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Multiscale evaluation of polyester geotextiles under hydrolytic degradation: from microstructural changes to mechanical performance

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Abstract

The durability of infrastructure depends on the stability and performance of the geosynthetics used. Among the factors affecting this durability, exposure to chemically aggressive environments is crucial in the progressive deterioration of these materials. Therefore, understanding the impact of such environments on geosynthetics is vital for ensuring the safety and longevity of civil engineering structures. To investigate the degradation mechanisms of polyester geosynthetics in acidic conditions and assess their durability, an accelerated aging protocol was employed. This study examines the impact of an acidic environment, simulated through an immersion test in a sulfuric acid solution with a concentration of 3.1 mol/L, on a polyester geotextile over periods of one, five, and six months, with a constant temperature of 80°C. Density changes were measured using a gas pycnometer, surface morphology was analyzed via scanning electron microscopy, and mechanical properties were assessed through tensile testing. The results revealed a significant reduction in tensile strength at advanced aging stages, with a decrease of up to 18% by the end of the test. This deterioration in mechanical performance correlates with changes in the geotextile's density and surface morphology.

Keywords: *geotextile, polyester, acidic environment, chemical degradation, durability*

1 Introduction

Geosynthetic products are the solution to extending the service life of civil and geotechnical structures while ensuring their safety during operation. These relatively recent products offer several advantages over traditional construction materials and techniques, particularly in terms of reducing the time and cost required to build structures. A wide range of geosynthetic products is currently available to meet the diverse requirements of structures, with geotextiles playing a significant role. Geotextiles are one of the most significant geosynthetics used in reinforcement systems.

In recent years, durability has become a major challenge, especially when the functional longevity of geosynthetic materials—often expected to exceed 50 to 100 years—is crucial in infrastructure applications (Sarsby, 2007). In underground applications, these products are often exposed to a variety of degradation agents for extended periods, which can lead to premature failure (Naga et al., 2025). The most common deterioration mechanisms include hydrolysis, oxidation (thermo-oxidation and photo-oxidation) and biological processes. These agents are the main cause of chemical aging. Additionally, the loss of chemical additives incorporated into the polymer matrix (in the event of contact with liquids), the absorption of substances from the external environment (which can lead to swelling), and creep, are factors contributing to physical aging. The interaction between geosynthetic products and their operating environment is a key consideration in their design, with the aim of achieving long-term performance that is consistent with the intended service life of the structure.

Polyethylene terephthalate (PET) is some of the most widely used polymers in geosynthetic manufacturing due to their excellent mechanical properties (van Schoors, 2007; Maddah, 2016). However, the resistance of polyester to aqueous environments is limited. Previous studies have

demonstrated that the deterioration of PET is primarily due to hydrolysis (Woodard and Grunlan, 2018), which is highly influenced by the pH of the environment (Nguyen-Tri et al., 2014; Ducoulombier et al., 2016; Krimi et al., 2016a; Cho et al., 2020; Naga et al., 2023) .

Extensive research has investigated the degradation of geosynthetics, predominantly concentrating on evaluating their mechanical and physical properties at the macroscopic level (Liu et al., 2013; Carneiro et al., 2014; Vieira and Pereira, 2015; Guimarães et al., 2017; Carneiro et al., 2018; Sardehaei et al., 2019; Naga et al., 2024a, 2024b). These investigations have elucidated the overall effects of various degradation agents, including chemical exposure, mechanical stress, and adverse environmental conditions. Nevertheless, the fundamental mechanisms driving these changes at the micromolecular level remain insufficiently explored. A comprehensive understanding of these structural and physicochemical transformations is essential to establish direct correlations between alterations in microscopic properties and reductions in the macroscopic performance of geosynthetics.

