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Review

State-of-the-Art Review on Experimental Investigations of Textile-Reinforced Concrete Exposed to High Temperatures

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Abstract: Textile-reinforced concrete (TRC) is a promising composite material with enormous potential in structural applications because it offers the possibility to construct slender, lightweight, and robust elements. However, despite the good heat resistance of the inorganic matrices and the well-established knowledge on the high-temperature performance of the commonly used fibrous reinforcements, their application in TRC elements with very small thicknesses makes their effectiveness against thermal loads questionable. This paper presents a state-of-the-art review on the thermomechanical behavior of TRC, focusing on its mechanical performance both during and after exposure to high temperatures. The available knowledge from experimental investigations where TRC has been tested in thermomechanical conditions as a standalone material is compiled, and the results are compared. This comparative study identifies the key parameters that determine the mechanical response of TRC to increased temperatures, being the surface treatment of the textiles and the combination of thermal and mechanical loads. It is concluded that the uncoated carbon fibers are the most promising solution for a fire-safe TRC application. However, the knowledge gaps are still large, mainly due to the inconsistency of the testing methods and the stochastic behavior of phenomena related to heat treatment (such as spalling).

Keywords: fire; high temperatures; textile-reinforced concrete; textile-reinforced mortars

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1. Introduction

Embedding reinforcing textiles into inorganic matrices is an innovative technique which offers the possibility to manufacture thin, slender, and lightweight but robust structural elements. This cementitious composite material is known by several names in the literature and in practice. Textile-reinforced concrete (TRC), textile-reinforced mortar (TRM), or fabric-reinforced cementitious matrix (FRCM) are the most common. Since its first applications in the early 2000s, TRC has found its way into practice in a wide range of applications, either as a standalone material or as a component in composite members/structures, as it can exhibit high load-bearing capacity and ductility [1]. Several examples of TRM/TRC applications have been presented in various manuscripts, such as [2]. Some of the most interesting examples are related to the construction of pedestrian bridges, shell structures with various shapes and curvatures, load-bearing and non-bearing wall elements (either single panels or sandwich-type elements), roof elements, pipes, and several sorts of strengthening schemes of existing elements (structural strengthening of concrete columns and beams, load-bearing masonry elements, and infill walls). Hence, its mechanical performance has been widely investigated in the past decades and this research is still ongoing [2].

Despite the years of continuous investigations of the mechanical performance of TRC, there is some difficulty in compiling the obtained knowledge as there is no standard testing method yet [3]. The situation is even worse when it comes to thermal loading of TRC.

Apart from variations in the specimen geometry, the clamping method, the loading rate, etc., the performed tests found in the literature also vary in the heating rate, the method and the position of the temperature measurements, and the exposure time. However, most importantly, they vary in the combination of the heating and mechanical loading conditions. The performance of the matrix and the bond may differ dramatically, depending on whether the mechanically loaded specimen is in a hot or a cooled down state. Additionally, the load level at which the heating is applied also affects the specimens' response severely. The effects of these variations of the testing conditions are shown later on in the Discussion section of this paper. Therefore, the experimentations are categorized into three cases:

- Heating at constant load, where the specimens are pre-loaded to a constant stress level before the heating initiates. In this case, the influence of the load level is the decisive parameter.
- Load while heated, where the specimens are first subjected to an increased temperature which remains constant after reaching a target value and then, while being in hot conditions, the mechanical loading initiates. The dominant parameter, in this case, is the target temperature.
- Residual capacity after heating, where the specimens are first exposed to high temperatures and then, after a cooling down phase, they are tested mechanically. The maximum reached temperature and the heating/cooling rates are the dominant parameters in this case.

The physical response of cement composites during exposure to high temperatures is not expected to differ significantly from the response of the unreinforced matrix. Due to the low fiber volume fraction that is commonly used in TRC, the thermal properties (thermal conductivity, specific heat capacity, etc.) are not strongly influenced by the fibers [4]. Additionally, TRC is characterized by its non-combustibility and no smoke/gas emissions [5]. However, the presence of the fibers (especially when they are polymer coated) might cause a stochastic spalling behavior, i.e., either triggering or preventing spalling [4].

Several studies have been conducted on structural elements with TRC parts. For example, fire tests on sandwich panels with TRC faces have been conducted [6–8]. The fire performance of TRC strengthened elements (of concrete or masonry) has been widely tested too [9–19]. However, in all these studies, the performance of the element does not depend solely on the thermal response and the thermomechanical performance of TRC, but also on the substrate and their interaction (i.e., bond strength). The effect of increased temperatures on the bond strength between the substrate (concrete or masonry) and the TRC strengthening layer has been studied by [20–27]. The performance of TRM/TRC systems under elevated temperatures and fire conditions has been discussed in the review study of [28], which emphasized the behavior of strengthening schemes.

This review focuses on the behavior of TRC as a standalone material under thermal loading. The state-of-the-art review is discussed in the following paragraphs, by presenting the relevant studies in the three categories, mentioned above ((i) heating at constant load, (ii) load while heated, (iii) residual capacity after heating). This is carried out separately for tension and flexure tests. Results of tests focusing on the textile-to-matrix bond are also presented and discussed. The results extracted from each publication are normalized, in order to be able to perform comparisons and identify possible trends in the overall behavior of TRC under high temperature exposure. Conclusions, however, should be drawn with caution, because the available experimental data are limited, and the testing procedures vary significantly.

2. Performance of the Textile-to-Matrix Bond

The performance of TRC under thermal loads does not only depend on the performance of the constituent materials, that is the reinforcing fibers and the matrix, but also on their interaction, thus, on the matrix-to-fibers bond. Since the coating of the textiles is a common practice for several reasons (improvement of the textile-to-matrix bond, activation of the inner filaments, protection of the reinforcement from chemically aggressive matrices [2]), the bond strength depends on the coating nature. Therefore, the bond strength deterioration due to high temperatures depends a lot on the presence and the thermal behavior of the coatings.

The study of De Andrade Silva et al. [29] investigated the residual bond behavior of coated versus uncoated carbon fiber-reinforced concrete specimens exposed to temperatures up to 600 °C, by double-sided pull-out tests. Liu et al. [30] tested the effect of temperature on epoxy-impregnated, single and double yarn specimens, of glass and basalt fibers, embedded into a cementitious matrix. The exposure temperatures were up to 600 °C and the specimens were tested after cooling down (residual capacity). The effect of temperature on the maximum load recorded at the pull-out tests is shown in Figure 1.

