from those obtained for the intact sample (Table 1): increases in T (20.8%) and ε_T (68.4%). The prolonged exposure periods of 28 and 56 days did not result in additional meaningful changes in these properties. Indeed, if the 95% confidence intervals are taken into account, there are no significant differences between the T and ε_T values obtained for geotextile I after 14, 28 and 56 days of thermo-oxidation. The average tensile force *vs.* elongation curve obtained for geotextile I after 56 days of thermo-oxidation is plotted in Figure 1. The curves corresponding to 14 and 28 days of thermo-oxidation were nearly identical to the one shown for 56 days and were excluded from Figure 1 to keep the image clear. The analysis of Figure 1 shows that, in addition to the already mentioned changes in T and ε_T, exposure to thermo-oxidation resulted in a decrease in the stiffness of geotextile I. This was immediately observable at low elongation: above 1-2%. Therefore, although there was no decrease in tensile strength (a common consequence of oxidation), exposure to thermo-oxidation resulted in substantial changes in the tensile behaviour of geotextile I, suggesting the existence of changes in the molecular structure of the HDPE chains. Future research, related to polymer chemistry, may help explain the effects of thermo-oxidation on geotextile I.

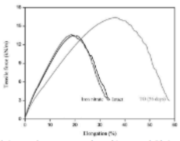

Figure 1. Average tensile force *vs.* elongation curves obtained for geotextile I before and after the degradation tests (single exposures).

The results for geotextile II after being exposed to thermo-oxidation were very similar to those observed for geotextile I (Table 2). Indeed, the variations in T were close (between +18.7% and +21.7%) to those found in geotextile I (between +20.5% and +20.8%); the corresponding ε_T also increased (increments of the same magnitude). In addition, the tensile force *vs.* elongation curves of geotextile II after thermo-oxidation (not shown) exhibited a pattern similar to that previously described for geotextile I.

In summary, geotextiles I and II behaved similarly during the thermo-oxidation tests. Consequently, it was not possible to evaluate the oxidation resistance enhancement of geotextile II due to its more robust stabilisation package. The difference between geotextiles I and II may be revealed by exposing them to thermo-oxidation for longer periods of time.

3.3 *Successive exposures*

As with single exposures, successive exposures to metal ion solutions and thermo-oxidation did not produce visible defects in geotextiles I and II. The tensile properties, T and ε_T, of the geotextiles after the successive exposures can be found in Table 3.

The prior exposure to copper and iron nitrate solutions had no influence on the thermo-oxidation resistance of geotextiles I and II. This conclusion applies to all three thermo-oxidation periods tested: 14, 28 and 56 days. Indeed, as can be seen by comparing the results presented in Tables 2 and 3, the T and ε_T of the geotextiles after the successive exposures to metal ion solutions and thermo-oxidation were quite similar to those observed after the single exposures to thermo-oxidation. Furthermore, the corresponding tensile force *vs.* elongation curves had also no significant differences. Thus, the stiffness changes in geotextiles I and II

Table 3. Tensile properties of geotextiles I and II after the degradation tests: successive exposures.

Successive exposure	Geotextile I T (kN/m)	Geotextile I ε_T (%)	Geotextile II T (kN/m)	Geotextile II ε_T (%)
Copper nitrate + TO (14 days)	16.57 ± 0.41	33.8 ± 1.5	17.84 ± 0.94	37.0 ± 2.1
Copper nitrate + TO (28 days)	16.56 ± 0.35	37.4 ± 4.5	17.91 ± 0.41	37.8 ± 1.2
Copper nitrate + TO (56 days)	16.79 ± 0.26	37.0 ± 3.0	17.96 ± 0.43	38.7 ± 2.1
Iron nitrate + TO (14 days)	16.41 ± 0.30	35.6 ± 4.2	17.92 ± 0.29	37.3 ± 1.9
Iron nitrate + TO (28 days)	16.53 ± 0.37	36.1 ± 2.5	17.72 ± 0.31	36.8 ± 1.4
Iron nitrate + TO (56 days)	16.88 ± 0.45	38.2 ± 2.5	17.81 ± 0.42	37.6 ± 0.2

were identical to those previously reported after the single exposure to thermo-oxidation (Section 3.2; example in Figure 1).

