MESOSCALE MODELING OF THE ELEVATED TEMPERATURE BEHAVIOR OF THE BASALT TEXTILE REINFORCED CONCRETE

M.T. Tran[1,2], X. H. Vu[1], E. Ferrier[1]

1 Université de Lyon, Université Lyon 1, Laboratory of Composite Materials for Construction (LMC2), 82 bd Niels Bohr, F-69622 Villeurbanne, France. Mail: manh-tien.tran@etu.univ-lyon1.fr, xuan-hong.vu@univ-lyon1.fr, emmanuel.ferrier@univ-lyon1.fr

2 Hanoi University of Mining and Geology (HUMG), Department of Material Resistance, 18 Pho Vien, Bac Tu Liem, Hanoi, Vietnam

ABSTRACT

The textile reinforced concrete (TRC) can be used for the reparation and the reinforcement of civil engineering works. There were several studies on the behaviour of the textile reinforced concrete (TRC) subjected to residual and thermomechanical loading. Most of the previous studies concern the experiments in which direct tensile tests were carried out to characterize the residual and thermomechanical behaviour of TRC. The experimental data of the residual and thermomechanical behaviour (at elevated temperature) of the basalt textile reinforced calcium aluminate concrete were available and obtained by other researchers in a previous study.

This paper presents a mesoscale modelling of the elevated temperature behaviour of the basalt textile reinforced concrete. The ANSYS MECHANICAL software was used in this numerical study. A two-dimension (2-D) finite element model was constructed using the PLAN183 element (two-dimension (2-D), 8 nodes, structural solid element) for the cementitious matrix and the basalt fibre. The cohesive element INTER203 (two-dimension (2-D), 6 nodes, cohesive element) was used for the interface between the basalt fibre and the matrix. This model gave interesting numerical results that were in agreement with the available experimental data.

From the principal characteristics of the constituent materials (the basalt fibre, the matrix and the fibre/matrix interface) (input data), the proposed mesoscale model allowed to numerically obtain, with little difference in comparison with the available experimental data, the “stress – strain” relationship of the TRC and the principal characteristics of the TRC (as ultimate strengths and strains, strengths and strains at typical points, Young’s modulus) when the TRC was subjected to different temperatures (25°C, 75°C, 150°C, 200°C, 400°C). Furthermore, a parametric study showed a significant influence of the basalt textile reinforcement ratio on the ultimate strength of the TRC. The increase of the ultimate strength of TRC with the basalt textile reinforcement ratio, for different temperatures, was successfully simulated. The numerical results of this study show that the mesoscale modelling allows to predict the TRC behaviour at elevated temperature. The successful mesoscale finite element modelling of TRC provides an economic and alternative solution in comparison with expensive experimental investigations.

KEYWORDS

Textile-reinforced concrete (TRC), numerical study, mesoscale modelling, basalt, elevated temperature, thermo-mechanical behaviour, residual behaviour

INTRODUCTION

The TRC (Textile Reinforced Concrete) composite consists of a mortar / concrete matrix reinforced by multi-axial textiles (carbon fiber, glass fiber, basalt fiber, etc.). The main purpose of this composition is to improve the mechanical properties of TRC material. Good tensile strength of textile could compensate for the traditional weakness of the cementitious matrix and the sensitivity of the matrix to cracking. So, textile reinforced concrete composite materials have become increasingly widely used to repair or strength the structure because of their advantages. When structures reinforced by the TRC composite material are subjected to fire, the TRC composite material simultaneously dealt to mechanical loading and high temperatures. For safety, it is must be taken into account evolutions in thermomechanical properties of the composite material TRC as a function of temperature.