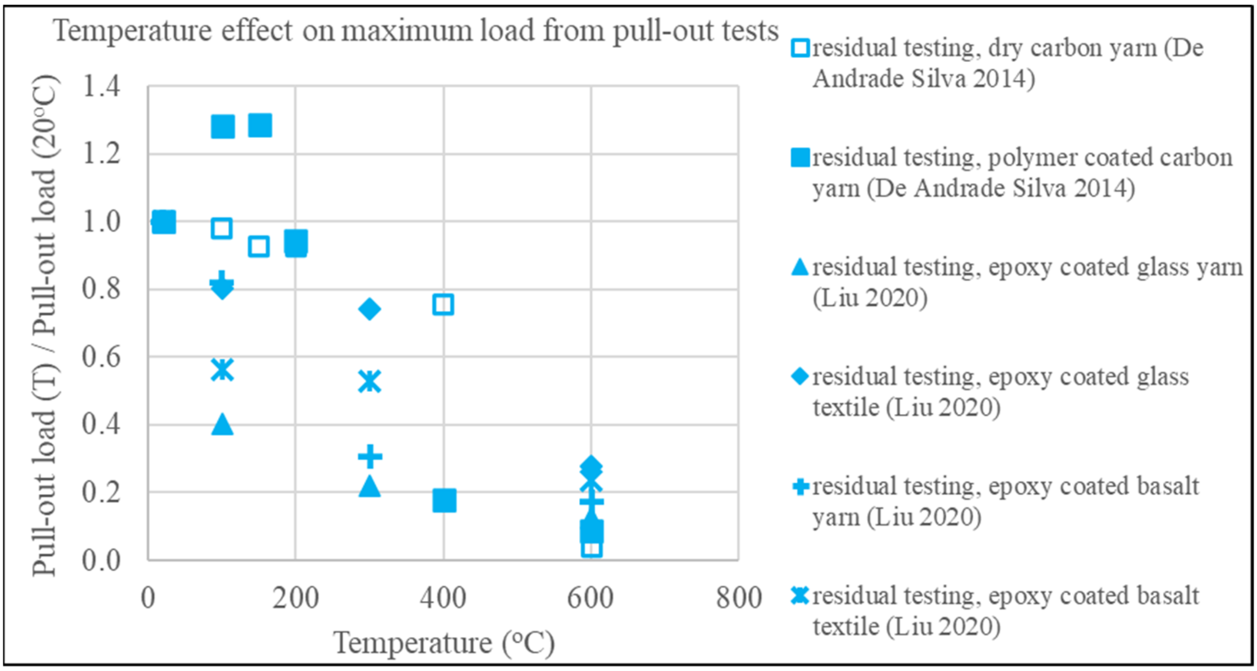

Figure 1. Influence of exposure temperature on the maximum pull-out load on TRC specimens.

The uncoated (dry) textiles were barely affected at temperatures up to 200 °C, regardless of the testing conditions. After exposure to 400 °C, the residual bond properties degraded due to chemical degradation of the matrix, dehydration, and changes in the interphase morphology. Hence, the pull-out load experienced a fast reduction.

Regarding the coated textiles, for temperatures below 200 °C, De Andrade Silva et al. [29] reported improved performance of the polymer-coated textile-reinforced specimens tested after cooling down (due to the melting and re-stiffening of the coating). On the contrary, all cases tested by Liu et al. [30] experienced significant reductions (ranging between 20% and 60%) after exposure to 100 °C. The differences between the results might lie in many parameters, such as the different thermomechanical behavior of each polymer coating, the different testing mechanism and different geometry, the matrix compositions, etc. Hence, the results are not adequate to draw reliable results.

After exposure to 300 °C and 400 °C, the residual bond strength deteriorated severely in all cases, since the polymer coatings were completely decomposed, leading to a loss of bond strength. After exposure to 600 °C, the degradation of the fibers was also severe and the pull-out load was very low, regardless of the surface treatment. In many cases, failure was reported due to fiber rupture and not due to pull-out. However, the results are still limited, and they present large variations; therefore, more research is necessary.

The studies of Rambo et al. [31,32] have also investigated the textile-to-matrix interface, by scanning electron microscopy analysis. However, these studies have focused on the performance of the composite rather than on the bond specifically. The observations generally comply with the results reported by De Andrade Silva et al. [29] and Liu et al. [30], but no pull-out tests have been conducted to compare the results numerically. Therefore, the results of these studies [31,32] are presented in the following paragraphs where the performance of the composite is discussed.

3. Tensile Performance of the Composite

3.1. Heating at Constant Tensile Load

The most realistic scenario of thermal loading of a structural element due to fire is heating while bearing a constant load. Additionally, in a fire event, the heating rate of the directly exposed elements (when the fire is fully developed) is very high. Depending, however, on the linings and the possible existence of a substrate, the TRC elements might not be heated up so quickly. Therefore, it is reasonable to investigate the material's performance at several heating rates.

Only three studies have been published where the TRC specimens were subjected to these conditions [33–35]. In all cases, the composite consisted of cement-based mortars reinforced with glass or carbon fibers. The results are presented in Figure 2, where it is observed that the heating rate and the load level played major roles in the results.

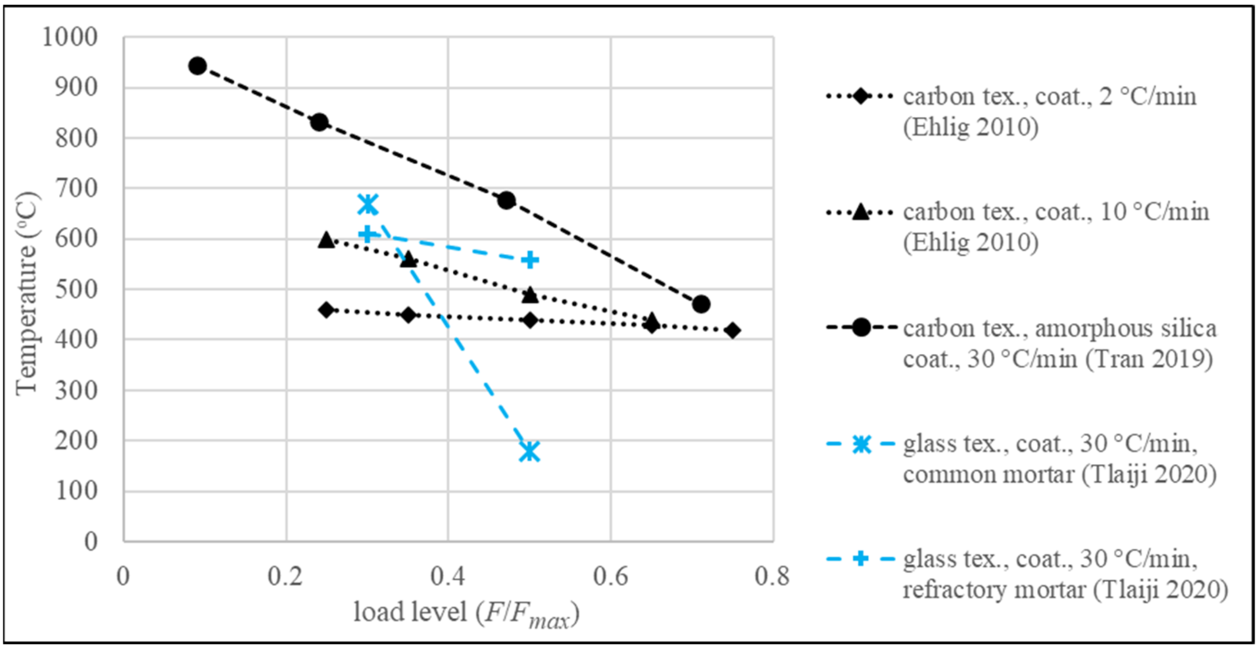

Figure 2. Failure temperatures against tensile load level for TRC specimens heated at constant load.