To address this research gap, accelerated aging tests were conducted in the laboratory, followed by multi-scale characterization integrating mechanical, physical, and microscopic analyses. Macroscopic evaluations were conducted using tensile testing and physical assessment with a pycnometer, alongside microscopic evaluations employing a scanning electron microscope. The geosynthetics were immersed in a controlled acidic environment (3.1 mol/L sulfuric acid at 80°C) for a specified duration. Although these severe testing conditions (elevated temperatures and high concentrations of chemical agents) are rarely encountered in real-world applications, they are intentionally applied to accelerate the degradation mechanisms of polymers (Broughton and Maxwell, 2007). As noted by Rowe et al. (2009), accelerated aging tests offer a practical approach to gaining insights into the long-term performance of these materials. Accelerated aging test provide an effective method for assessing changes in material properties over a short period within a reasonable timeframe.

The objective of this study is to enhance the understanding of the impact of an acidic environment on the mechanical and physical properties of geosynthetics, as well as on their surface morphology. This research aims to elucidate the interactions between the polymer structure and aggressive environmental conditions. Identifying degradation mechanisms at both the macroscopic and micromolecular levels is crucial for a better understanding of the long-term performance of geosynthetics. This knowledge enables the optimization of material selection, adaptation of their chemical formulation, and improvement of their design to enhance resistance to aggressive environments. Ultimately, this research contributes to more accurate predictions of the durability of geosynthetics and the optimization of their use in infrastructures exposed to severe conditions, thereby ensuring sustainable and efficient solutions in the fields of civil engineering and geotechnical engineering.

2 Materials and methods

2.1 Geotextile characteristics

The geosynthetic investigated in this study is a knitted geotextile made from polyethylene terephthalate (PET). The key properties of the geotextile in its as-received state are presented in Table 1.

Table 1. *Main characteristics of the geotextile (reference specimens)*

Parameters	Standards / Techniques	Quantity
Structure		Woven geotextile
Polymers		Polyester
Tensile properties	ASTM 4595 (ASTM 4595, 2023)	
Ultimate tensile strength (MD-CMD)		71.78(±4.07) – 68.18 (±3.84) kN/m
Elongation at ultimate tensile strength (MD-CMD)		14.90 (±0.54) - 15.77 (±0.58) %
Physical properties		
Unit area mass [a]	ASTM 5261 (ASTM 5261, 2018)	250 g/m^2
Density	Using a gas pycnometer	1.4758 g/cm^3
Fibers diameter[b]	Using SEM	21µm

In brackets is the standard deviation.
[a]Information provided by the manufacture.
[b]Information found by scanning electron microscopy

2.2 Accelerated aging test

In this study, a woven geotextile was submerged in a diluted sulfuric acid solution with a concentration of 3.1 mol/L, maintained at a steady temperature of 80°C±2. The immersion tests were conducted in darkness to prevent UV exposure to the samples and were carried out over different durations of one month, five months, and six months. Although these harsh test conditions (temperature and chemical concentration) are not typically encountered in real-world scenarios, they are employed to accelerate the degradation of the polymers (Broughton and Maxwell, 2007).

To maintain a consistent solution concentration, daily pH measurements were taken, and adjustments were made every 20 days. After the tests, the specimens were rinsed with deionized water and dried at 40°C. Prior to testing, all specimens were preconditioned in the dark at 23°C for at least 24 hours.

2.3 Evaluation of damage suffered by the woven geotextile

2.3.1 Assessment of geotextile density

The density of the geotextile fibers was determined at room temperature using a gas pycnometer (Micromeritics AccuPyc II 1340) (Figure 1a), with a precision of 0.0001, utilizing helium as the measuring gas. The products were cut into small fragments, as shown in Figure 1b, to fit into a 10 cm^3 cell. An average density was calculated from five measurements.

