01 *(0.105)*	1.85 *(0.072)*	495.12 *(0.358)*	1.42 *(0.225)*
300 °C	510.65 *(0.284)*	1.64 *(0.039)*	309.56 *(0.059)*	1.14 *(0.026)*

The load vs displacement graphs are presented in Figs. 4, 5, where the behaviour between the reference specimens and those exposed to elevated temperatures is illustrated. The observed modes of failure for the Carbon fibre textile coupons could be classified as follows: *a)* first significant crack in the clamping area followed by subsequent cracks throughout the length of the coupon. In this case, failure occurred due to the rupture of the fibres away from the clamps. *b)* formation of a significant crack in the clamping area followed by slipping of the fibres. From post-test observations, it was apparent that the temperature level influenced the type of failure. More specifically, the coupons tested without being exposed to elevated temperatures followed *type a* mode of failure developing one or two significant cracks throughout their length (Fig. 6a). The coupons have been exposed to 100 °C and 200 °C before testing exhibited the same mode of failure, but the cracking was extensive and followed the pace of the transverse bundles (Fig. 6b and c). The coupons exposed to 300 °C exhibited *type b* mode of failure developing a significant crack in the clamping region followed by significant slippage of the fibres (Fig. 6d).

Basalt textiles failed mainly due to the rapture of the fibres in a crack formed away from the clamps. In one case only, (B_coupon_20) failure occurred due to excessive slippage of the fibres in a crack formed in the vicinity of the clamps (Fig. 7a). It seems that the temperature does affect the mode of failure (Figs. 7b-d). The behaviour of the stitch-bonded yarns was altered for both types of fibres. More specifically, the yarns used as reference exhibited a controlled type of tensile failure, mainly due to a combination of tensile rupture and slippage of the filaments.

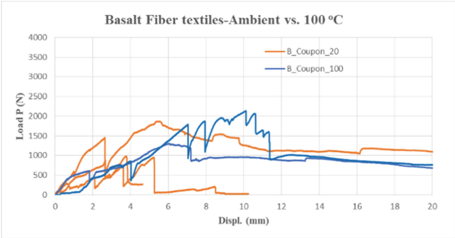
In contrast, those exposed to elevated temperatures before testing failure occurred suddenly due to rupture of the fibres (Fig. 8). The tests on the rovings suggested that the strength between 20 °C and 100 °C increases - both for Carbon and Basalt fibres. Although in the case of the former additional tests need to be conducted due to slippage at the grips. For the Carbon fibres, the rovings exhibited the same tendency up to 200 °C, whereas in Basalt, the strength started to decrease. For both types, the tensile strength at 300 °C showed a significant decrease in tensile strength. The 100 °C Carbon fibre coupons in tension demonstrated a better behaviour than the reference specimens whilst the 200 °C and especially the 300 °C were significantly weaker. In the Basalt fibre coupons, the tensile behaviour seems that was not severely affected by the exposure to elevated temperatures; on the contrary, the specimens heated at 100 °C exhibited better performance.

In general, exposure to temperatures above 100 °C, as the SEM samples indicated, deteriorate the coating of the fibres and hence affect the bond to the surrounding mortar (Fig. 8).

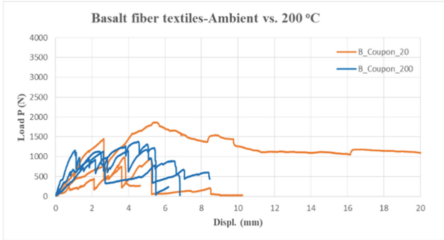


c)

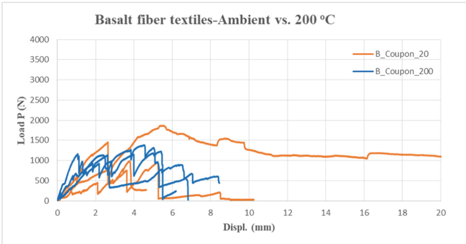
Fig. 4. Load vs. Displ curves for ambient vs. a) 100 °C b) 200 °C and c) 300 °C for carbon fiber textiles.



a)



b)



c)

Fig. 5. Load vs. Displ curves for ambient vs. a) 100 °C b) 200 °C and c) 300 °C for basalt fiber textiles.

a)

b)

c)

d)

Fig. 6. Modes of failure for carbon fiber textiles subjected to a) environmental temperature b) 100 °C c) 200 °C and d) 300 °C