For a slow heating rate, such as 2 °C/min, the results on carbon-reinforced TRC showed that the failure temperature remained constant at 420–460 °C (thus below the oxidation point of carbon fibers which is around 500 °C [36–38]), meaning that the duration of exposure was also constant. In this case, failure was time- and temperature-dependent, and the load level did not seem to affect the results. Failure probably occurred due to the deterioration of the bond between the reinforcement and the matrix, which was triggered by the coating burn-off, a process controlled by temperature and exposure duration. On the contrary, for higher heating rates the dependence on the load level became more prominent. For low stress levels, the failure temperature was significantly higher than for high stress levels. No arguments were given in the aforementioned studies about this behavior. However, it could be assumed that the pre-formed cracks at higher load levels allowed for faster heating of the reinforcement locally (in the vicinity of the cracks), leading to an earlier failure. Another possible explanation is the effect of the thermal shock induced by the high heating rates. It is well known that normal concrete is severely affected by the thermal shock induced by high heating rates [39]; hence, a similar effect on the cement-based matrices might be the reason that caused the earlier failure. This is also supported by the fact that in the study of Tlaiji et al. [35], the specimens with refractory (thus, more thermally stable) matrices suffered less damage than identical specimens with a common cement-based matrix exposed to the same conditions.

3.2. Loading at Increased Temperatures or after Cooling Down

Most of the published experimental investigations concern TRC subjected to one of the following two cases: (i) *load while heated* or (ii) *residual capacity after heating*. The range of testing temperatures among different studies varies from slightly elevated temperatures (in the order of 75 °C) up to 1000 °C. The heating rates of the available test results vary from 2.5 to 25 °C/min. However, the temperature in many cases was not monitored by sensors embedded inside the specimens. To ensure uniform heating of the specimens, the target temperature was usually kept constant for an amount of time (exposure duration) which varied between 30 and 120 min. Many different matrix compositions were investigated within these studies, including common cementitious mortars, high alumina refractory cement, and lime-based mortars. Finally, glass, carbon, and basalt fiber reinforcements were used.

In an attempt to draw new overall conclusions, a comparative study was conducted, based on the available experimental data. However, we are reminded that the testing conditions vary a lot, and, as discussed previously, it makes more sense to compare results from specimens tested under the same conditions; thus, the results are compared separately for *load while heated* conditions and *residual capacity after heating* conditions. Moreover, we are also reminded that other testing parameters, such as the specimen's size and shape, clamping method, loading rate, etc., also have an impact on the results, whereas the standard deviations of the results were not always available. Therefore, the comparison is only made to identify possible trends in the constitutive behavior of the material and the effect of important parameters.

3.2.1. Initial Stage

A common observation from all the available data [31,32,34,40–45] is that the originally three-staged response (in ambient conditions) decayed to a two-stage response and gradually to practically linear, with increasing temperature. At temperatures above 400 °C, almost all tested specimens had a linear behavior until failure, indicating an already severely cracked matrix. Therefore, the initial stage is only considered for temperatures up to 400 °C.

It can be observed from Figures 3 and 4 that it is practically impossible to extract safe results regarding the behavior of the initial stage of TRC at high temperatures. The reason is that the results of the considered studies vary significantly. An important remark is that the behavior of this stage is strongly dependent on the matrix composition and less on the reinforcement. Hence, apart from the inconsistency in the testing methods, another factor that leads to a large inconsistency of the results is introduced: the matrix composition. Many of the studies that are included in Figures 3 and 4 were performed with refractory cement matrices, consisting of alumina cement and/or aggregates. The compositions, however, varied a lot, and in many cases they are not given in detail.

A remark that can be made for the cracking stress (σ_1) and the elastic modulus (E_1) is that there is a descending trend when the load is applied in heated conditions, regardless of the fiber material and the use of coating (Figures 3a and 4a). However, when testing the residual behavior, σ_1 and E_1 might either present a decay or an increase for temperatures up to 300 °C (Figures 3b and 4b). This is observed for all cases of matrix, namely refractory cement, ordinary Portland cement (OPC), and lime-based mortars. Additionally, it is noted that in most of the cases where an increase in the residual cracking stress was noted, coated textiles had been used [31,40,43]. Hence, this phenomenon might be attributed to the effect of the improved bond strength that is observed at residual capacity tests at temperatures up to 300 °C (see Section 2). However, it could also be attributed to the effect of the mortar's strength increase after exposure to temperatures even up to 300 °C (which is also common for concrete), mainly caused by the shrinkage due to water evaporation [31]. The results of Kapsalis et al. [45] showed a good agreement between the degradation of the cracking stress and the elastic modulus of the TRC specimens and the same properties of the unreinforced matrix. Nonetheless, based on the aggregated results from all the available studies, no trends can be spotted in the effect of the matrix at the first stage of TRC's behavior (which is mainly controlled by the matrix). Hence, it becomes obvious that more research is needed to interpret the results of Figures 3 and 4.