In the literature, there are several studies on the behaviour of the TRC composite material under the action of thermomechanical loading. Namely, Colombo et al. (2011) carried out tensile tests on the TRC composite specimens based on the AR glass fiber reinforced Portland cement matrix at different temperatures, or Rambo et al. (2015,2016,2017) carried out on the basalt fiber reinforced concrete specimens at hot and residual condition. Nguyen et al. (2016) realized recently the direct tensile tests at elevated temperature on the TRC composite based on the mortar matrix reinforced with AR glass fibers. Most of these studies showed a ‘‘stress-strain” relationship of thermomechanical or residual behaviour of the TRC composite material which can be divided generally into two or three distinct zones. As the results in the literature, ultimate strength and the Young's modulus of TRC composite material at different zones depended considerably on parameters such as the fiber type (carbon fiber, glass fiber or basalt fiber…), the properties of the fiber (resistance, Young modulus), the reinforcement ratio, the cementitious matrix type, the pre-impregnation treatment of the interface between fiber and matrix by products of different natures, etc.

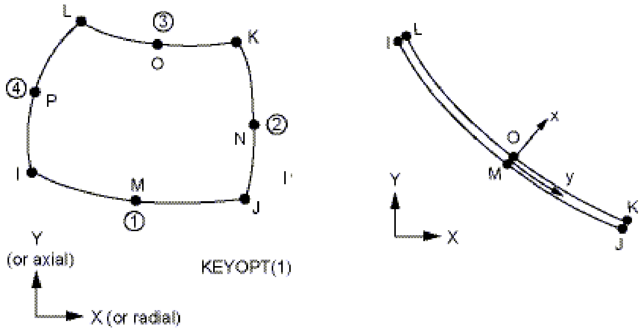
A numerical approach will reduce the number of tests to characterize the mechanical behaviour of TRC composite material at elevated temperature. It mean that a numerical model is constructed by different methods (finite element, different finite, analytic) and tests are numerically performed using a computer to calculate. In the literature, there were several numerical studies concerning the mechanical tensile behaviour of different fiber textile – reinforced concrete (TRC) composites at 25°C and elevated temperature. Rambo et al (2017) have recently done a modelling of the temperature effect on the tensile behaviour of composite material of refractory concrete reinforced with basalt textiles. J. Donnini et al. (2017) in their article, they performed on simulations by the code of finite elements to validate the experimental results. These are numerical studies at different scales to contribute considerably to our knowledge of the mechanical behaviour of TRC composites at different temperatures.

In this article, by using the finite element method, the residual behaviour of basalt textile reinforced refractory concrete composite material can be characterized at different temperatures on a mesoscale. It means that from the residual behaviour of refractory concrete matrix, basalt textile and interface between both materials at elevated temperature, the overall residual behaviour of the TRC composite can be determined by using the ANSYS MECHANICAL 15.0 software. In the 2-D finite element model, two element types (PLAN183 element for the fiber and matrix elements and the INTER203 element for the fiber/matrix interface) will be used. The experimental results in the publications of Rambo et al (2015, 2016, 2017) will be used as the input data in the numerical model. An agreement between these two results will demonstrate the conformity of this numerical model.

NUMERICAL PROCEDURE

Element types

The element types chosen for the mechanical analysis in the 2-D model were PLAN183 element (2D 8-Node Structural Solid) for the cementitious matrix and basalt textile, and INTER203 cohesive element (2-D 6- Node Cohesive) for the interface between basalt textile and matrix.



PLAN183 element *INTER203 element*

Figure. 1: Element types used in the 2-D model.

Model of the materials

Concerning the material model for the basalt fiber, the perfect elastic model was chosen because it simulated almost mechanical behaviour of basalt textile under loading action. It mean that the basalt fiber provides a linear behaviour up to material failure. The ultimate strength of basalt textile was declared as resistance value in this material model. For the refractory concrete, the material model of bilinear behaviour was chosen in this numerical model. The "stress – strain" relationships of the refractory concrete are presented in the figure 3-b. In regards to the element of the interface between fiber and matrix, the cohesive bilinear zone material model (CZM) was used in this numerical study. This material model was proposed by Alfano et al (2001) in their work and was later used and developed in the ANSYS software for the interface between two materials. The interface element provides bilinear behaviour, and this model assumes that the separation of the material interfaces is dominated by the displacement jump tangent to the interface as shown in the figure 2. The relation between tangential cohesive traction Tt and tangential displacement jump δt can be expressed as:

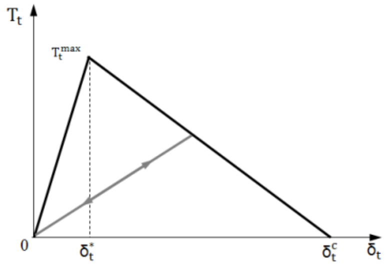


Figure. 2: Cohesive bilinear zone material model for the interface.

$$T_t = K_t \delta_t (1 - D_t) \qquad (1)$$

Where : Kt is the tangential cohesive stiffness ; τmax is the maximum tangential cohesive traction; δt* is the tangential displacement jump at maximum tangential cohesive traction; δtc is the tangential displacement jump at the completion of debonding; Dt is the damage parameter associated with mode dominated bilinear cohesive law, defined as:

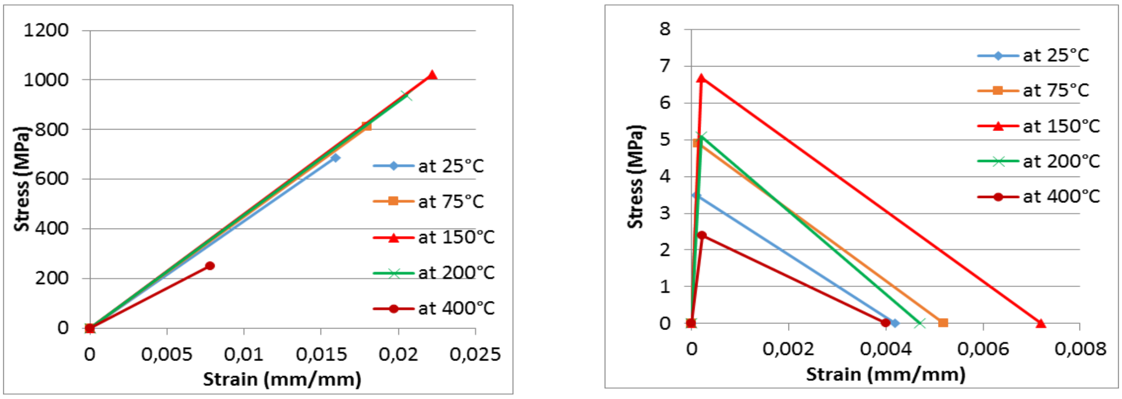
$$D_t = \begin{cases} 0 & \delta_t^{max} \le \delta_t^* \\ \left(\frac{\delta_t^{max} - \delta_t^*}{\delta_t^{max}}\right)\left(\frac{\delta_t^c}{\delta_t^c - \delta_t^*}\right) & \delta_t^* \le \delta_t^{max} \le \delta_t^c \\ 1 & \delta_t^{max} > \delta_t^* \end{cases} \qquad (2)$$

Material properties

Concerning the material properties at different temperatures, the experimental results of Rambo et al (2015, 2016, 2017) were taken as input data in the numerical model. These data were also used in the different finite analysis proposed by Rambo in his works. In order to correspond with the finite element model in our numerical study, the Young's modulus of the basalt textile and the concrete matrix need to modify. The calculated parameters in numerical model were also summarized in the following table 1.