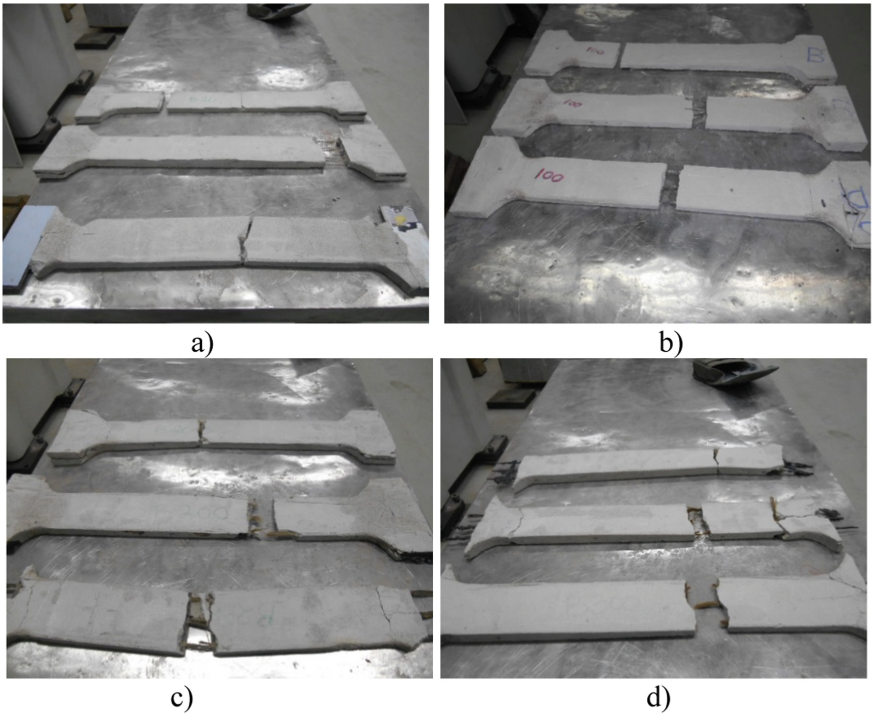


Fig. 7. Modes of failure for basalt fiber textiles subjected to a) environmental temperature b) 100 °C c) 200 °C and d) 300 °C

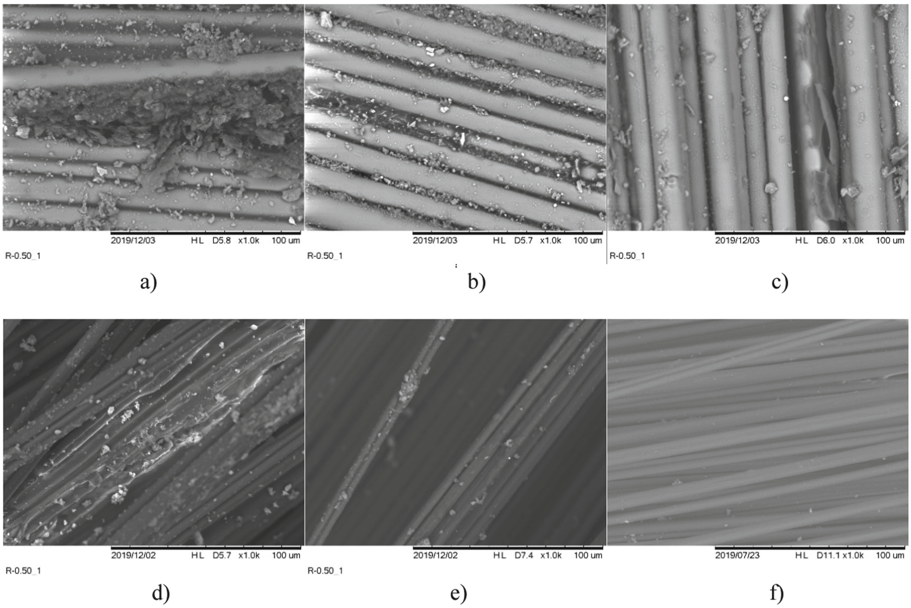


Fig. 8. Changes in the surface conditions of the Basalt fibers from a)100 °C b) 200 °C and c) 300 °C and the Carbon fibers from d) 100 °C e) 200 °C and f) 300 °C

5 Conclusions

Tensile tests on TRM coupons and fibre rovings taken from the same textiles were performed to assess the residual tensile strength after exposure to three target temperatures-100 °C 200 °C and 300 °C.

The initial results can be summarized as followed:

- At a temperature of 100 °C the inorganic matrix increases its flexural strength by 19%. From this temperature onwards and up to 300 °C, flexural strength loses 33.3% of its original strength.
- In the case of Carbon fibre rovings, it seems that there is an increase in the tensile strength up to 200 °C; the tensile strength becomes approximately six times higher. However, further investigation needed since slippage of the fibres at the grips was observed during the tests. At 300 °C the rovings demonstrated a considerable loss in their tensile strength.
- Similar results were found for the Basalt fibres, which increased their tensile strength up to 100 °C (by 25.3%). Further increase of the temperature caused significant loss of the original strength (up to 43.3%).
- The exposure to elevated temperatures affected the type of failure modes that the Carbon textile coupons exhibited during the tests. For the Basalt fibre textiles, such behaviour was not observed.

The SEM analysis showed that temperature affected the coating of the fibres and hence the bonding to the mortar.

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