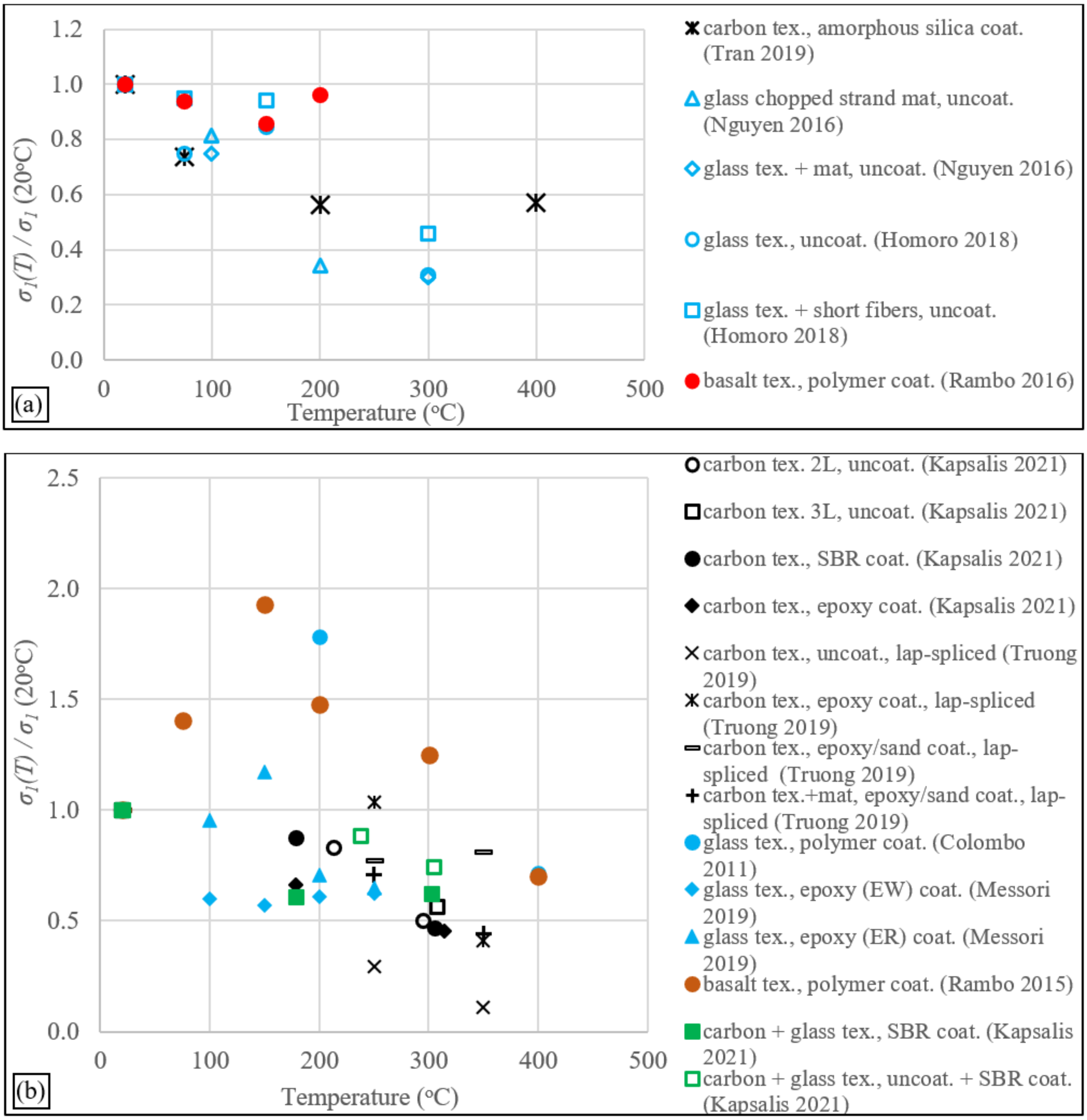

Figure 3. First cracking stress (σ_1) versus exposure temperature for various TRC compositions; (**a**) specimens loaded while in heated conditions; (**b**) specimens tested after cooling down.

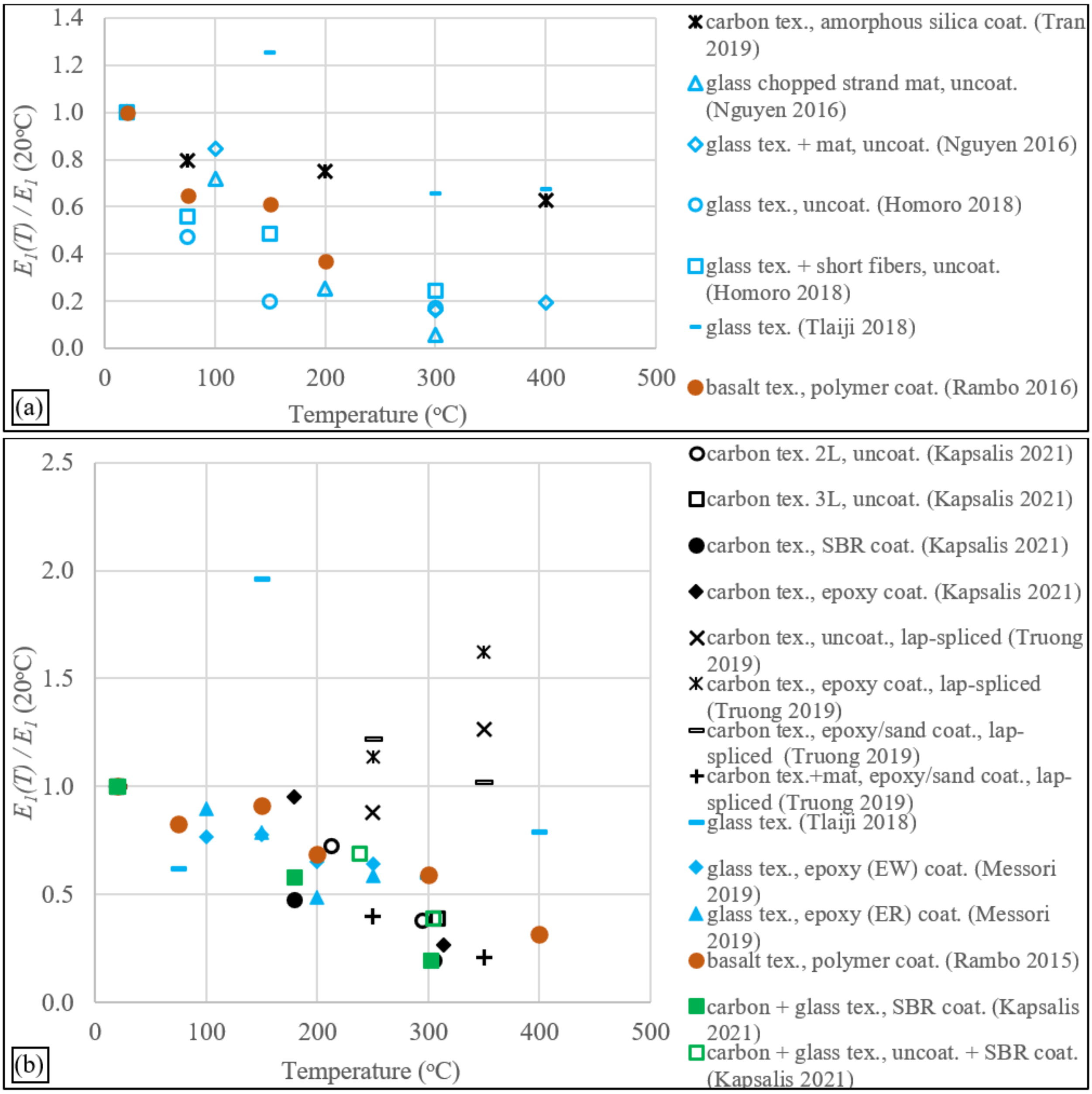

Figure 4. Elastic modulus (E_1) versus exposure temperature for various TRC compositions; (**a**) specimens loaded while in heated conditions; (**b**) specimens tested after cooling down.

