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A Critical Evaluation of Mechanical and Fire Performance of Flax Fiber Epoxy Resin Composites

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In the present work, the mechanical behavior of flax fiber reinforced polymers (FFRPs) intended for racing applications is evaluated when subjected to different environmental conditions. A significant drop of mechanical performance in the presence of water (both 100% relative humidity and water submersion) is observed, highlighting also the fact that panels themselves already contain a fraction of water, probably absorbed onto the flax fibers prior their impregnation with the resin, that, where removed, may influence the mechanical behavior. Moreover, the flame behavior of the FFRP composite is also assessed in comparison with the widely applied carbon fiber reinforced polymers (CFRPs) to highlight the effect of the different reinforcement. Both FRPs are produced with the same flame retarded resin to highlight the contribution of the different reinforcement. The evaluation of the flame behavior of the FFRP panels shows that it completely burns during the cone-calorimetric test, involving in the fire both the matrix and the reinforcement with a stronger and faster heat release than the corresponding CFRP based on the same resin. The above observations seem thus to discourage their use in critical conditions, where the decrease of mechanical performance and the event of fire incidental condition may dramatically and negatively affect the final application.

1. Introduction

The growing industrial demand for sustainable materials has led to a paradigm shift in the focus from synthetic fossil-based component to counterparts derived from renewable resources. This New Deal is investing the composite sector too, where an effort is put in trying to switch from fossil to renewable feedstocks. While a wealth of literature is devoted to the production of resins from renewable resources[1–3] and, recently, to the attempt at recycling composites to reuse at least the reinforcing fraction,[4–7] the easiest approach to sustainability in fiber reinforced composites is the switch to natural fibers. Thanks to their low environmental impact and low cost, recently natural fiber reinforced composites (NFRCs) have been studied as an alternative to synthetic FRCs in many applications, such as in nonstructural car body parts (door and instrument panels, internal engine covers, etc.).[8]

However, natural fibers still suffer from strong drawbacks and limitations, such as the variable fibers quality and their significant tendency to moisture absorption that, in turn, detrimentally leads to lower fiber/matrix interfacial adhesion thus affecting composite properties. In this framework, the literature analyzed different fibers and tried to assess their behavior in terms of equilibrium moisture contents (EMCs), that was found to be higher for fibers with high lignin contents, owing to lignin ability to absorb water and deform. Hence, flax fibers appear as some of the most promising candidates, due to the average low lignin content and high cellulose fraction that guarantees good mechanical properties and strength to the fiber,[2] and indeed their application in different contexts has been widely reported. While their average performance might be sufficient for standard applications, where simple lightweight materials are sought after, in the case when a composite is required also for its relevant mechanical performance, such as in primary load bearing structures, the use of natural fibers is still critical. In extreme applications, such as aerospace or racing, the substitution of traditional carbon fiber reinforced polymers (CFRPs) still appears highly challenging, due to the drawbacks that still limit the performance of natural fiber-based composites.

In the present work, the authors analyze the mechanical behavior of flax fibers epoxy composites intended for racing applications when subjected to different environmental conditions.

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Table 1. Mechanical performance evaluated via 3 PB tests for the differently treated flax fiber composites.

Sample	Laminate thickness [mm]	Flexural modulus [GPa]	Standard deviation [GPa]	Ultimate stress [MPa]	Standard deviation [MPa]
Flax – RT air	2.28	11.4	1.3	169.3	8.2
Flax – 60°C air	2.25 (−1.3%)	11.7	0.9	164.3	3.0
Flax – 100% RH	2.37 (+3.9%)	6.2	0.2	126.8	0.2
Flax – 60°C water	2.67 (+17.0%)	2.1	0.02	60.1	0.4

RH, relative humidity; RT, room temperature; 3 PB, three-point bending.

Moreover, due to the extreme events that may occur in a race context, the flame behavior of such flax fiber reinforced polymers (FFRPs) has also been assessed in comparison with the more traditionally and widely applied CFRPs to highlight the effect of the different filler. Both FRPs are produced with the same flame retarded resin, in order to emphasize the contribution of the different reinforcement.

2. Results and Discussion

A woven flax fiber epoxy resin laminate, intended for high temperature resistance applications, has been tested for evaluating its mechanical properties both as received and after different conditioning treatments, all of them carried out for 30 h, as described hereafter:

- Room temperature (RT) (30°C), in air (no conditioning): flax – RT air;
- RT (25–50°C), relative humidity (RH) 100%: flax – 100% RH;
- Temperature 60°C, in air: flax – 60°C air;
- Temperature 60°C, submerged in water: flax – 60°C water.

Conditioning treatments were carried out on specimens already cut in a dimension suitable for three-point bending (3 PB) testing, so no re-shaping is required afterwards; lateral surface area where flax fibers are exposed has not been protected on purpose, with the aim of evaluating the effect of damages and scratches that may occur during lifetime applications. Moreover, conditioning at RH 100% has been carried out in environmental condition, thus following the day/night/day environment summer temperature cycle (average 10/35°C of temperature difference).