Table 49: Calculated parameters used in the numerical model

Temperature	Basalt textile		Cementitious matrix		Interface
	Young module (GPa)	Tensile strength (MPa)	Young module (GPa)	Tensile strength (MPa)	Tmax (MPa)
25°C	43.20	688	34	3.5	2.9
75°C	45.00	810	29	4.9	4.6
150°C	46.05	1023	32	6.7	4.3
200°C	45.67	938	24	5.1	4.3
400°C	32.23	251	11	2.4	1.8

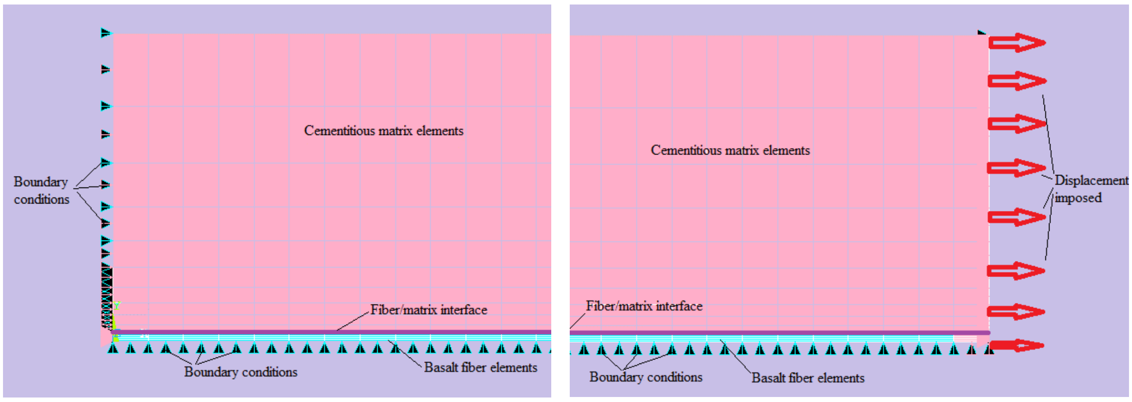


For basalt textile *For concrete matrix*

Figure. 3: Mechanical behaviour of materials in the numerical model at different temperatures

Meshs, boundary conditions and loads.

In regards to the dimension of basalt TRC composite specimen, a half sample model was constructed and analysed in the ANSYS Mechanical software thanks to the symmetry of loading, boundary conditions and materials. The reinforcement of basalt textile was made by a layer with the thickness depending on the reinforcement ratio. The reinforcement ratio was calculated based on the relation of the basalt textile cross section divided by the cross-section of the sample (1,99%). The thickness of the basalt textile layer was 0.1294mm in the numerical model. Concerning the meshing of the elements, the type of rectangular mesh with different sizes was chosen. The basalt textile layer in the TRC composite material is divided equally by five over its thickness. The cementitious matrix layer was also divided by ten over its thickness but with different sizes for the transmission between the fiber and matrix element sizes (see fig. 4). Concerning the boundary conditions, the displacement ΔX = 0 was imposed with all the nodes at the left end of the sample, and then, ΔY = 0 with all the nodes at the sample axis. The boundary conditions of sample were conducted in symmetry way as shown in the following figure 4.



At the left end *At the right end*

Figure. 4: Configuration of the matrix, fiber and interface elements in the 2-D model.

The tensile load was imposed by the move of the right end of the sample. In the numerical program, there were two charging steps for the purpose of clearly characterizing the behaviour of the composite at the first zone. The load application speed was modified by the time in the loading steps and sub-steps including the first time points and the last points of step 2. In order to exploit the numerical results in precise way, the imposed shift must be slowly applied. In this way, it could be obtained a lot of sub-steps in a load step.

RESULTS AND DISCUSSIONS

The numerical model with the reinforcement ratio of 1.99% showed the tension behaviour of basalt TRC composite at different temperatures. The figure 5 present "stress – strain" relationships of numerical results obtained at different levels of elevated temperature in comparison with experiment of Rambo et al (2015, 2016, 2017). In the figure 5, it could be found that basalt TRC composite gave the typical behaviour with three distinguishable linear phases in direct traction test as shown in the literature. The typical values of the "stress - strain" relationship as ultimate strength, cracking resistance, Young's modulus of trois phases were presented in the following table 2.

