



Article Characterizing the Tensile Behaviour of Woven and Composite Fabrics under UV Exposure

Soon Yuan Jie¹, Leow Zhi Hoe¹, Suvash Chandra Paul² and Vivi Anggraini^{1,*}

- ¹ Civil Engineering Discipline, School of Engineering, Monash University Malaysia, Jalan Lagoon Selatan, Bandar Sunway 47500, Selangor Darul Ehsan, Malaysia
- ² Department of Civil Engineering, International University of Business Agriculture and Technology, Dhaka 1230, Bangladesh
- * Correspondence: vivi.anggraini@monash.edu

Abstract: Geotextiles exposed to sunlight undergo a certain degree of UV degradation. In this study, woven and composite geotextiles were subjected to outdoor weathering tests at various exposure levels (i.e., 1, 2, 3, 4, and 5 months) to characterize their tensile behaviour. Each month, geotextiles were subjected to tensile tests according to modified ISO 13934 standards. Later, micro-scale approaches were undertaken to analyze the microstructure characteristics of the geotextiles and confirm the experimental results using scanning electron microscopy (SEM) and Fourier-transform infrared (FTIR) spectroscopy. Results indicated that woven geotextiles underwent tensile strength degradation and became more brittle after 5 months of UV exposure, which showed the highest degradation of 69.55% for strength retained, followed by composite geotextiles that only indicated a minimal degradation of 94.19% for strength retained. The corresponding strain indicated a more pronounced degradation, with retained strain percentages of 80.74% and 82.63% after 5 months of UV exposure for woven and composite geotextiles, respectively. Surface micrographs of composite geotextiles indicated that the remarkable microcracks began to develop on the polymer surface after the second month and continued to develop after that. Surface degradation of woven geotextiles under SEM was characterized by the loosening of fibre alignment, and this phenomenon was found to become significant after the first month of UV exposure. FTIR analysis of geotextiles revealed a notable chemical structure alteration in the polymer (i.e., polypropylene) that was observed through the formation of peak absorbance in the 1713 cm^{-1} wavenumber after UV exposure. Overall, the results from all laboratory tests agreed well with each other and this study thus provides clear evidence of the UV degradation of geotextiles in response to outdoor weathering.

Keywords: geotextiles; UV degradation; Fourier-transform infrared (FTIR) spectroscopy; scanning electron microscopy (SEM); tensile strength

1. Introduction

A wide variety of geotextiles have been evolved and are generally categorized into woven, non-woven, and composite. Recently, the use of geotextiles in the form of containment systems has significantly replaced parts of the conventional coastal and riverbank erosion protective systems [1,2]. Conventional use of hydraulic structures in coastal and riverbank erosion protective systems requires large-scale granular materials, often placed in multilayers to serve as bridging filter layers (i.e., erosion protection). Successful development of such containment systems has significantly replaced the necessity of multilayered granular materials, thereby reducing the cost and carbon footprint in marine-related construction fields. Such innovative use of geotextiles as a hydraulic structure has been widely acknowledged and utilized in a variety of construction projects around the world [3–7]. This research focuses on a geotextile containment system, namely a geotextile tube (hereafter, Geotube[®]). Its vast applications include shoreline erosion protection, island creation, wetland creation, land reclamation, etc. Due to the wide use of Geotube[®] in coastal



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). and marine construction, its durability requirement is of great importance. Geotube[®], in particular, is subjected to prolonged sunlight exposure during the pre-installation and installation processes, which is believed to cause deterioration [1]. Recently, greater emphasis has been placed by users and manufacturers of Geotube[®] on reducing its degradation under ultraviolet (UV) exposure. UV radiation degrades the performance of Geotube[®] through its adverse property changes and reduces its expected service life. As a result, UV degradation of Geotube[®] has gained significant attention from academic researchers.