3.2.2. Post-Cracking Stage (Stage III)

Regarding the failure stress (σ_3) of the composites, decay is noted for the *load while heated* conditions (see Figure 5a), although the variations in the data are vast, even among similar TRC compositions (e.g., reinforced with uncoated glass fibers). In two cases [35,46], the decay is not monotonic, but some fluctuations are observed. The fluctuations observed for temperatures up to 300 °C in the studies of Tlaiji et al. [35,46] were attributed to the dehydration and re-hydration phenomena of the matrix and the subsequent expansion and shrinkage. The value of $\sigma_3(T)/\sigma_3(20\ °\text{C})$ ratio, however, did not exceed 1 in any case. The same researchers also highlighted the effect of the matrix composition on the thermomechanical performance, by conducting the same tests on specimens with a common cement-based matrix [46] and a refractory cement matrix [35]. It was, however, concluded, in the latest study [35], that the main factor determining the performance of the heated specimens was not the chemical composition of the matrix but the size of the aggregates.

Consequently, the specimens manufactured with the refractory matrix suffered, in some cases, higher degradations than the specimens with the common matrix. This contradicted the previously mentioned results from the same study (see Section 3.1) where, in the case of heating the specimens while bearing a constant tensile load, the specimens with the refractory matrix resisted much higher temperatures. Therefore, there is a clear indication that the matrix composition does not affect the performance of TRC in a straightforward way, but in combination with the testing conditions. Thus, more research is needed.

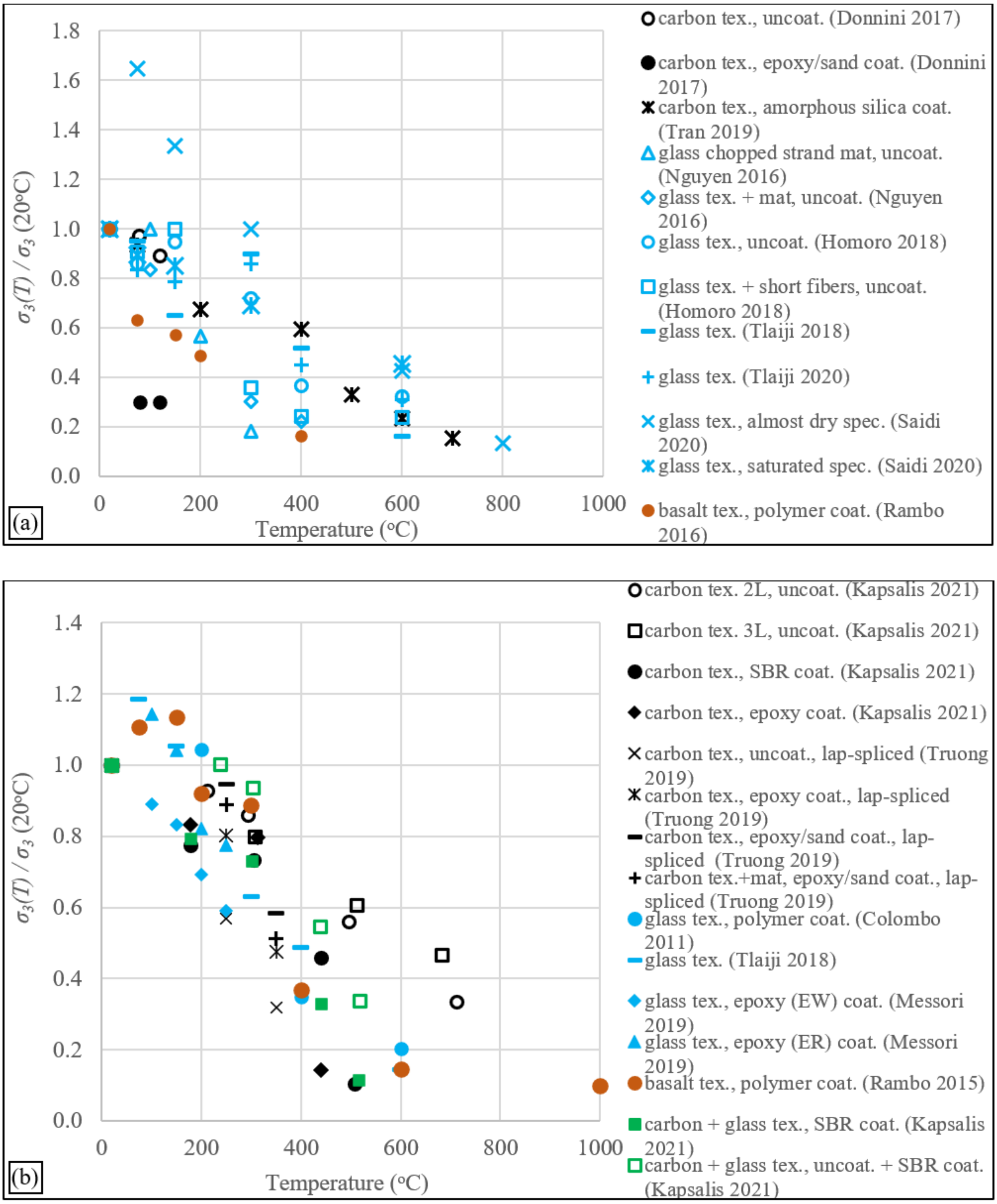

Figure 5. Ultimate stress (σ_3) versus exposure temperature for various TRC compositions; (**a**) specimens loaded while in heated conditions; (**b**) specimens tested after cooling down.

Another significant parameter for the performance of TRC at high temperature is the water content. The study of Saidi et al. [47], however, is the only one where this parameter was investigated by performing identical tests on identical specimens, varying only by their water content ("almost dry" or "saturated"). Interestingly, the "almost dry" specimens of this study are the only ones where an increase in maximum stress was observed, at temperatures between 20 °C and 150 °C (see Figure 5a). This was attributed to shrinkage by the evaporation of the small amount of water that remained in the specimens. On the contrary, the "saturated" specimens experienced a continuous drop of σ_3, similar to all the other specimens tested in *load while heated* conditions. This was attributed to the increase in the internal pore pressure, which can cause micro-cracks and internal damage in the matrix and fiber-matrix interface. Except for [47], none of the studies cited in Figure 5a reported a drying procedure before conducting the thermomechanical tests. In all cases, the specimens were tested shortly after the completion of a 28-day wet curing; thus, it can be safely assumed that all tested specimens had a considerable amount of water inside their pores. This explains the lack of strength increase in all those studies and, hence, the agreement between all these studies and the saturated specimens from the study of Saidi et al. [47].

On the other hand, the tests of the *residual capacity* (see Figure 5b) indicate that the mechanism of the polymer melting and re-hardening after cooling down results in a better textile-to-matrix bond (as discussed in Section 2). This is shown by the increase in σ_3 for temperatures below 200 ºC. The only exception was in the case of an epoxy-impregnated glass textile with an aliphatic diethylenetriamine hardening agent (namely EW) of the epoxy resin [43]. However, specimens from the same study with identical properties, except for the hardening agent of the epoxy resin (namely ER), also presented an increase in σ_3 after exposure to temperatures up to 150 ºC. Despite the one exception, the scatter of the experimental data for the residual strength is surprisingly lower than the other properties. The data presented in Figure 5b also indicate that the use of uncoated carbon fibers leads to the slowest reduction in the failure strength of the composite; thus, they comprise the most promising solution for applications of TRC with possible exposure to high temperatures [45].