As results, it could be found that there was an agreement between the ultimate strength of the reinforcement ratio of 1.99% and that of the specimen reinforced by 5 basalt tissue layers in the Rambo's experiment at different temperatures. In comparison between two both results at room temperature, the ultimate strength for the numerical model and the Rambo's work was 13.67 MPa and 13.49 MPa, respectively (see table 2). In the temperature range from 75°C to 150°C, ultimate strength of TRC composite in numerical model also increased 14% and 15% compared to that at room temperature, respectively. In comparison with experimental results corresponding in the experiment of Rambo et al, this value was 15.60 MPa and 14.94 MPa, respectively for two results at 75°C, and 15.82 MPa and 15.30 MPa, respectively for two results at 150°C (see table 2). As results of numerical model in the temperature range from 200°C to 400°C, ultimate strength of TRC composite in numerical model decreased slightly 4% at 200°C and greatly 63% at 400°C relative to that at room temperature. In comparison with experimental results corresponding, the ultimate strength was 13.08 MPa and 12.40 MPa, respectively for two results at 200°C, and 5.00 MPa and 4.98 MPa, respectively for two results at 400°C (see table 2).

Table 2: Synthesis of the numerical results obtained and experiment of Rambo

Results	First crack values				Post crack values					
	PBOP (kN)	σBOP (MPa)	εBOP,I (%)	Et,I (GPa)	PUTS (kN)	σUTS (MPa)	Et, II (GPa)	Et, III (GPa)	εt, II (%)	εUTS,III (%)
Numerical at 25°C	-	3.54	0.013	33.90	-	13.67	0.40	0.69	0.40	1.65
Experiment of Rambo at 25°C	2.85	3.45	0.011	34.64	11.13	13.49	0.45	0.67	0.42	1.58
Numerical at 75°C	-	5.00	0.023	22.90	-	15.60	0.39	0.68	0.52	1.79
Experiment of Rambo at 75°C	3.73	4.85	0.021	28.57	11.48	14.94	0.31	0.79	0.71	1.66
Numerical at 150°C	-	6.78	0.028	31.53	-	15.82	0.23	0.70	0.72	1.79
Experiment of Rambo at 150°C	5.1	6.65	0.024	31.63	11.74	15.30	0.12	0.73	0.62	1.64
Numerical at 200°C	-	5.21	0.024	23.86	-	13.08	0.15	0.73	0.47	1.48
Experiment of Rambo at 200°C	4.19	5.09	0.036	23.82	10.22	12.40	0.15	0.64	0.39	1.50
Numerical at 400°C	-	2.51	0.025	11.16	-	5.00	0.15	0.62	0.40	0.83
Experiment of Rambo at 400°C	1.87	2.42	0.025	10.93	3.79	4.98	0.36	0.90	0.47	0.68