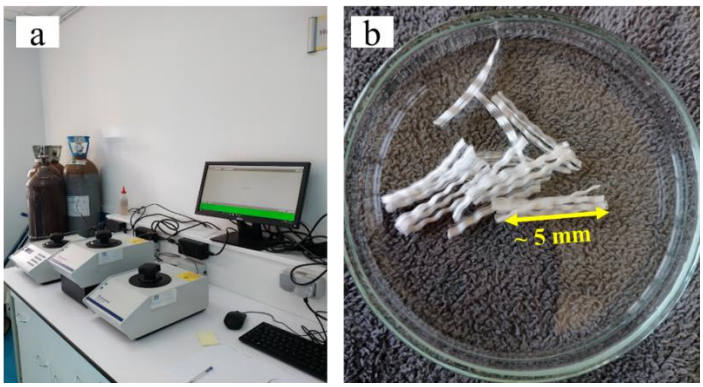


Figure 1. *Density measurement: (a) density measuring instrument; (b) geotextile fibers.*

2.3.2 Surface morphology

Surface degradation resulting from the aging test was examined using a QUANTA 650 scanning electron microscope. Imaging was performed in secondary electron mode using the Everhart-Thornley Detector (ETD) at an accelerating voltage of 3 kV and a working distance of 10 mm. This mode was selected for its sensitivity to topographical variations, allowing for detailed visualization of the surface changes in the material after exposure to the harsh environment.

2.3.3 Mechanical behavior

The damage experienced by the geotextile during the aging tests was evaluated through tensile tests in accordance with ASTM 4595. These tests were conducted using the INSTRON 5900 universal testing machine (Figure 2). Each sample tested comprised a minimum of five specimens with a 95% confidence interval calculated according to Montgomery & Runger, 2018. In this study, the tensile tests were carried out on wide strips with a strain rate of 10 ± 3% per minute and a preload of 1% maximum tensile strength. Mechanical behavior is evaluated by measuring the ultimate tensile strength determined from the force-elongation curve obtained during a tensile test.

Before the tensile test, all specimens were preconditioned for at least 24 hours at 21 ± 2°C and 50–70% relative humidity (RH), which were also the atmospheric test conditions.

