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Characterization of thermomechanical properties of a textile reinforced concrete (TRC) under high temperature

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ABSTRACT: One of the limitations of the experimental thermomechanical approach is to identify the properties and develop a method of characterization. Therefore, this paper presents the development of an experimental study that characterizes the behaviour of two textile reinforced concretes (TRC) subjected to elevated temperatures and represents the real state of TRC under combined thermal and mechanical loading effect. The thermomechanical load is applied on two types of TRC; they both have three layers of grid alkali-resistant glass but each has a different cementitious matrix (normal mortar and refractory one). The TRC specimen is subjected to two loading paths. The evolution of certain properties and the maximum holding temperature of the TRC corresponding to a stress ratio of this material can then be determined. In addition, to fully understand the mechanisms that occur within the TRC material for some temperature levels, an X-Ray tomography observation and a thermogravimetric analysis are carried out.

1 INTRODUCTION

The development of composite materials in the civil engineering sector follows two main orientations: full or partly new composite structures and the composite strengthening of existing RC structures. The last family of rigid composite materials concerns fiber/cement composites for which the polymer matrices are replaced by mineral ones (phosphate binders, sulphate binders, magnesium binders). The composite material eliminates the risk of reinforcement corrosion and allows to improve the mechanical properties of strengthened structures, Orlowsky et al (2011) and Brameshuber (2006). Another important function is desired in textile fireproof function. One of the limitations of the experimental thermomechanical approach is to identify the properties evolution under high temperature and develop a method of characterization.

The present experimental study is a part of an important experimental campaign that we will undertake to provide experimental data on textile cement composites and to allow the construction of reliable analytical models. This study involves two configurations of composites and its main objective is to analyze the influence of matrix nature on the tensile behavior at different temperatures ranging from room temperature (approximately 25°C) up to high temperatures (maximum 600°C). The maximum temperature level (600°C) of the tests is selected according to the maximum thermo-mechanical resistance of the two studied TRC (see 4.1 and 4.2). For that, flat specimens were prepared and then tested to failure in tension while under the influence of various steady state (path 1) or transient state (path 2). Identification of mechanical and chemical properties is finally carried out.

2 COMPOSITES CONFIGURATION

2.1 Matrices and fabrics

Two dissimilar matrices are tested in this study, normal mortar and refractory one. The compressive and tensile strengths of the normal mortar, experimentally identified, are respectively 23 MPa and 4.5 MPa. The compressive and tensile strengths for the fire mortar are respectively 14.4 MPa and 3.3 MPa. The textile type, grid alkali resistant (AR)-glass, used in this study has the same thread in two directions of the grid. This grid is large and the opening between the meshes axis is 8×8mm which allows the passage of small aggregates. The nomimal weight of this textile is 300g/m^2. Each yarn has 1600 filaments and a weight of 1200 Tex. The diameter of each filament is 19µm.

2.2 Textile reinforced concrete

The cementitious matrix and the reinforcement textiles are cast in a mold to obtain a plate of TRC having the dimensions 800mmx 500mmx 5mm (length × width × thickness). After 7 days, the rectangular plates are cut, resulting in specimens of 700 mm × 45 mm × 5 mm (length × width × thickness). The TRC materials (3G.AR and 3G.AR.Fire) are made and kept in the laboratory atmospheric condition, stored at ambient temperature for at least a month before testing. This curing ensures that the 3G.AR and 3G.AR.Fire composites obtain a mechanical strength that is close to their maximum because of a well advanced hydration of their matrices. To prepare the specimen for the test, four aluminum plates are glued to the ends of each specimen using an epoxy adhesive (Eponal 380) to ensure transfer efficiency of the mechanical load. At least 3 days after the bonding, the TRC sample is drilled at each end to be compatible with the used “ball joint” loading heads.