3 PB tests were carried out on at least five specimens per batch and the averaged results are gathered in **Table 1**. As clearly highlighted in **Figure 1**, displaying the stress–strain curves most representative of the average behavior of the batch they belong to, the different conditioning strategies substantially impact the mechanical performance of FFRP panels. Conditioning the samples at 60°C, at first sight seems to leave the sample almost unaffected in terms of flexural modulus and ultimate stress; however, when taking into account the overall flexural behavior, the material seems to slightly stiffen, probably owing to some slight moisture removal. This behavior seems thus to suggest that flax fibers composites contain a fraction of water in the normal conditions, as also supported by the measurement of the average thickness of the specimen that, once again, slightly decreases (Table 1). After

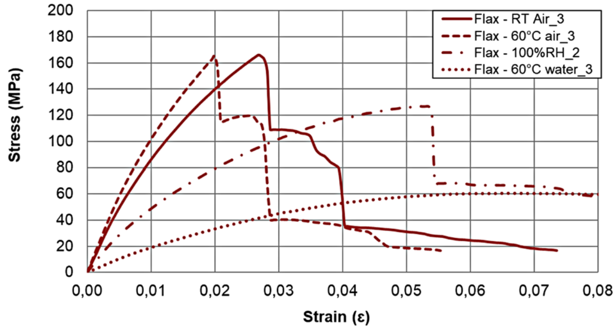

Figure 1. Three-point bending (3 PB) representative curves of the differently conditioned flax fiber epoxy composites, as stated in the legend box. The displayed curves were selected to best match the average behavior of the whole tested batch.

30 h at RH 100%, the panel thickness is instead increasing significantly, the flexural modulus of the laminate is almost halved (−45%), and the ultimate stress drops down by a quarter of the reference sample value (−25%). After 30 h submerged in water at 60°C, the flexural modulus of the laminate is about a fifth of the value for the pristine sample (−82%), while the ultimate stress is about a third of the initial value (−65%).

The previously discussed data highlight the extreme suffering of these composites in environmental conditions. This observation seems to discourage their use in critical conditions, where the decrease of mechanical performance might dramatically affect the final application.

Beside the above discussed dramatic sensitivity to external conditions, that negatively affects the FFRPs, one of the main risks associated with extreme racing context is the potential for a fire event. In this regard, the understanding of the fire behavior of flax fiber composites, in comparison to the most widely used CFRPs, is of paramount importance. The safety of the drivers, professionals, and audience is strongly related to the ability of the materials applied in racing vehicles to delay any accidental ignition and, in the case it occurs, withstand fire conditions. While it is well renown that FRPs, being based on organic resins, are not intrinsically fire resistant, a remedy can be found by using fire retardant additives,[9,10] as it is the case of the commercial resin presently used, or fire shielding membranes.[11,12] The present investigation has been carried out in mild heat flux conditions (35 kW m^{-2}), that represent the first stage of a developing fire, in order to test the ability of such materials to help preventing the fire spreading. The obtained results, summarized in **Figure 2** with the trend of one specific specimen representative of the