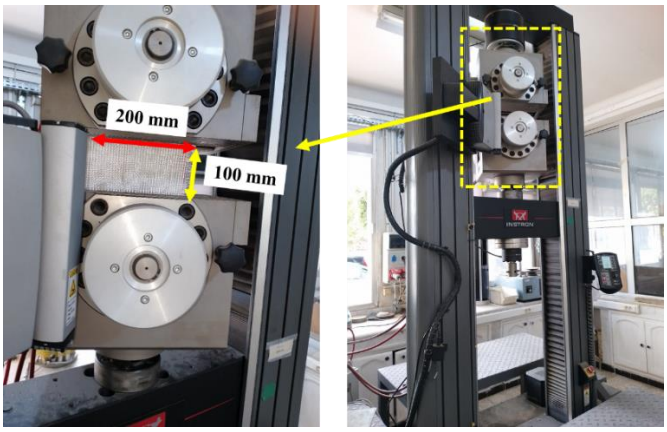


Figure 2. *Tensile test machine.*

3 Results and discussion

3.1 Analysis of geotextile density evolution

Figure 3 illustrates the evolution of the density of geotextile fibers after exposure to an acidic environment for different periods: one month, five months, and six months. The values of density are expressed as the percentage of the initial density retained, meaning the ratio between the density measured after degradation and the density of the unexposed (virgin) sample. The analysis of the results reveals a gradual increase in density over time, although the extent of this increase varies with the duration of exposure. After one month of aging, a modest increase in density is observed, amounting to a 1.5% rise compared to the initial value. This suggests that at the onset of exposure, the effects of the acidic environment are limited, inducing only minor modifications in polymer density. Conversely, after five months of aging, a significant increase in density, up to 25%, is observed. This substantial increase can be attributed to several physico-chemical mechanisms affecting the material's structure, particularly the reduction in the amorphous phase content due to hydrolysis reactions (Mathur et al., 1994). The amorphous regions of the polymer, characterized by a disordered arrangement of chains, are particularly vulnerable to hydrolysis reactions due to their relatively large free volume compared to the crystalline phase. This susceptibility can result in the scission of polymer chains. Fragments of the cleaved polymer chains may infiltrate the surrounding environment, thereby increasing the density of the polymer (Mathur et al., 1994). This increase in density can also be attributed to chemicrystallization, which directly contributes to the increase in density by increasing crystallinity (Xiong et al., 2016). This phenomenon is further explained by the fact that under the influence of hydrolysis reactions, the initially entangled polymer chains become more mobile, facilitating their rearrangement into a more ordered configuration, thus leading to an increase in crystallinity (Perthué et al., 2016; Forsgren et al., 2020; Salehi and Pircheraghi, 2021; Suljovrujic et al., 2021; Blivet et al., 2021; Rapp et al., 2022) and, consequently, an increase in the density of the geotextile. Furthermore, the test temperature could play a crucial role in these structural transformations by activating the mobility of macromolecular chains and promoting their reorganization into a crystalline phase (secondary crystals), a process known as recrystallization or thermal activation (Ketsamee et al., 2023). A sudden decrease of approximately 12% compared to the density recorded after five months of aging was observed, although the density remained higher than that of the intact sample. This decrease could be explained by the fact that the effects of chemicrystallization and thermal recrystallization reached a maximum threshold after five months of exposure. Beyond this period, the crystalline phases begin to degrade under the prolonged effect of the acidic environment, leading to a reduction in crystallinity and, consequently, a decrease in the overall density of the material. Similar results were observed by (Mathur et al., 1994). These mechanisms underscore a correlation between the increase in crystallinity and the decrease in the amorphous phase, as illustrated in Figure 3, thereby

demonstrating the interaction between chemical degradation and structural rearrangements that result in significant changes in the material's physical properties, particularly its density. The demonstration illustrated in Figure 3 remains probable until they are proven through other analyses, which will be the subject of our future research.

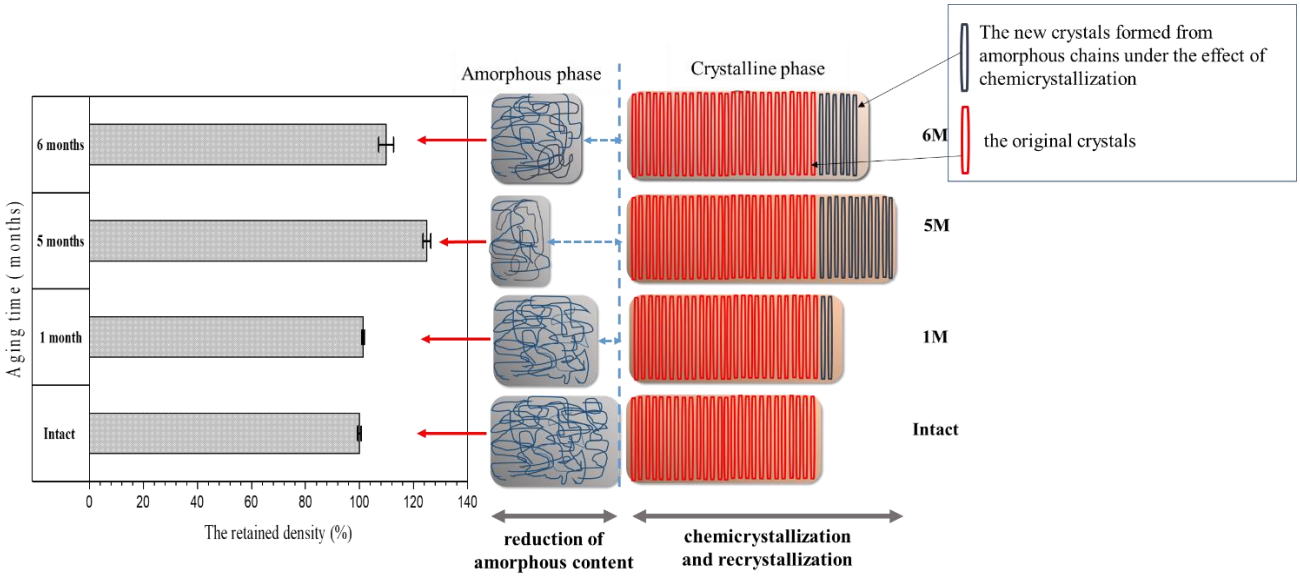


Figure3. *Density evolution and corresponding microstructure schematization over aging time.*

