# Investigation of Mode I fracture toughness of red Verona marble after thermal treatment

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**ABSTRACT.** The present paper aims to assess the effect of freeze/thaw cycles on fracture behaviour of a natural stone: the red Verona marble. A wide variety of specimen types and methods to determine Mode I fracture toughness of natural stones are available in the literature and, in this context, the model originally proposed for plain concrete, i.e. the Two-Parameter Model (TPM), is adopted. Such a method is able to take into account the slow nonlinear crack growth occurring before the peak load, typical of quasi-brittle materials, with the advantage of easy specimen preparation and simple test configuration.
In the present paper, the atmospheric ageing is simulated by means of thermal pre-treatments consisting of freeze/thaw cycles. Experimental tests are carried out using three-point bending Single-Edge Notched (SEN) specimens, according to the TPM procedure. The effects of thermal treatment on both mechanical and fracture parameters are examined in terms of elastic modulus and fracture toughness, respectively.

**KEYWORDS.** Mode I Fracture Toughness; Red Verona Marble; Thermal Treatment; Two-Parameter Model.

## INTRODUCTION

Exterior building panelling made in natural stone was widely employed in the past, but it is used even today. One of the materials for such a panelling is the red Verona marble, a natural sedimentary stone, composed of lime-kilns and fine grains, with a colour variation from red to pink. Due to its formation, it contains defects such as inclusions and cracks. For such a reason, the evaluation of its mechanical properties is needed in order to ensure suitable safety of marble panelling in service.
In particular, fracture toughness is able to describe the material behaviour related to fracture failure [1, 2]. While a single-value measure of such a mechanical parameter is appropriate for brittle materials, a resistance-curve (R-curve) is required in the case of quasi-brittle materials, as the red Verona marble is, to take into account that fracture resistance increases with crack extension, promoting stable crack growth before the load peak.
Moreover, the above panelling is directly subjected to atmospheric agents during service life, of both chemical and physical nature, able to produce an ageing of the marble. Among the physical atmospheric agents, the temperature variations induced by seasonal range are also included.

In the present paper, the fracture behaviour of the red Verona marble is experimentally examined, focusing the attention on the effects caused by a thermal pre-treatment, consisting in freeze/thaw cycles, on peak failure load and critical stress-intensity factor. More precisely, the specimens employed in the experimental campaign are extracted from plates panelling the Auditorium of the University Campus in Parma. Such an investigation is here developed in order to understand the parting of a marble plate occurring from the Auditorium panelling. A possible cause seems to be the material ageing produced by temperature variations induced by seasonal range.

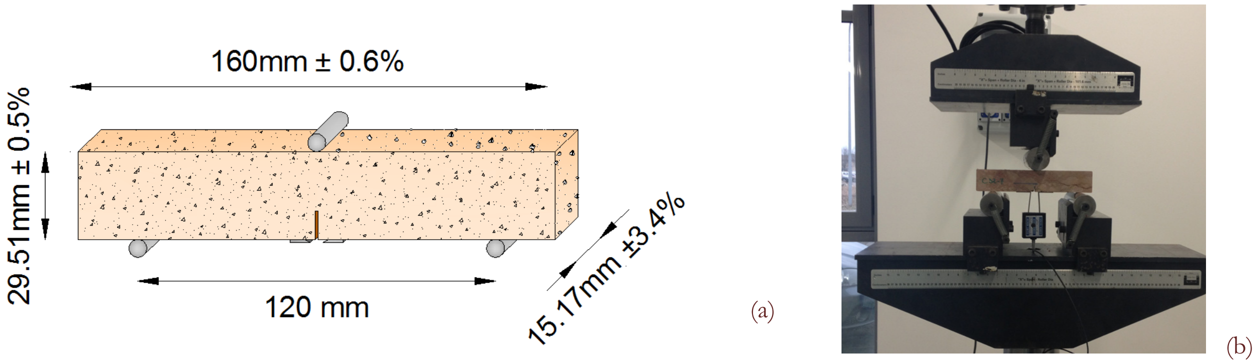


Figure 1: (a) Specimen geometry mean values and variations; (b) experimental set up of the Instron testing machine.

The investigations found in the literature are mainly aimed at analysing the influence of thermal pre-treatments, carried out at constant temperature, on fracture failure and toughness of natural stones [3-7] but, to the best knowledge of the present authors, no experimental data regarding the effects of such pre-treatments on the red Verona marble fracture parameters are available. Recently, the Two-Parameter fracture Model, originally proposed for concrete, has efficiently been employed to determine the critical stress intensity factor of a no-thermally-pre-treated Carrara marble [8]. Therefore, also for the easiness in specimens preparation and the simplicity of loading configuration, such a model is herein used to evaluate the fracture behaviour of both thermal pre-treated and as-received red Verona marble specimens.