3 EXPERIMENTAL PROCEDURE

3.1 Experimental device

The machine Zwick 20kN-furnace (Figure 1) is used in this study to test TRC specimens. It is fitted with a small furnace provided with heating resistors that can reach a high temperature, potentially up to 1200°C. This temperature is controlled by integrated thermocouples. The maximum velocity of temperature rise in the furnace is 30°C/ minute. The specimen is placed in the middle of the furnace that measures 300x100mm and is attached by two “ball joint” loading heads, designed by a previous study, Contamine et al (2011), which allow applying a tensile force and controlling the alignment of the specimen.

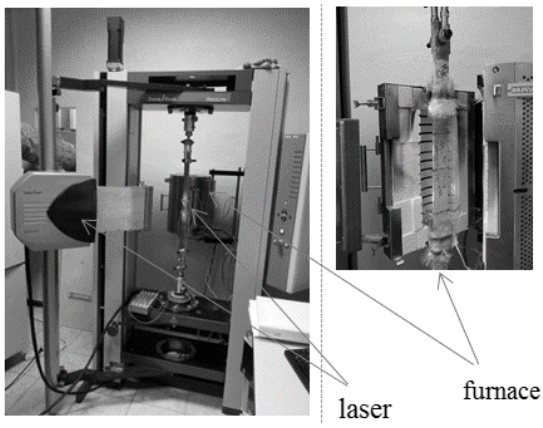
3.2 Thermomechanical tests description

This section presents the steady-state test and the transient-state test.

3.2.1 Steady-state test (SS)

In steady-state test, the specimens were heated to a specified temperature then loaded until failure while the same temperature was maintained. All samples are subjected with a heating increase rate in the furnace (ranging from 2,5°C/minute to 20°C/minute) corresponding to each temperature level (ranging from 75°C to 600°C). When the temperature reached the target value, it is then kept constant for one hour. The tensile force applied on the specimen is monotonically increased until the maximum force that the specimen can resist. The increase in the axial force was controlled and piloted by transverse displacement with a displacement rate of 3000 µm/min.

This mechanical load was combined with the measurement of the axial strain of the specimen using a laser sensor. The Figure 2 presents this test in terms of the evolution of the temperature and of the force as a function of time.



(a) (b)

Figure 1. (a) The machine Zwick 20kN-furnace; (b) Furnace and specimen installed for a thermomechanical tensile test.

3.2.2 Transient-state test (TS)

In the transient-state tests, showed in Figure 3, the specimens were initially gripped at both ends and then subjected to a tensile force with a maximum load equal to a selected percentage of the maximum strength of TRC obtained at 25°C (30% and 50%). After that, the temperature rises to the maximum that the TRC can resist.

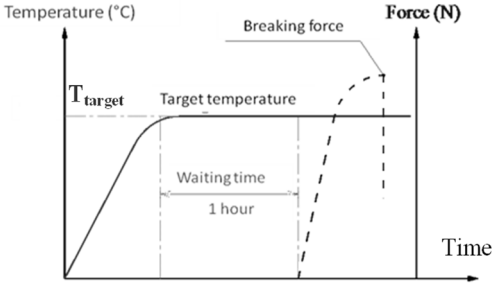


Figure 2. Steady-state (SS) path.

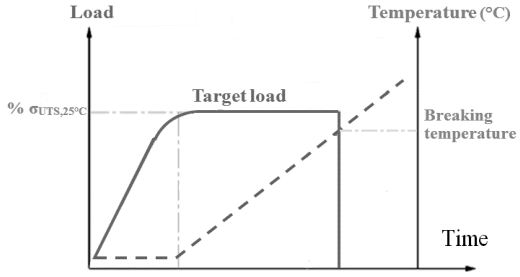


Figure 3. Transient-state (TS) path.

3.3 Materials characterization

3.3.1 Micro-structural characterization

Examination of the samples by X-ray tomography was performed using a tomography GE Phoenix v | Tome | Xs. The tomograph consists of an x-ray tube (transmitter), a digital detector and a set of mechanical axes (support for the test piece) enclosed in a radioprotection cabin. A software is also needed to drive the tomograph and reconstruct the tomographic images. The resolution depends strongly on the size of the sample and the power of the x-ray source. No pretreatment was carried out on the samples. The volume observed by the tomograph is 15 × 15

× 10 mm^3. This size made it possible to have a resolution of 10µm a priori sufficient for examining the fibre-matrix interface and the voids of the matrix.