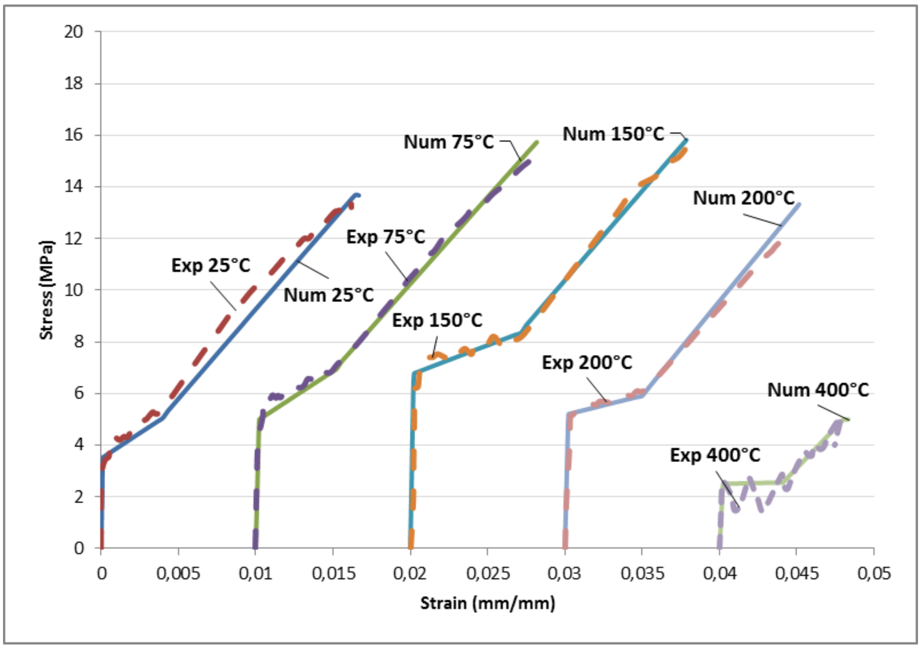


Figure. 5: Comparison of numerical and experimental results at different temperatures.

Concerning the cracking resistance of basalt TRC composite in the numerical model with the reinforcement ratio of 1.99%, it could be said that the evolution of this value as a function of temperature was like that of unreinforced matrix. Because when the matrix reached the limited state for cracking, the strain of composite material is still very small for a basalt textile contribution to improve the cracking stress value of composite material. It could be also found the same results in the works of Rambo in comparison between two both together. At room temperature, the cracking resistance of basalt TRC composite was 3.54 MPa and 3.45 MPa, respectively for numerical and experimental results. In the temperature range from 75°C to 200°C, this value increased 41%, 92% and 47%

relative to that at room temperature, respectively for temperature of 75°C, 150°C, and 200°C. In comparison with experimental result of Rambo et al, the cracking resistance was 5.00 MPa and 4.85 MPa at 75°C, 6.78 MPa and 6.65 MPa at 150°C, 5.21 MPa and 5.09 MPa at 200°C, respectively for both results. At the temperature of 400°C, there was a reduction (about 30%) of the cracking resistance relative to that at room temperature. The evolution of cracking resistance depending on the temperature is presented in the following figure 6.

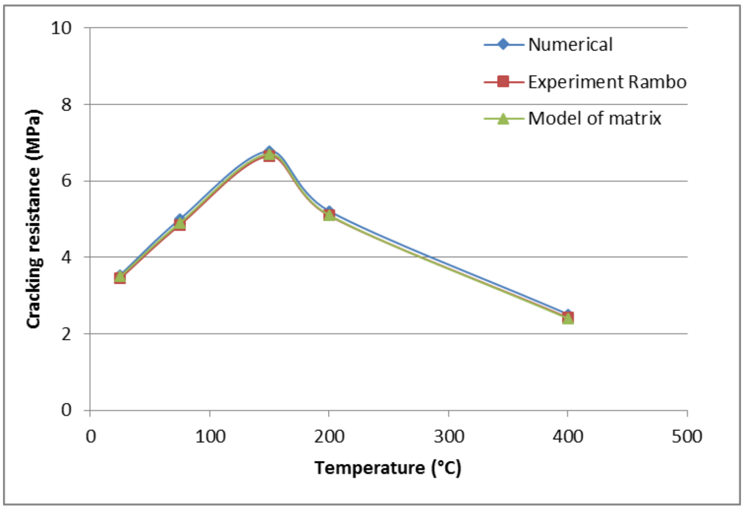


Figure. 6: Evolution of cracking resistance in the numerical and experimental results.

In regards to the Young's modulus of basalt TRC composite in three distinguished phases, the numerical model gave interesting results in comparison with that of Rambo's experiment. As results in the table 5, the Young's modulus in first phase was 22.90 GPa, 31.53 GPa and 23.86 GPa, respectively for the temperatures of 75°C, 150°C and 200°C, while this values in the Rambo's experiment was 28.57 GPa, 31.63 Gpa and 23.82 GPa, respectively for these temperatures above. In relation to that at room temperature, the Young's modulus in first phase in the numerical model at 400°C reduced 67.08% and reached a value of 11.16 GPa. Concerning the Young's modulus in thirst phase, it could be seen that the values presenting in the table 5 was not varied widely as the Young's modulus in first phase. Because of in this phase, there was only the work of basalt textile after complete cracking of the concrete matrix, so the Young's modulus of TRC composite fully depended on that of basalt textile which was not too varied in the input data (see table 1). The Young's modulus of thirst phase varied in the range from 0.62 GPa to 0.73 GPa, while this value in Rambo's experiment also varied in the low range from 0.64 GPa to 0.90 GPa. As results presented in the table 2, it could be seen that there was an agreement between two both results.