Similar observations can be made from Figure 6, regarding the post-cracking modulus (E_3) of the TRC compositions. The results are still limited and scattered, but a trend can be identified for temperatures up to 300 °C: the coated textiles result in worse behavior when loaded at heated conditions (compared with ambient behavior) and in better behavior when their residual capacity is tested. The use of uncoated carbon fibers leads to a practically stable residual post-cracking modulus.

Regarding the strain at maximum stress (ε_3), Figure 7 shows that the scatter is vast for temperatures up to 300 °C and no straightforward trend can be identified. Some cases had increasing and decreasing values of ε_3, sometimes with extreme values of the ratio $\varepsilon_3(T)/\varepsilon_3$ (20 °C) (such as values of 3 and above, as seen in Figure 7a). The strain at failure depends significantly on the textile-to-matrix bond properties and the anchorage conditions of the specimens. As expected, the higher values are observed for polymer-coated textiles, where the bond deteriorated due to the polymer's degradation, and thus the post-cracking stiffness dropped. However, there are cases where E_3 and ε_3 did not monotonically increase or decrease with increasing temperature. The fluctuations which are observed for temperatures up to 400 °C indicate the stochastic nature of the bond strength degradation due to high temperatures.

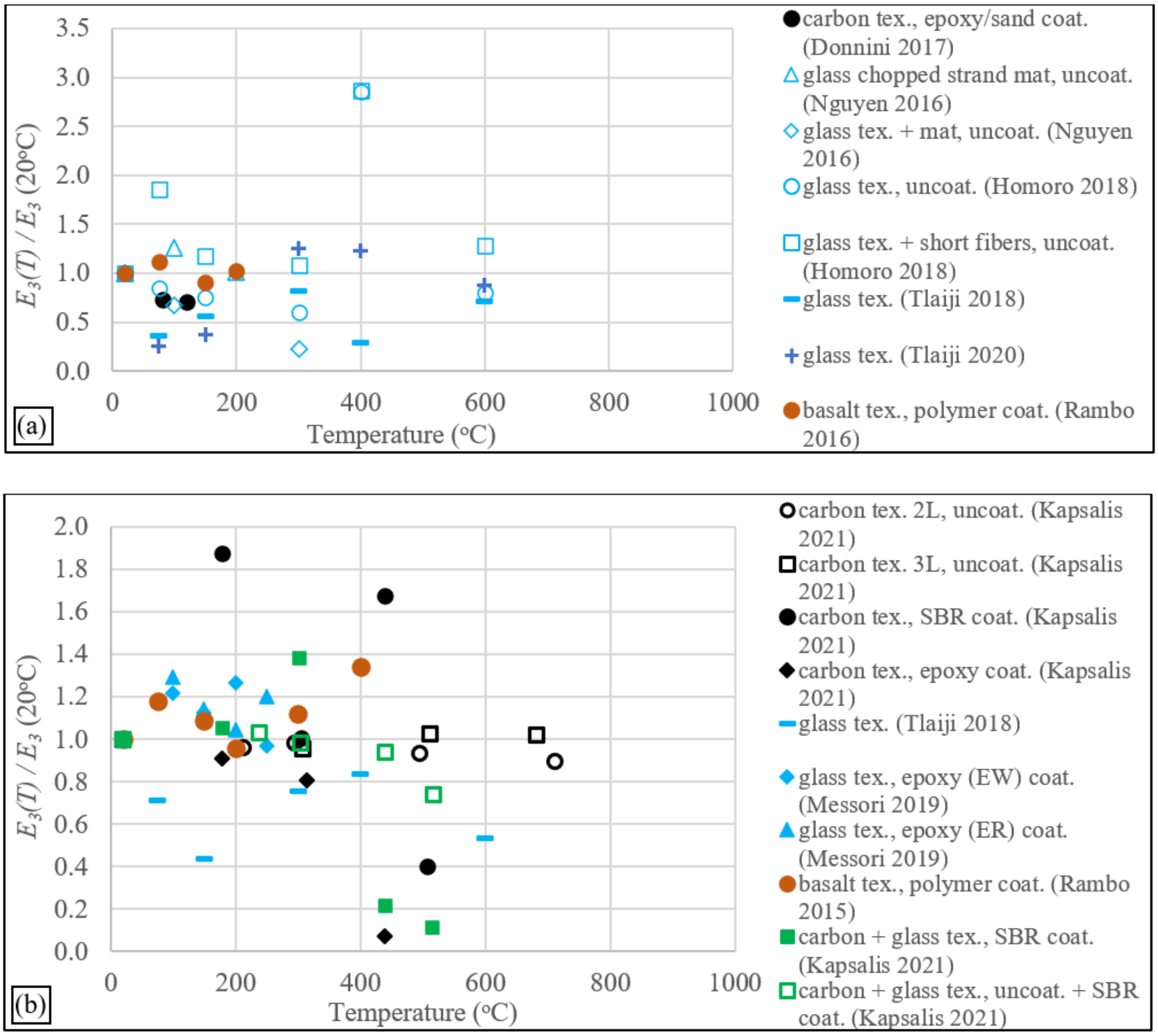

Figure 6. Post-cracking modulus (E_3) versus exposure temperature for various TRC compositions; (**a**) specimens loaded while in heated conditions; (**b**) specimens tested after cooling down.

From Figures 5–7, it is clear that direct comparison between parts (a) and (b) cannot be made, since the data vary significantly. This indicates that the testing conditions are one of the most influential parameters for the behavior of TRC at high temperatures. One of the mains reasons for this is the already-discussed phenomenon of the polymer coating melting and re-stiffening after cooling down, which leads to an improved bond. Indeed, most of the experimental data where σ_3 presented an increase were obtained from specimens reinforced with coated textile reinforcement [31,40,43]. Therefore, as indicated already in Section 2, it is again shown that the presence of coating (or impregnation) is—in combination with the loading conditions—a decisive parameter for the performance of TRC under high temperatures.

Another important remark based on these results is that the effect of the fiber material is not straightforward. Despite the superior performance of carbon fibers at increased temperatures, compared with glass and basalt fibers [48], such a case is not observed from the comparisons of the discussed studies. On the contrary, it is observed that the decay laws of σ_3, E_3, and ε_3 of carbon, glass, and basalt fibers do not present a trend that can be clearly linked to the material (see Figures 5–7). This indicates that at this temperature range the effect of the testing conditions and the textile finishing is far more significant than the fiber material.