3.3.2 Thermal analysis

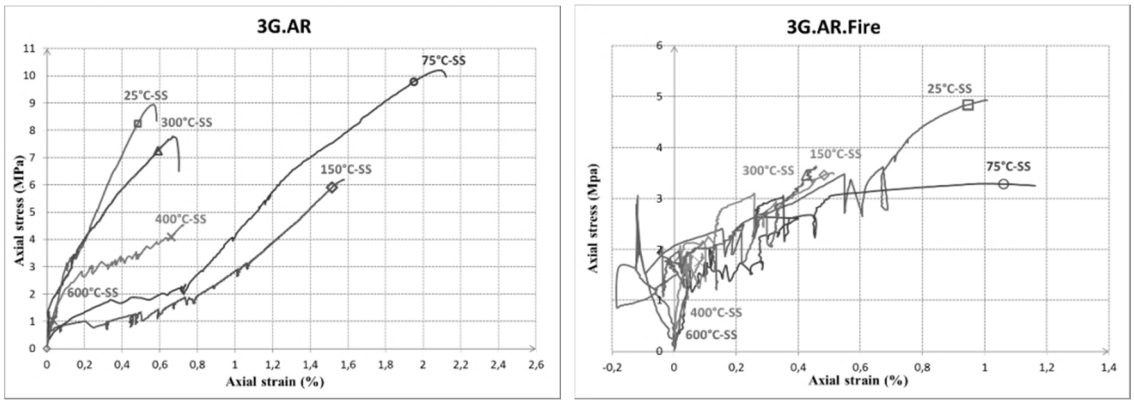
Thermal analysis (ATG and DSC) detects atomic and inter/ intramolecular interactions related to an imposed external temperature change. ATG thermogravimetric analysis measures the change in mass of a material as a function of temperature and time, in a controlled atmosphere. However, DSC, "Differential Scanning Calorimetry" measures the heat flux associated with phase transitions or reactions, such as fusion, crystallization, solid phase transition, glass transition, hardening, sorption, etc.

The most important products of the hydration reactions of an ordinary cement are the calcium silicate hydrate (C-S-H) and the portlandite, also called calcium hydroxyde (CH) (Sha et al (1999)). Different authors have described the reactions that occur with an increase of temperature in cement paste and concrete:
• 30–105 °C: the evaporable water and a part of the bound water escape, Noumowé (1995).
•110–170 °C: the decomposition of gypsum (with a double endothermal reaction), Noumowé (1995) and Platret (2002), the decomposition of ettringite, Zhou et al (2001), and the loss of water from part of the carbo-aluminate hydrates, Nonnet et al (1999), take place.
•180–300 °C: the loss of bound water from the decomposition of the carbo-aluminate hydrates, Noumowé (1995), Richard (1999) and Khoury (1992).
•450–550 °C: the dehydroxylation of the portlandite (calcium hydroxyde), Noumowé (1995) and Platret (2002).
•700–900 °C: the decarbonation of calcium carbonate, Noumowé (1995), Grattan-Bellew (1996) and Michel (2009).

4 RESULTS AND DISCUSSION

4.1 Results of steady-state (SS) tests of 3G.AR and 3G.AR.Fire

The influence of different temperatures on composite materials tested in this study is presented in Figure 4. The axial stress as a function of the axial strain is representing the behaviour of TRC at 25°C, 75°C, 150°C, 300°C, 400°C and 600°C. For 3G.AR (Figure 4a), the axial stress-axial strain curves at temperatures varying from 25°C to 150°C show three distinguishable phases in the behaviour of the 3G.AR composite. However, at 300°C and 400°C, two phases are observed. Additionally, at 600°C, the curve is quasi-linear, and only one phase is shown. However, the axial stress-axial strain curves of 3G.AR.Fire (Figure 4b) are disordered. The behaviour of this composite is almost the same on all temperature levels, only the ultimate strength changes. From the curves presented above (Figure **4**), mechanical properties of two studied composites can be identified, Tlaiji et al (2016). Consequently, the evolution of the average ultimate tensile strength (σ_{UTS}) as a function of the temperature is presented in Figure 5Figure **1** for both composite materials 3G.AR and 3G.AR.Fire kknowing that they have almost the same rate of reinforcement (V_f=2%). By comparing 3G.AR and 3G.AR.Fire, it is observed that the resistance as a function of temperature levels is higher in 3G.AR. While the maximum strength decreases by about 84% for 3G.AR and about 69% for 3G.AR.Fire when the temperature level changes from 25°C to 600°C.