CONCLUSIONS

In this article, a finite element model was developed to characterize the elevated temperature behaviour of the basalt TRC composite on the mesoscale. This numerical model was validated and verified again the data from experimental tests performed by Rambo et al. The following conclusions can be drawn from the numerical results and experimental research:

The numerical model also agrees reasonably with experimental results on mechanical behaviour of basalt TRC composite at elevated temperature. Consequently, the model can be used to predict the basalt TRC composite behaviour at elevated temperatures (from 25°C to 400°C) from behaviour of the constituent materials. It could give also the mechanical properties of basalt TRC composite such as cracking and ultimate strength, strain at typical points, the Young modulus of the three zones on the "stress – strain" relationship. This paper shows the similar values on the "stress – strain" curve at different temperatures between the two numerical and experimental results.

In the future, it could be necessary to develop a 3D model with the thermomechanical properties of the constitutive materials (carbon textile and refractory concrete) validated by the experiment, under the action of mechanical and thermal loading in order to predict the thermomechanical behaviour of carbon textile – reinforced refractory concrete composite. In this model, it is also necessary to take into account the physicochemical, thermomechanical phenomenon in the specimen as the incompatibility of the deformation between fiber and cementitious matrix at high temperature, the variation of the reinforcement ratio as a function of temperature, etc.

ACKNOWLEDGMENTS

This research has been performed with the financial support of the LMC2 (thanks to its industrial projects) for the experimental works. This research has also been realized with the financial support of a doctoral scholarship from the Ministry of Education and Training of Vietnam. We would like to thank the team of technicians of the Civil Engineering Department of the IUT Lyon 1, University Lyon 1 for their technical support.

REFERENCES

I. Colombo, M. Colombo, A. Magri, G. Zani and M. di Prisco (2011). "Textile Reinforced Mortar at High Temperatures", *Applied Mechanics and Materials*, 82, 202-207.

D. A. S. Rambo, F. A. Silva, R. D. T. Filho, N. Ukrainczyk, and E. Koenders (2016). “Tensile strength of a calcium-aluminate cementitious composite reinforced with basalt textile in a high-temperature environment,” *Cement and Concrete Composite*, 70, 183–193.

D. A. S. Rambo, T. Filho, B. Mobasher (2017). “Experimental investigation and modelling of the temperature effects on the tensile behavior of textile reinforced refractory concretes”, *Cement and Concrete Composites*, 75, 51-61.

D. A. S. Rambo, F. A. Silva, R. D. T. Filho, O. F. M. Gomes (2015). “Effect of elevated temperatures on the mechanical behavior of basalt textile reinforced refractory concrete,” *Materials and Design*, 65, 24–33.

T. H. Nguyen, X. H. Vu, A. Si Larbi, E. Ferrier (2016). “Experimental study of the effect of simultaneous mechanical and high-temperature loadings on the behaviour of textile-reinforced concrete (TRC),” *Construction and Building Materials*, 125, 253–270.

J. Donnini, F. D. C. Basalo, V. Corinaldesi, G. Lancioni, A. Nanni (2017). "Fabric-reinforced cementitious matrix behavior at high-temperature: Experimental and numerical results, *Composites Part B*, 108, 108–121.

G. Alfano and M. A. Crisfield (2001). “Finite element interface models for the delamination analysis of laminated composites: mechanical and computational issues,” *International Journal for Numerical Methods in Engineering*, 50, 7, 1701–1736.