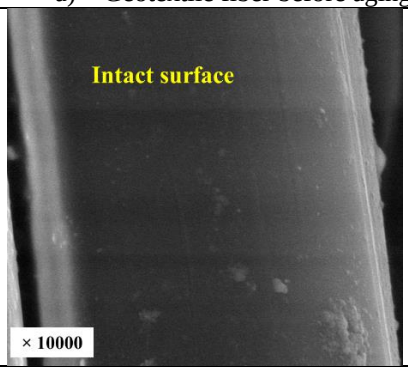
3.2 Surface morphology analysis

The surface of the woven geotextile was examined by scanning electron microscope (SEM). The investigation encompassed intact geotextile sample, as well as those exposed to the accelerated aging test (AAT) over three test periods (one, five, and six months). This analysis aimed to evaluate how the aggressive chemical agent influenced the geotextile's surface morphology.

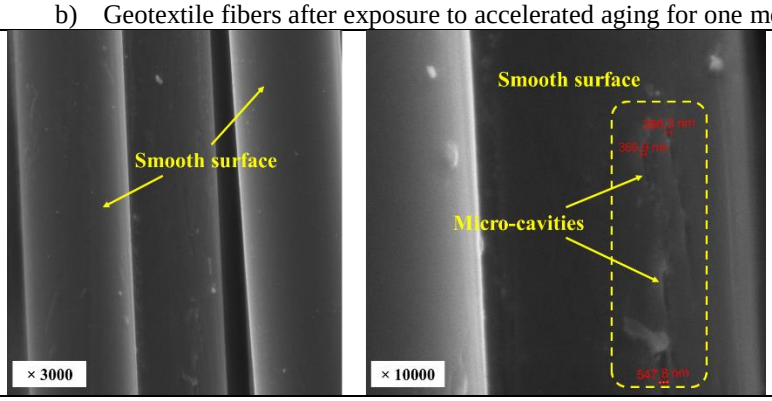
Scanning electron microscopy (SEM) images (Table 2 part a) demonstrate that the surfaces of the unaged fibers exhibit a relatively smooth morphology. Following one month of accelerated aging, the fibers maintain an intact surface devoid of visible cracks or microcavities, although initial signs of degradation are locally evident (Table 2 part b). Specifically, a few microcracks begin to manifest in isolated regions of certain fibers. These defects, however, remain sporadic and are discernible only through a comprehensive and systematic analysis of the samples, indicating that, at this juncture, the degradation process is still in its nascent stages. These surface changes can be attributed to hydrolysis, a mechanism that causes homogeneous degradation under the effect of H^+ diffusivity within the polymer matrix (Launay et al., 1999, 1994). After five months of aging (Table 2 part c), the microcracks become markedly more prominent, extensively covering the entire surface of the fibers. The width of these cracks is estimated to be approximately 700 nm. After six months (Table 2 part d), the advancement of the degradation process is evidenced by an enlargement of the microcavities, with sizes now ranging between 1 µm and 1.6 µm. This progression corroborates the cumulative effect of hydrolysis degradation, leading to the progressive rupture of the polymer chains (Krimi et al., 2016b).