(a) (b)

Figure 4. Behaviour of (a) 3G.AR and (b) 3G.AR.Fire in Steady-State (SS) tests.

4.2 Results of transient-state tests of 3G.AR and 3G.AR.Fire

The failure temperature for each percentage of maximal strength obtained on 25°C (30% $\sigma_{UTS,25°C}$ and 50% $\sigma_{UTS,25°C}$) was reached when the tensile load could no longer be sustained.
Figure 6 shows the temperature that cause failure of the specimens for 30% $\sigma_{UTS,25°C}$ and 50% $\sigma_{UTS,25°C}$ tension load. In this figure, the horizontal axis represents the specimen temperature, and the vertical axis represents the load. It should be noted that there was a brutal drop (of 72%) of failure temperature when the stress was increased from 30% $\sigma_{3G.AR,25°C}$ to 50% $\sigma_{3G.AR,25°C}$ for 3G.AR. Whereas this decrease is almost nil (5%) for the other TRC 3G.AR.Fire, hence the positive effect of fire mortar.

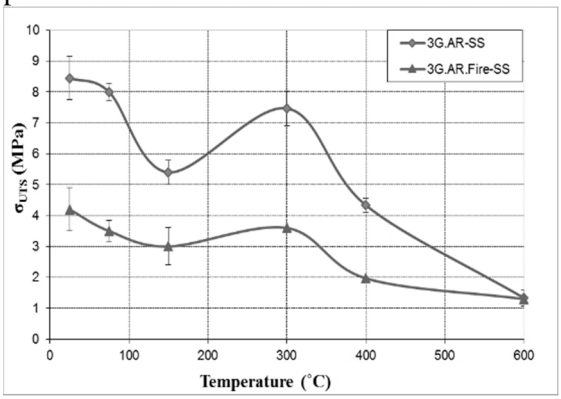


Figure 5. Average ultimate tensile strength (σ_{UTS}) of 3G.AR and 3G.AR.Fire as a function of the temperature.

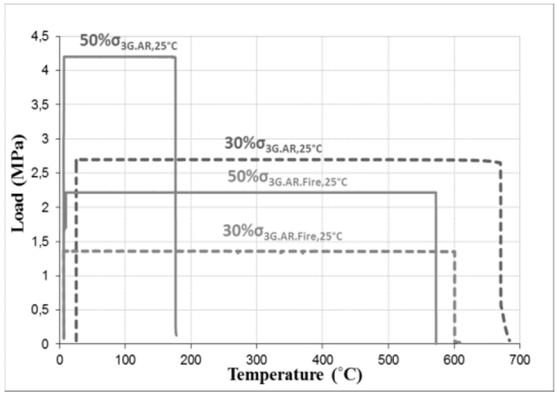
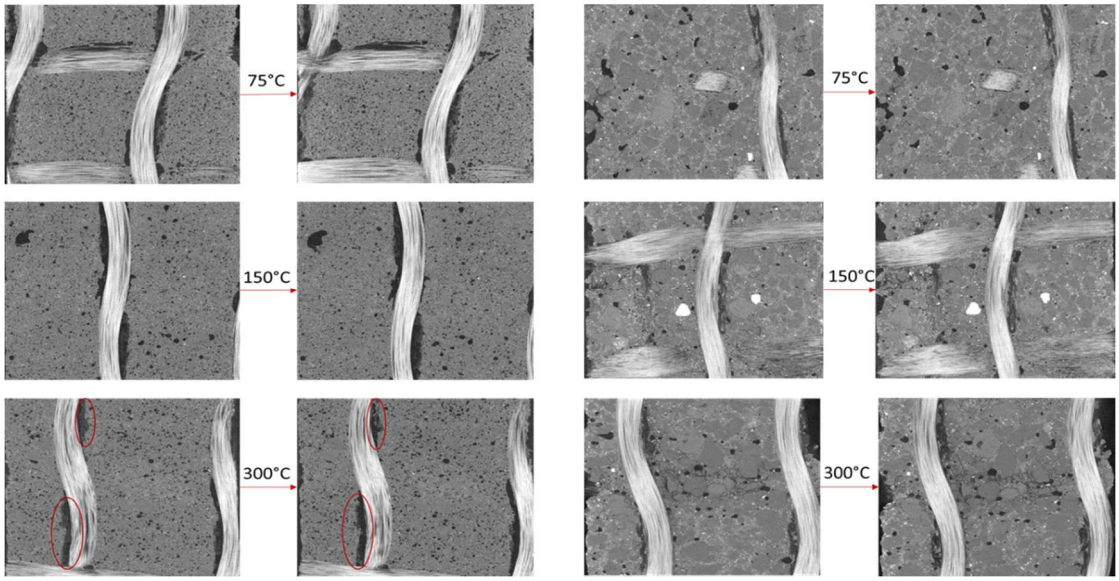