## SPECIMEN DESCRIPTION AND EXPERIMENTAL PROCEDURE

For the experimental tests, we have used 14 red Verona marble specimens obtained from the same panel of stone and prepared in the same direction in order to minimize the errors generated due to the sampling. The prismatic specimens, having the geometry shown in Fig. 1a, have a notch in the middle cross-section with depth equal to about 9.54mm ± 8%.

We consider two cases (as-received and thermal pre-treated specimens) and, therefore, the minimum number of samples according to the indications contained in the UNI EN 12371 [9] is 14, since at least 7 specimens are needed for each test condition. The specimens tested are as follows: 7 as-received specimens (signed as C0-X), and 7 specimens subjected to 32 thermal cycles (signed as C32-X).

The thermal treatments, consisting in freeze/thaw cycles, are regulated by UNI 11186 [10]. The specimens are immersed in water at room temperature for 48 hours, in order to ensure a proper imbibition. Then, they are subjected to daily thermal cycles, each one to maintain the specimens at a temperature of -28°C for 6 hours and to spend the remaining 18 hours in water at room temperature. According to the UNI EN 12371 [9], periodic visual analysis of the specimen surface integrity are performed during the thermal cycles in order to assess possible damages caused by the thermal treatments. In the present study, this control has been made every 4 cycles and, on the scale from 0 (undamaged specimen) to 4 (specimen broken into two or more parts), the worst result obtained from our treated specimens is 2, i.e. small crack (<1mm) or detachment of small fragments (<30mm$^2$) have occurred.

The specimens are subjected to three-point bending by using an Instrom testing machine (Fig. 1b). The tests are performed under crack mouth opening displacement (CMOD) control by employing a clip gauge with an average speed of 0.05 mm/h and, according to the Two-Parameter Model (TPM) [7], the specimen is unloaded when the load is about 95% of the peak load along the post-peak branch, and subsequently reloaded in order to determine the unloading compliance.

## EXPERIMENTAL RESULTS

From the analyses of the fracture surfaces of the as-received as well as the thermally pre-treated specimens, we can observe two different types of specimen:

(a) The first type, named A-type and related to the as-received specimens (C0-2, C0-4, C0-5, C0-6) and the thermally pre-treated ones (C32-3, C32-4, C32-6), shows wide portion of Fe-hydroxides (represented by black crust coating the bioclasts or by refilling of stylolites) embedded in the matrix with allochemical grains on such failure surfaces;

(a) The second type, named B-type and related to the as-received specimens (C0-1, C0-3, C0-7) and the thermal pre-treated ones (C32-1 and C32-7), shows wide portion of matrix with a packstone texture, with compacted thin-shelled bivalves and interstitial micritic matrix on such failure surfaces.

Such types have different fracture behaviours, as can be observed from the graphs reported in the figures below, resulting from a statistical analysis of the data of each specimen type.

The experimental results regarding the specimens C32-2 and C32-5 are not plotted in the following graphs, since their failure is reached when the material behaves again elastically and, consequently, we are not able to determine the correct value of the peak load and of the corresponding critical Stress Intensity Factor (SIF).

From Fig. 2a, referred to the case of as-received specimens, we can observe that:

(i) For small values of the relative crack extension (lower than 10%), the peak load values are greater. This happens for the B-type: the mean value of the peak load is equal to 567.77 N, and its variation is about 3.38%;

(ii) For high values of the relative crack extension (greater than 10%), the peak loads obtained from the tests are smaller than the previous ones. This happens for the A-type: the peak load mean value is equal to 310.63 N and its variation is about 24.38%. We can observe that the reduction of the peak load mean value with respect to the first type is about 83%.

Also the experimental data related to the case of thermally pre-treated specimens are plotted in Fig. 2b: in this case, the difference between A-type and B-type is less significant, with a peak load mean value equal to 311.31 N and a variation of about 18.20%.

In the case of as-received specimens, Fig. 3a shows that:

(i) For B-type, the variation of the initial compliance is very small and, therefore, the mean value of the Young Modulus is equal to 50.02 GPa with ±7.55%;

(ii) For A-type, instead, the variation of the initial compliance is more significant and, therefore, the mean value of the Young Modulus is equal to 46.18 GPa with ±29.44%.