Table 2. *SEM micrographs illustrate the surface morphology of undamaged and damaged geotextile fibers subjected to accelerated aging test conducted over one, five, and six months.*

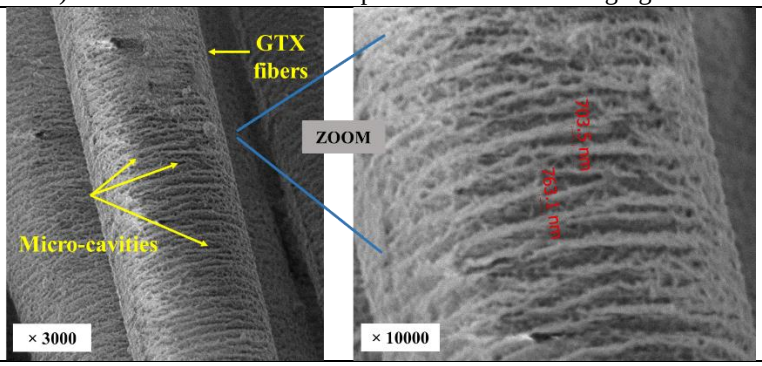
a) Geotextile fiber before aging test



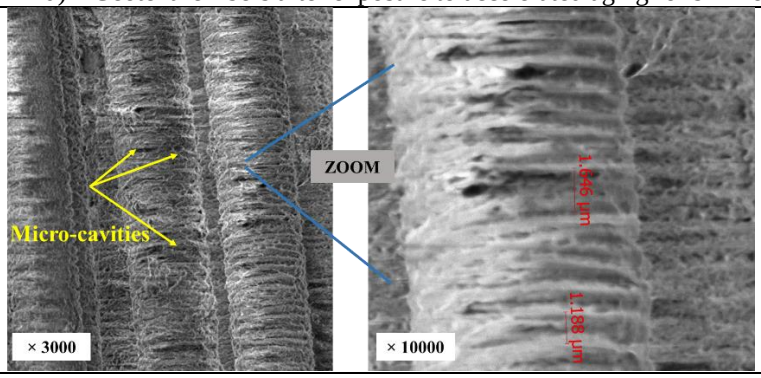
b) Geotextile fibers after exposure to accelerated aging for one month



c) Geotextile fibers after exposure to accelerated aging for five months



d) Geotextile fibers after exposure to accelerated aging for six months



3.3 Tensile behavior

The mechanical performance of the geotextile was assessed following accelerated aging tests. This evaluation involved examining changes in maximum tensile strength (TS_{max}). The progression of this mechanical characteristic, expressed as retained values, is depicted in Figure 4a. Figure 4b shows the correlation between tensile strength, density, and the average cavity width. It should be noted that the average width of the microcavities was estimated using scanning electron microscopy (SEM). To do this, the width of several microcavities was measured after each degradation period, and then an average of these values was calculated to obtain a representative estimate.

After one month of aging, no significant change in tensile strength was detected. However, extended exposure to aging conditions resulted in a notable degradation of mechanical strength (TS_{max}). A reduction in maximum tensile strength was recorded, amounting to 12.41% and 17.61% compared to the initial value after five and six months of aging, respectively. This decline in mechanical performance can be attributed to the formation of micro-cracks due to hydrolytic degradation (Table 2, parts c and d). These cracks serve as stress concentration zones, thereby weakening the geotextile structure and leading to a marked deterioration of its mechanical properties. Notably, the increase in crack diameter observed during aging correlates with a progressive decrease in tensile strength, as illustrated in Figure 4b. Furthermore, a strong correlation between the evolution of density and the material's strength was observed, particularly after six months of degradation (Figure 4b), which is another significant factor contributing to the loss of mechanical strength. This is likely due to the decrease in crystallinity (indicated by the decrease in density), as it is well established that the crystallinity of the polymer influences its mechanical strength (Spieckermann et al., 2010; Simões et al., 2012; Ewais and Rowe, 2014; Rozanski et al., 2018). However, after five months of degradation, this relationship is no longer evident (a notable reduction in strength was observed despite an increase in density). This can be explained by the predominance of another, more critical degradation mechanism related to the deterioration of the material surface. At this advanced stage of aging, physical alterations (cracks) may exert a more significant influence on the mechanical properties than the overall density of the material.