Figure 6. The temperature to cause failure of the specimens in the Transient-State (TS) test.

4.3 Tomography results

The results of the x-ray analysis are presented as gray level images. Each constituent of the composite has an x-ray absorption and transmission coefficient, which produces a difference in the gray level representation of each element. Figure 7 shows different raw images for 3G.AR (Figure 7a) and 3G.AR.Fire (Figure 7b). The reference specimen corresponds to an unfired sample of the composite which is treated each time on the temperature levels of 75°C, 150°C and 300°C. According to these images, the fibers and the matrix can be distinguished at different

temperature levels with the difference of their levels of gray. No differences are observed between the images subjected to the different temperatures up to 300° C. Only a disappearance of the gray zone between the fibers and the matrix of the TRC 3G.AR treated at 300° C is observed. This phenomenon corresponds to the degradation of the matrix resulting from its chemical decomposition or the transformation of one hydrate from the matrix to another. Therefore a thermogravimetric analysis (cf.4.4) is made in order to understand the mechanisms that occur within the normal mortar and the fire one.



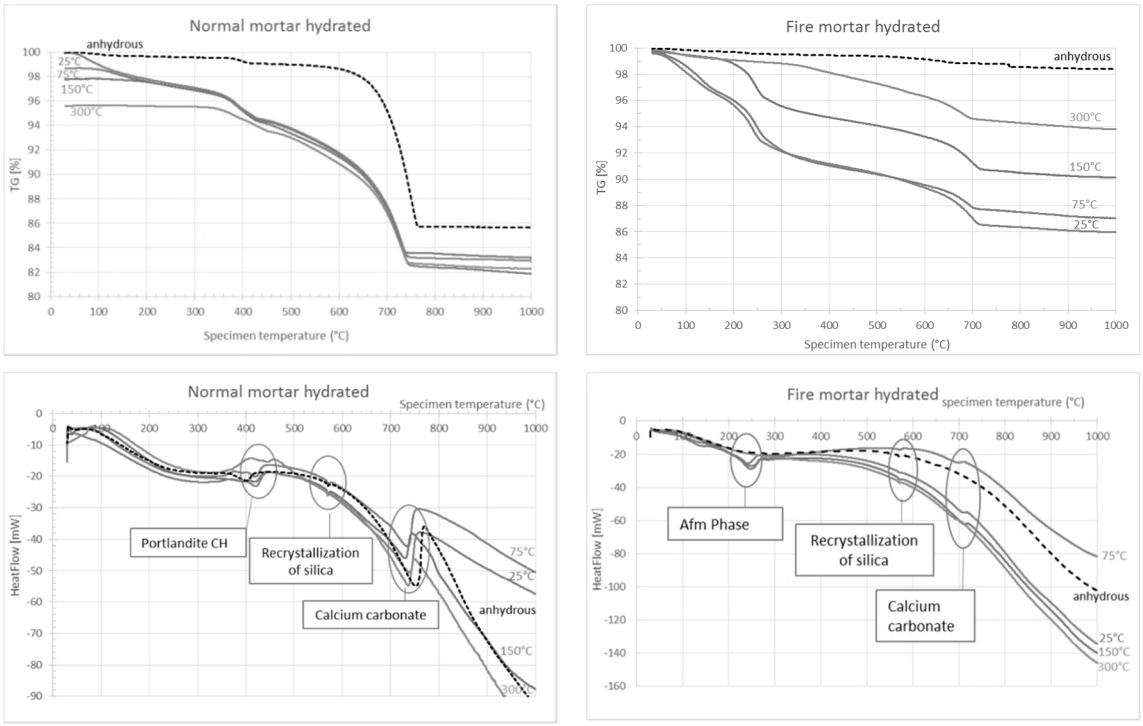
(a) (b)