Knowing that the exposure to metal ion solutions had no influence on the tensile behaviour of geotextiles I and II (Section 3.2), the changes found in the successive exposures are attributable only to the thermo-oxidation process. As the changes that occurred were identical to those caused by the thermo-oxidation process alone, the previous exposure to copper and iron nitrate solutions did not notoriously affect the subsequent thermo-oxidation process, and no synergisms were observed between the degradation agents. Thus, under the tested conditions, no evidence was found that the metal ions copper and iron acted as catalysts in the thermo-oxidation process of the HDPE geotextiles.

3.4 *Effect of metal ion iron on the thermo-oxidation process: HDPE vs. PP geotextiles*

The impact of metal ion iron on the thermo-oxidation process was compared between the studied HDPE geotextiles and PP geotextiles (Figure 2). The PP geotextiles (results presented in Carneiro et al. 2019 and processed to create Figure 2) were tested under conditions close to those described in Section 2.2. The data presented in Figure 2 correspond to the successive exposure of the geotextiles to iron nitrate and 28 or 56 days of thermo-oxidation, with the variations in T being relative to the T values observed after the isolated exposure to thermo-oxidation. In Figure 2, geotextiles I and II are denoted by HDPE-I and HDPE-II, while PP-I, PP-II and PP-III designate three PP geotextiles with different stabilisation packages.

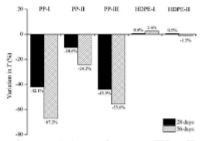

Figure 2. Effect of metal ion iron on the thermo-oxidation process: HDPE *vs.* PP geotextiles.

As shown in Figure 2, contrary to what happened for geotextiles I and II (where no meaningful influence was detected), prior immersion in iron nitrate led to a reduction (in some cases, quite pronounced) in the resistance of PP geotextiles to thermo-oxidation. For PP geotextiles, metal ion iron acted as a catalyst for the thermo-oxidation process, accelerating it significantly and leading to a decline in the mechanical resistance of the materials (the different behaviours of geotextiles PP-I, PP-II and PP-III can be attributed to the different efficiencies of their stabilisation packages). Thus,

in contrast to what was observed for geotextiles I and II, the combined action of the degradation agents was more pronounced (i.e. more damaging) than the sum of their isolated actions. Finally, it should be noted that HDPE typically exhibits a higher resistance to thermo-oxidation than PP. Thus, although no catalytic action from of iron (and copper) was observed in the thermo-oxidation process of geotextiles I and II, such an action may become detectable under different conditions, for example, by extending the duration of the exposure to thermo-oxidation. Testing HDPE geotextiles with less efficient stabilisation packages may also reveal the catalytic effect of metal ions.

4 CONCLUSIONS

This work evaluated the effect of metal ions (copper and iron) on the thermo-oxidation resistance of two HDPE woven geotextiles. The materials were exposed, in isolation and consecutively, to two degradation tests: immersion in copper and iron nitrate solutions, and thermo-oxidation. The isolated action of the metal ion solutions did not result in noticeable changes in the tensile behaviour of the geotextiles. In contrast, clear alterations were found when the geotextiles were submitted to thermo-oxidation. In those cases, both tensile strength and respective elongation increased – by approximately 20% and 65-84%, respectively. Moreover, the geotextiles have become less rigid, with the reduction in stiffness observable even at low elongation (1-2%).

The successive exposures to metal ion solutions and thermo-oxidation did not cause additional changes in the tensile behaviour of the geotextiles (when compared to the changes observed after the isolated exposures to thermo-oxidation). Thus, the combined action of the degradation agents was equivalent to the sum of their individual actions. Under the conditions studied, the metal ions copper and iron were not able to accelerate the thermo-oxidation process of the HDPE geotextiles. Indeed, both copper and iron did not show evidence of acting as catalysts in the thermo-oxidation process. When compared to PP geotextiles (tested under identical conditions), the HDPE geotextiles were remarkably less affected, not revealing the catalytic action of metal ion iron, previously demonstrated in PP geotextiles. Knowing that HDPE is less prone to oxidation than PP, further studies (under more demanding oxidising conditions or with poorly stabilised HDPE geotextiles) may be useful to clarify if the metal ions copper and iron can effectively catalyse the oxidation process of HDPE geotextiles.

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