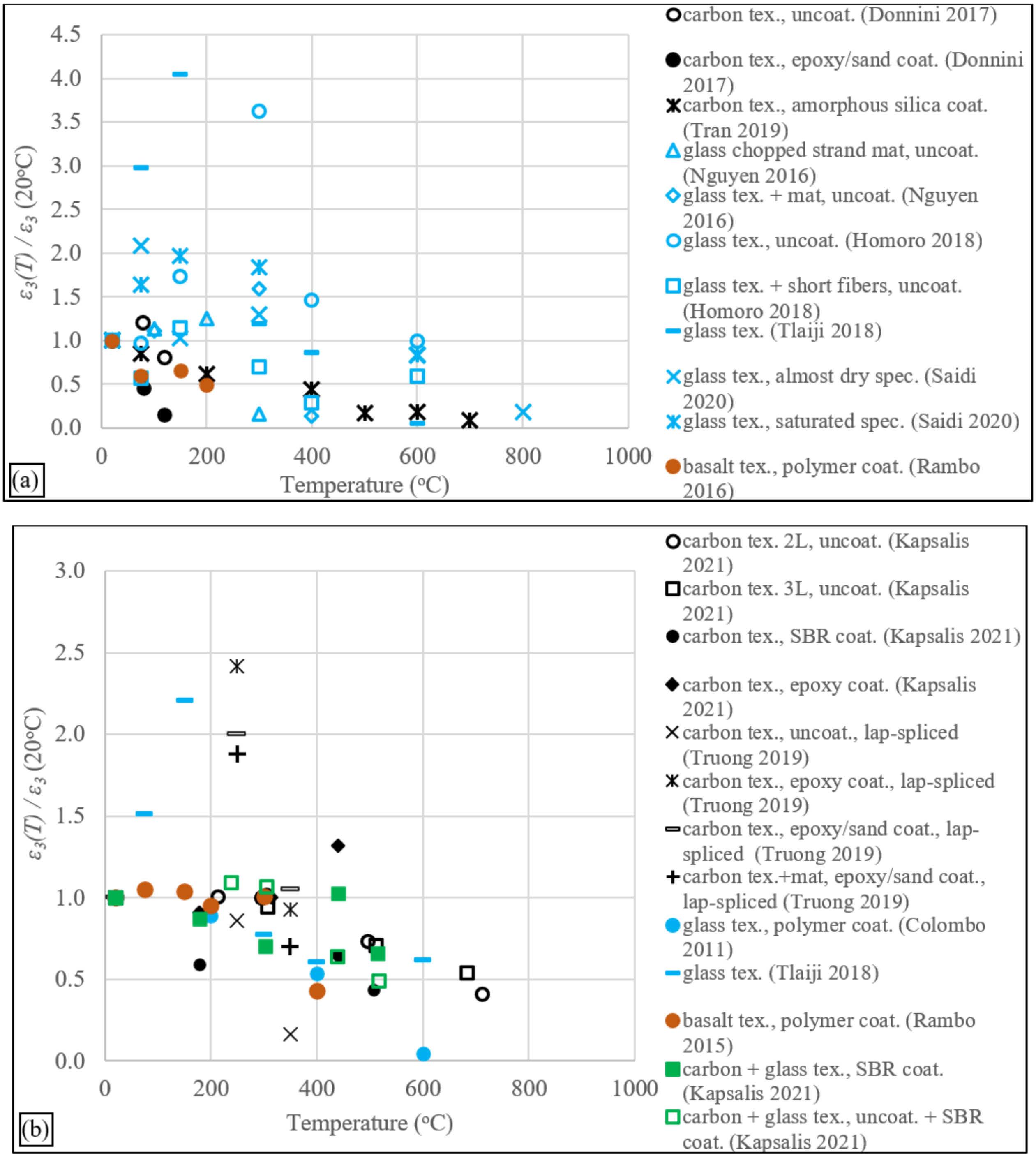

Figure 7. Strain at maximum stress (ε_3) versus exposure temperature for various TRC compositions; (**a**) specimens loaded while in heated conditions; (**b**) specimens tested after cooling down.

As a final remark, some results regarding the effect of the testing conditions can be extracted from the studies of Rambo et al. [32] and Tlaiji et al. [46]. They are the only ones who conducted tests with *load while heated* and *residual testing* conditions at identical specimens and with the same test set-ups; therefore, a direct comparison of the testing conditions can be made. As Rambo et al. [32] reported, the specimens tested after cooling down had superior performance (higher stress for the same strain) to the specimens tested in hot conditions. Additionally, the cracking pattern of the cooled down specimens was always denser than the specimens tested in hot conditions, indicating an improved bond. The study of Tlaiji et al. [46] however showed that for temperatures around 300 °C, the residual tensile strength (σ_3) can be lower than the one measured while heated, although for temperatures above 400 °C the differences between the two testing methods became insignificant. The elastic modulus (E_3) was also higher after cooling down from temperatures around 150 °C, while the differences were insignificant for temperatures above 300 °C. Finally, the strain at ultimate stress (ε_3) was significantly higher for specimens tested at heated conditions, which is expected since the melted coating leads to more severe debonding and slippage of the reinforcement.

4. Flexural Performance of the Composite

The flexural performance of TRC has been studied less than the tensile behavior. Six studies have been published discussing tests on TRC specimens with rectangular prism cross-sections (in all cases, the dimensions of the specimens were not more than 500 mm × 100 mm × 40 mm) and one study with tests on I-shaped beams. Two of these studies were conducted with heating applied while the specimens bore a constant load, and the rest studied the residual performance of the heated specimens.

In the study of Antons et al. [49], flexure tests were performed on TRC specimens (cementitious matrix reinforced with glass fibers) heated while bearing a constant load, and the discussion focused on the strain evolution with increasing temperature as a function of the load level. The results showed that below 300 °C, the stress level does not affect the strain increase with temperature, but for temperatures above 300 °C, the stress level started affecting the strain development, which was faster for higher loads. The failure temperature dropped with increasing load levels, as it had been observed by the tensile tests in heating at constant load conditions, with high heating rates (see Figure 2).

Another case where TRC was tested in flexure with simultaneous mechanical and thermal loading is the study discussed by Kruger and Reinhardt [50] and Buttner et al. [51]. This is the only one where fire resistance tests (following the German standards) were conducted on medium-scale TRC elements. The specimens were I-shaped beams made of fine-grained OPC matrix and alkali-resistant glass (uncoated or epoxy-impregnated) or uncoated carbon fibers. The superiority of using uncoated carbon fibers was proven by the much longer fire exposure durations that the carbon-reinforced specimens endured. Additionally, the carbon fiber-reinforced elements presented decreasing deflection at some point, probably due to the negative thermal expansion coefficient of carbon fibers, which led to compressing the bottom flange of the beam.