In Fig. 3b, analogous results are reported for the thermally pre-treated specimens. We can observe that, also in this case, the difference between the two types is less significant than that for the as-received specimens. Fig. 3b also shows a sensible variation of the initial compliance and, consequently, the mean value of the Young Modulus is equal to 34.07 GPa with ±44%.

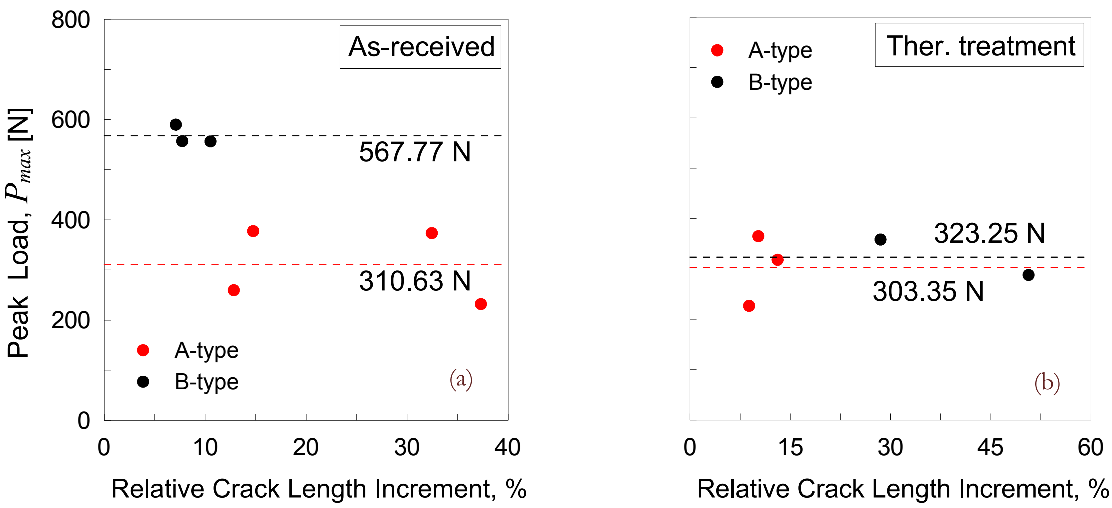


Figure 2: Peak load against relative crack length increment for: (a) the as-received and (b) the thermal pre-treated specimens.

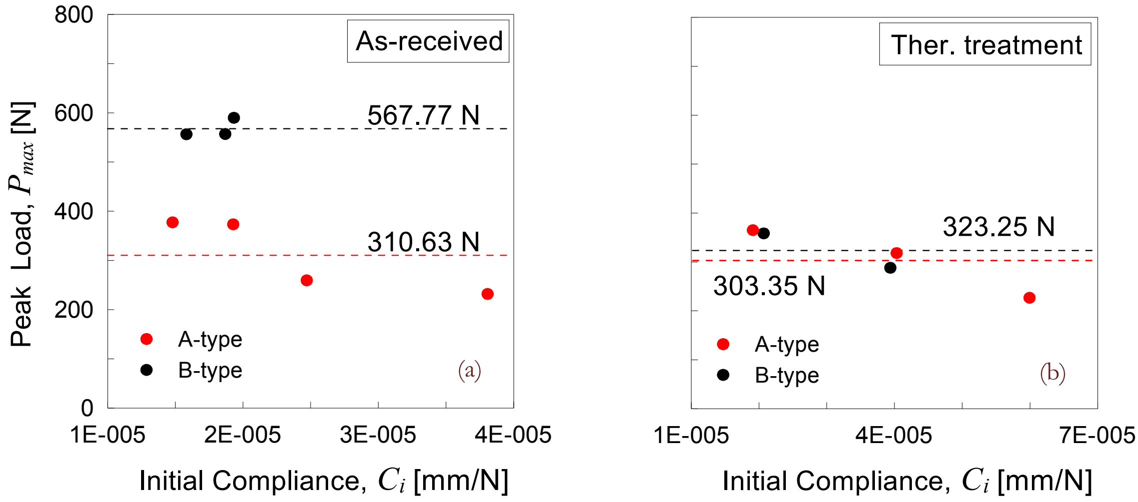


Figure 3: Peak load against initial compliance for: (a) the as-received and (b) the thermal pre-treated specimens.