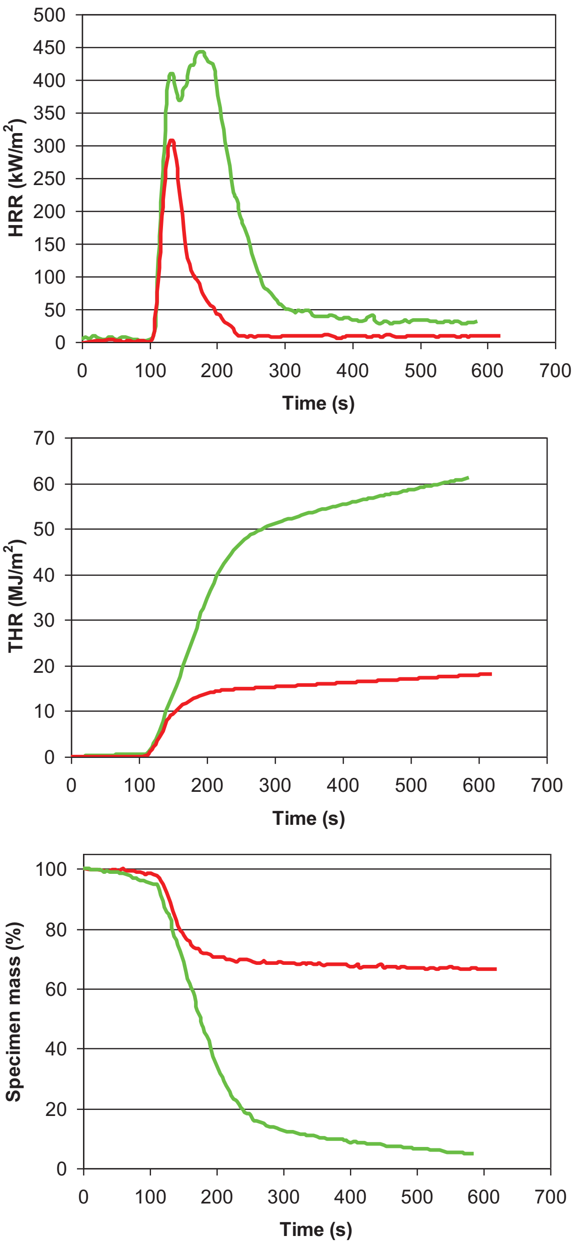

Figure 2. Cone-calorimetric test results for FFRP (flax – RT air, green) and CFRP (red). From top to down: HRR, THR, and specimens mass versus time plots for the most representative specimen with respect to the average batch behavior. CFRP, carbon fiber reinforced polymer; FFRP, flax fiber reinforced polymer; HRR, heat release rate; RT, room temperature; THR, total heat released.

whole batch, clearly show that the two samples have an almost identical time to ignition (TTI), as expected being based on the same resin. The ignition process is, indeed, related to the heat flux and the contemporary release of flammable volatile degradation products that, in the presence of an external trigger, can ignite when reaching critical concentration.

Being the resin the component that envelops the internal reinforcement and face toward the outside, it is obviously the first fraction to undergo degradation and release of volatile compounds. What is significantly different between the two samples is the profile of the HRR and the THR trends. Indeed, when the FFRP is ignited, it undergoes a stronger heat release, as detected by both the release rate and the total heat released (Figure 2). At the same time, it can be observed that FFRP loses almost all of its weight during the test, while CFRP shows a residue, reached after the first outburst of the flame, that is about 65% wt of the initial mass: this latter value well compares with the resin content of the sample. Hence, it is clear that FFRP can completely burn once ignited, including in the process both the resin and the reinforcement. On the other side, CFRP in mild heat flux can retain the carbon fibers for at least the initial step of the fire.

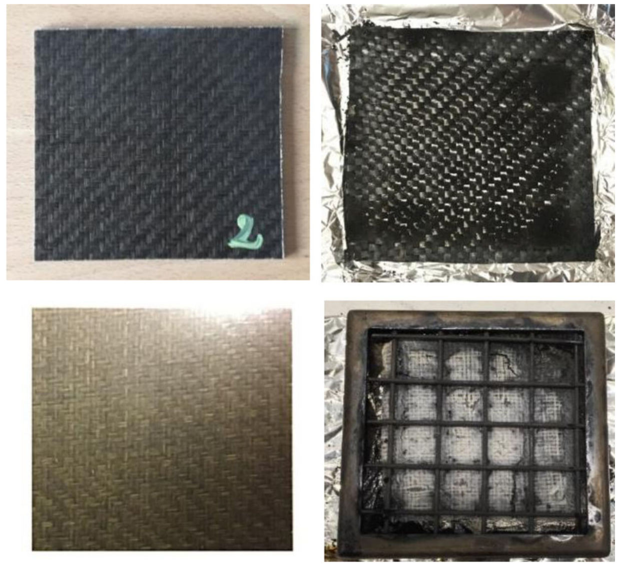

Figure 3. Pictures of the CFRP (top row) and FFRP (flax – RT air, bottom row) before (left) and after (right) the cone-calorimetric test. CFRP, carbon fiber reinforced polymer; FFRP, flax fiber reinforced polymer; RT, room temperature.

The latter observation finds support in the aspect of the samples after the cone-calorimetric tests, as highlighted in **Figure 3**: the picture of the CFRP after fire testing clearly shows the carbon fiber fabric that is almost completely preserved with respect to the pristine sample prior testing, while FFRP practically disappeared. The latter observation should thus lead to an intrinsic safety consideration: while CFRP structures, even if ignited, can retain at least for a short while their shape and provide a safer environment in a racing context, the FFRP appears highly dangerous in the fact that the reinforcement is not only lost in the flame, but it contributes to the feeding of the flames themselves. Keeping in mind that the resin used for panel production is conveniently modified to retard ignition with respect to common epoxies,[11] the flame behavior highlighted with the present tests makes FFRP panels unfitting for application in extreme conditions, in particular when the fire scenario cannot be completely ruled out.

3. Conclusion

The evaluation of the FFRP mechanical performance of panels exposed to different environmental conditions demonstrates the

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extreme suffering of these composites in the presence of water, highlighting also the fact that panels themselves already contain a fraction of water that, where removed, might influence the mechanical performance. Moreover, an evaluation of the flame behavior of the FFRP panels in comparison with the CFRP shows that the former burns entirely during the process, involving in the fire both the matrix and the reinforcement with a stronger and faster heat release than a CFRP based on the same resin, contemporary losing their shape and, in turn, their performance.

The above observations seem thus to discourage their use in critical conditions, where the decrease of mechanical performance and the event of fire incidental condition might dramatically and negatively affect the final application.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Data will be made available upon request.

Keywords

CFRP, cone-calorimeter, epoxy resin, flame behavior, flax composite, mechanical properties, three-point bending

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