The flexural performance of carbon fiber-reinforced specimens was also discussed in the studies of Xu et al. [52,53] and Shen et al. [54]. They performed tests on the residual capacity of OPC or CAC (calcium aluminate cement) matrices, reinforced with epoxy-impregnated carbon textiles and with non-impregnated ones. The negative effect of the epoxy impregnation was intense in the studies of Shen et al. [54] and Xu et al. [53]. The specimens with epoxy-impregnated textiles were practically destroyed by the intense delamination (after exposure to 300 °C and 400ºC, respectively), which was attributed to the degradation of the epoxy resin that severely deteriorated the textile-to-matrix interface. Additionally, in all cases, the failure was brittle, presenting several shear cracks. On the contrary, the specimens with uncoated textiles presented much better residual performance, even up to 800 °C, with a ductile behavior. The effect of the utilized matrix (CAC vs. OPC) was only tested in the second study of Xu et al. [53]. It was concluded that the CAC matrix is slightly better than the OPC, with the difference in load-bearing capacity and surface deterioration being obvious only at 800 °C. Finally, the effect of adding short polypropylene fibers was tested in the first study of Xu et al. [52]. It was observed that the addition of PP fibers drastically improved the flexural performance at ambient conditions, and after exposure to 120 °C, but they had no effect on the mechanical behavior when the specimens were exposed to 200 °C for 90 min since the polymer had melted.

Li et al. [55] studied the residual flexural behavior of basalt fiber-reinforced alkali-activated mortar (AAM) after exposure to temperatures up to 800 °C. The basalt reinforcement was impregnated with epoxy resin. Short, hooked steel fibers were also added to the mixture. The witnessed thermal degradation was mainly attributed to the deterioration of the interface between the matrix and the reinforcement. This was the effect of not only the epoxy resin degradation, but also of the deterioration of the matrix. The AAM suffered increasing deterioration with increasing temperature, by forming cracks, undergoing a microstructural change at 600 °C, and phase transformation at 800 °C (as indicated by scanning electron microscopy, energy dispersive spectroscopy, and X-ray diffraction). This study also showed the effect of the steady-state exposure duration. The target temperatures were kept steady for one or two hours. The exposure duration had a significant effect for the first cracking point for a temperature of 400 °C, with the exposure duration of 2 h leading to lower stress and deflection capacity. This was not observed for temperatures lower or higher than 400 °C. The effect of the exposure duration was more evident for the peak stress and deflection. For temperatures of 400–600 °C, longer exposure led to higher degradation. In the study of Nguyen et al. [41], the effect of exposure duration was also investigated. The exposure durations were 30 or 120 min, but the target temperature was only 100 °C; hence, no effect of the exposure duration was identified.

Finally, Kapsalis et al. [56] also tested the residual flexural performance of TRC. This is, however, the only study where this was carried out after fire exposure. The small-scale specimens that were manufactured for this study were subjected to fire tests with durations of 15 or 30 min following the ISO 834 [57] temperature–time curve. The matrix was an OPC mortar with short polypropylene fibers, and the reinforcement was carbon or glass fibers or a combination of both. In all cases, the textiles were coated with an SBR (styrene-butadiene rubber) polymer. The bending tests that were conducted after a natural cooling down showed that specimens of this geometry, reinforced with SBR-coated textiles, have no residual capacity after standard fire exposure for 30 min. The specimens exposed to fire for 15 min experienced less degradation. The post-cracking stiffness dropped by 48% and the maximum load dropped by 25%. The main reason for the large difference in the behavior after 15 and 30 min of exposure lay in the mass loss of the polymer coating of the textiles. Coating burn-off tests indicated that after 15 min, the mass loss was less than 30%, whereas after 30 min more than 90% of the coating was burnt off.

An important remark based on the studies discussed in this section is that the presence of a polymer coating (or impregnation) on the textile reinforcement affects the performance of TRC significantly (as shown in Sections 2 and 3, as well). When thermoplastic coatings are exposed to high temperatures (and if sufficient time is provided, depending on the exposure duration and the heating rate), the polymer might be fully burnt off, leading to complete loss of the bond properties between the reinforcement and the matrix [56]. On the other hand, thermoset resins (such as epoxy resins) have a more stable behavior for temperatures up to 250 °C [43], but also suffer severe degradation at higher temperatures [51]. They also bear an increased risk of triggering spalling due to the sudden evaporation [53,54].

5. Conclusions and Knowledge Gaps

The main conclusions that can be drawn from this comparative study concern the identification of the key parameters that influence the thermomechanical behavior of TRC.

The textile finishing is one of the most important parameters affecting the behavior of the composite at high temperature (in combination with the thermomechanical testing conditions and the temperature range), since variations of the finishing of the reinforcement leads to large variations of the performance of the composite. On the other hand, variations of the fiber material (glass, carbon, or basalt) do not lead to large variations on the results. The use of uncoated textiles seems to provide the most stable performance at high temperatures, whereas the uncoated carbon fibers prove to be the best solution for the residual performance of TRC exposed to temperatures of 500 °C or higher. It is recommended that the final choice is balanced between the advantages of uncoated textiles at high temperatures and the advantages of coated textiles at ambient conditions.

The effect of the heating rate has only been studied on specimens subjected to *heating at constant load* conditions. Slow heating rates lead to failure at temperatures of around 400 °C–450 °C, regardless of the load level; fast heating rates (in the order of 10 °C/min and higher) result in higher failure temperature (around 600 °C–900 °C, depending on the composition) for a load level of 10% of the maximum capacity, but this drops linearly with increasing load level.

Nonetheless, there are extremely few studies which investigated the performance of TRC to heating rates that correspond to realistic fire conditions. Additionally, the effect of the heating rate (as well as the cooling rate) is yet unclear. The heating and cooling rates are expected to strongly affect the performance of cementitious mortars (similarly to normal strength and high strength concrete) as well as their spalling behavior. Additionally, the heating rate is expected to affect the behavior of TRC at high temperatures when the reinforcement is coated, because this would affect the burn off rate of the coating. These phenomena have not been systematically investigated yet. The effect of increased temperatures on the textile-to-matrix bond properties is also not well understood, since the relevant studies are scarce. In addition, more systematic research also needs to be carried out to draw safe results regarding the effect of the exposure duration and the matrix composition.

Finally, this review highlighted the necessity to establish commonly accepted guidelines and methods for testing TRC specimens in thermomechanical conditions. Testing parameters such as load-imposing methods, heating and cooling rates, exposure durations, temperature measurements and moisture conditions should be standardized in order to encourage more systematic and thus comparable investigations. This way, the identification of trends in the thermomechanical performance of TRC (and the establishment of analytical models to describe this behavior) could be carried out with higher reliability. This necessity will be further pronounced in the near future, since the investigations on textile-reinforced inorganic matrix composites are increasing, mainly due to the emerging durability considerations. The use of alternative binders, such as alkali-activated materials (AAMs), is also gaining a lot of attention, and studies on the fire behavior of textile-reinforced AAMs are already underway. Testing protocols should be established to ensure the systematic study on this promising trend.

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