Figure 7. Raw images of (a) 3G.AR and (b) 3G.AR.Fire at 75°C, 150°C and 300°C

4.4 Thermogravimetric analysis

Upon heating, the cement paste undergoes a continuous sequence of more or less irreversible decomposition reactions. This section reports studies on the normal mortar and the fire one subjected to various temperature regimes up to 300 °C. This work has been carried out to study the effect of temperature in the mineralogical composition of mortar hydration products. Therefore, the aim of this work is to have a better knowledge of the reactions that take place in a cement paste during a fire. The results of the thermogravimetric analysis on normal mortar samples and fire mortar ones, previously preheated at different temperature levels (25°C, 75°C, 150°C and 300°C) and cooled (up to ambient temperature), are summarized in Figure 8. The first weight loss located between 25°C and 200°C, is the result of dehydration reactions of several hydrates (C-S-H, carbo-aluminates, ettringite…) due to loss of water. A comparison between the curves representing pre-heated-cooled cement paste reveals that the amount of hydrates decreases with the increase of the temperature level and disappears at 300°C for the normal mortar and the fire one. For the fire mortar (Figure **8**b), a difference between 200°C and 280°C is observed. It corresponds on the decomposition of the Afm phase [Baquerizo et al 2015] which can be calcium monocarboaluminate or calcium monosulfoaluminate. The results show that the samples heated to 300°C do not present this weight loss and the corresponding heatflow peak. Moreover, this peak corresponding to the Afm phase does not exist in the normal mortar. On the other hand, portlandite CH, which existed in the normal mortar and not in the fire mortar, decomposes between 400°C and 450°C (Figure **8**a). One can remark that for the two types of mortar, the

recrystallization of silica is presented on 580°C, and the decarbonation of calcium carbonate is presented on 700°C. These results are consistent with what have been found in previous studies, Noumowé (1995), Platret (2002), Michel (2009). Finally, the results (Figure 8a,b) show that the samples heated to temperatures up to 300°C always present the third weight loss.



(a) (b)

Figure 8. Thermogravimetric (TG) results of (a) the preheated-cooled normal mortar (of 3G.AR) and (b) of the preheated-cooled fire mortar (of 3G.AR.Fire); TG tests carried out on mortar samples that were previously preheated at different levels of temperature and cooled up to ambient temperature.

5 CONCLUSION

This study concerns the experimental and comparative study of two types of TRC with different cementitious matrices (normal mortar and fire one) and 3 layers of grid alkali-resistant glass. TRC composites are tested in two different thermomechanical regimes (the steady-state regime and transient-state one), which allow to show the behaviour and the real resistance under fire of these two TRC composites. In addition, in order to understand well the drop in the resistance between 75° C and 150° C and then its rise between 150° C and 300° C, an observation of the fiber/matrix interface and the state of these two components is made using a tomograph. No differences are observed between the images of the two studied TRC before and after subjected to the different temperatures up to 300° C. Finally, a thermogravimetric analysis is carried out in order to understand the chemical mechanism produced in the matrix of the two studied TRC.

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