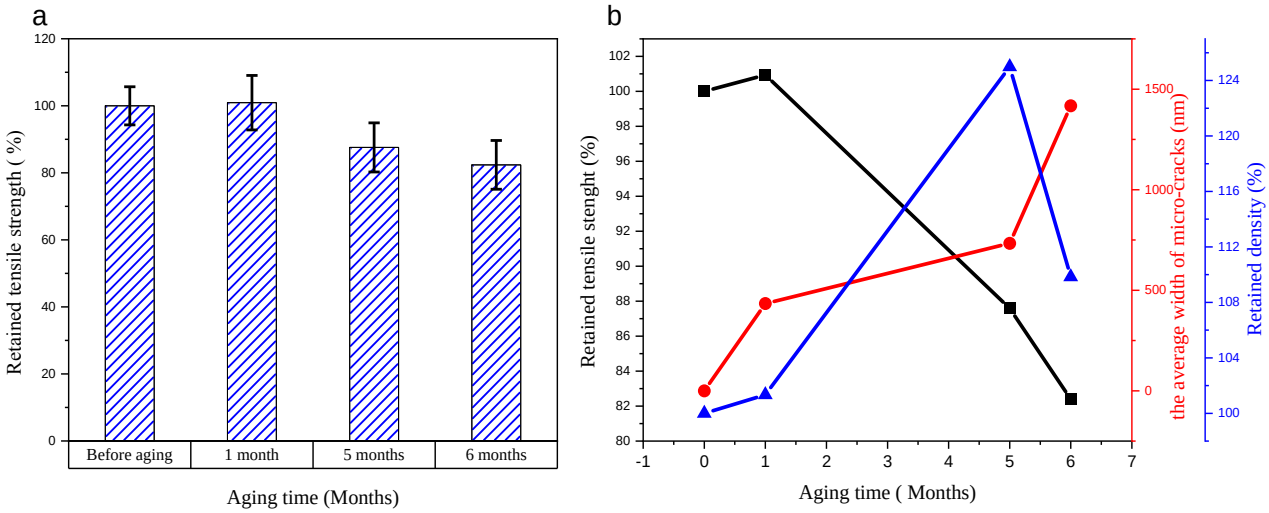


Figure 4. *Changes in (a) maximum tensile strength; (b) maximum tensile strength, average micro-crack width, and retained density over aging time.*

4 Conclusion

This research thoroughly explored how exposure to an acidic environment affects the physical and mechanical characteristics of polyester geotextiles, focusing on alterations in density, surface morphology, and tensile properties.

The findings reveal that the density of geotextiles gradually increases during acid exposure, with a notable rise during five months, mainly due to physicochemical processes like hydrolysis, which drive chemical crystallization, and the thermal influence of the test temperature. Nonetheless, from the sixth month, a reduction in density was noted, likely resulting from the degradation of crystalline phases under prolonged acidic conditions.

Examination of the surface morphology showed the gradual emergence of microcracks, which intensified over time, indicating the breaking of polymer chains. After five months, these cracks became more evident and spread across the entire fiber surface, hastening the degradation process.

Chemical aging significantly affects mechanical behavior, causing a steady decline in tensile strength, especially after five and six months, which correlates with the development of microcracks and changes in density. However, the density increase after five months was insufficient to offset the loss in mechanical strength, underscoring the importance of the material's surface condition in evaluating its durability.

These findings illustrate that the mechanical degradation of polyester geosynthetics in an acidic environment is a complex process, influenced by several interrelated factors, including changes in surface morphology and micromolecular degradation processes. Understanding these interactions is crucial for better assessing the longevity of geosynthetics used in infrastructure and for developing manufacturing strategies to enhance their performance in harsh environments, ensuring their long-term effectiveness.

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