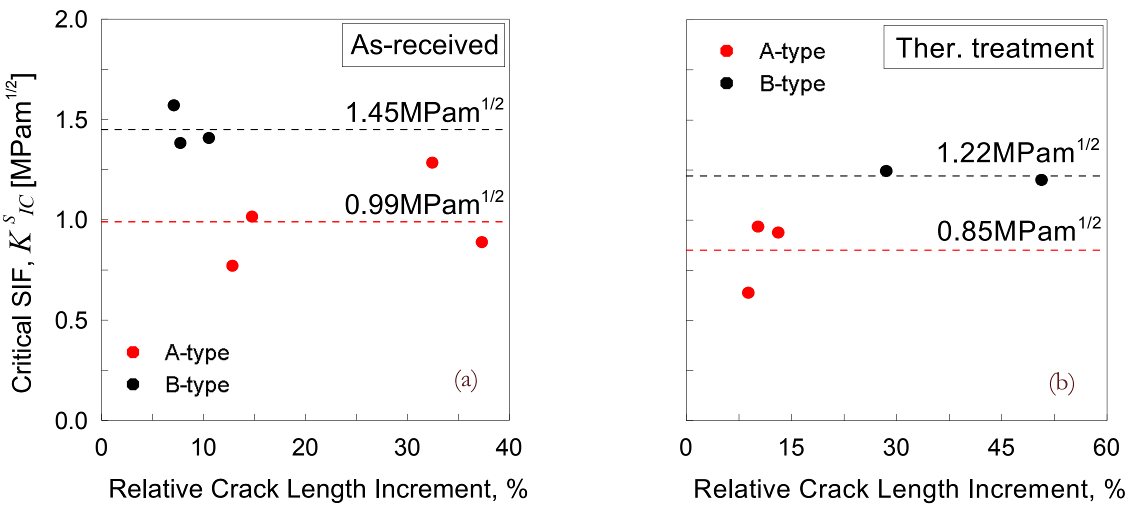


Figure 4: Critical SIF against relative crack length increment for: (a) the as-received and (b) the thermal pre-treated specimens.

The different mechanical behaviour of the two specimen types can also be observed in terms of critical Stress Intensity Factor (SIF) values. For the as-received specimens, Fig. 4a shows that:

(i) In the case of B-type, the critical SIF, $K^S_{Ic}$, reaches higher values with a small scatter of data. The critical SIF mean value is equal to 1.454 $MPa\sqrt{m}$, and its variation is about 7.02%;

(ii) In the case of A-type, the critical SIF, $K^S_{Ic}$, reaches values significantly smaller than the previous ones, and the scatter of data is greater. The critical SIF mean value is equal to 0.990 $MPa\sqrt{m}$, and its variation is about 22.27%. The reduction of the critical SIF with respect to the first specimen type is about 32%.

In Fig. 4b, analogous results are plotted for thermally pre-treated specimens, and we can observe that:

(i) For B-type, the critical SIF, $K^S_{Ic}$, reaches again higher values, but with a larger variation of the corresponding relative crack extension. The critical SIF mean value is equal to 1.223 $MPa\sqrt{m}$, and its variation is about 2.58%;

(ii) For A-type, the critical SIF, $K^S_{Ic}$, reaches values significantly smaller than the previous ones. The critical SIF mean value is equal to 0.848 $MPa\sqrt{m}$, and its variation is about 21.52%. The reduction of the critical SIF with respect to the first specimen type is about 38.8%.

## CONCLUSIONS

From the above tests on as-received specimens, we have obtained a peak load equal to 420.84 ± 147.93 N, a Young modulus equal to 47.83 ± 10 GPa, and a fracture toughness equal to 1.189 ± 0.299 $MPa\sqrt{m}$. Then, from the tests on the thermal pre-treated specimens, we have obtained a peak load equal to 311.31 ± 56.67 N, a Young modulus equal to 34.07 ± 15.27 GPa, and a fracture toughness equal to 0.998 ± 0.243 $MPa\sqrt{m}$.

The degradation of the red Verona marble mechanical properties due to the thermal cycles is evident, and can be quantified in terms of mean values: the peak load reduction is equal to about 26%, the Young modulus reduction is equal to about 28.77%, and the fracture toughness reduction is about 16%.

Moreover, for the first specimen type (A-type), the presence of wide portion of Fe-hydroxides:

(i) eases the stable crack growth behaviour related to its petrographic nature;

(ii) induces dispersion of results in terms of initial compliance and, therefore, of elastic modulus, such a behaviour being connected to its chaotic dispersion inside the matrix.

On the other hand, the second specimen type (B-type) is characterised by wide portions of material with allochemical grains. Such portions:

(i) partially inhibit the stable crack propagation, such a behaviour being related to its petrographic nature;

(ii) produce a mechanical behaviour rather constant in terms of initial values of compliance and, therefore, of elastic modulus, such an attitude being connected to its rather homogeneous distribution inside the matrix.

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