Previous studies have focused on the characterization of the UV degradation of Geotube[®] based on laboratory UV weathering test simulations of outdoor conditions [8]. No attempts have been made to assess the UV degradation of Geotube[®] under field weathering conditions. Laboratory UV weathering simulates degradation in a shorter time period compared to field UV weathering. Nonetheless, laboratory UV weathering tests do not reflect the actual environmental situation where several environmental factors, such as relative humidity, pH value, pollution, light intensity, temperature, moisture content, etc., could potentially bias the results. The lack of detailed assessment towards the behavioral change of Geotube[®] under outdoor UV weathering has led to the inability to provide a holistic assessment towards its durability performance. Therefore, this study aims to bridge the research gap by providing a holistic assessment of the behavioral change of Geotube[®] subjected to field UV weathering. The exacerbated degradation of Geotube[®] will be evaluated under the field UV weathering due to the combined effect of environmental impacts and prolonged exposure duration [9].

This study focused on the load-bearing components of the Geotube[®], namely woven and composite geotextiles, in order to assess their durability performance. Relevant assumptions on material homogeneity have been made, since this field experimental study was conducted based on small-scale geotextiles under the consideration of limited budget and space availability. The strength retained (expressed in percentage) after several periods is related to the durability of engineered fabrics. Tensile strength is often referred to as the main criteria to assess the UV degradation of engineered fabrics [1,7,9–14]. Significant attention has been paid to ensure that the engineered fabrics have sufficient strength to resist rupture and failure during the installation process. Hence, tensile strength was adopted for this experimental study to assess the tensile characteristics of engineered fabrics subjected to outdoor UV weathering. Furthermore, micro-scale approaches were undertaken to analyze the microstructure characteristics of the engineered fabrics and confirm the experimental results via the use of scanning electron microscopy (SEM) and Fourier-transform infrared (FT-IR) spectroscopy.

The major objectives of this experimental study were (i) to assess the tensile properties of UV-exposed engineered fabrics based on the constant rate of extension (CRE) tensile testing machine, (ii) to investigate the microstructure characteristics of UV-exposed engineered fabrics via the use of the variable pressure scanning electron microscope (VPSEM), and (iii) to examine the chemical structure alteration of UV-exposed engineered fabrics via the use of Fourier-transform infrared (FT-IR) spectroscopy.

2. Materials and Methods

2.1. Engineered Fabrics

Geotube[®] is typically made from either woven, non-woven, or a combination of these engineered fabrics (i.e., composite). Woven fabric has the characteristics of interlaced filaments positioned perpendicular to each other. Filament placed in the longitudinal and transverse directions is named warp and weft. Meanwhile, the non-woven fabrics have the characteristics of randomly positioned filaments that are bonded by either mechanical, chemical, or thermal processes [6]. The structure of filaments in both engineered fabrics determines their properties, such as tensile strength and strain, which are the focus of this study. Generally, woven fabrics have greater strength compared to non-woven fabrics due to their fabric weaving patterns [15]. The strain of engineered fabrics has been studied in the past. Rawal, Shah, and Anand [6] claimed that the non-woven fabric was more

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extensible compared to woven fabric, where the fibres experience structural realignment when subjected to tensile loading, whereas woven fabrics have straight-oriented interlaced filaments. The merits of both woven and non-woven engineered fabrics are combined to produce the composite fabrics.

2.2. Ultraviolet Radiation

Incoming solar radiation from the sun is categorized into (a) infrared rays, (b) visible light, and (c) UV rays. The UV radiation of the light spectrum can be further categorized into (i) UV-A (315–400 nm), which poses some damage towards the geosynthetic polymers, (ii) UV-B (280–315 nm), which causes severe damage towards the geosynthetic polymers, and (iii) UV-C (100–280 nm), which causes extreme damage towards the geosynthetics [11]. Meanwhile, both infrared rays and visible light serve as thermal heat sources, which further exacerbate the degradation of engineered fabrics [11]. The synergistic effect of incoming solar radiation (i.e., infrared, visible, and ultraviolet) on the degradation of engineered fabrics, which is referred to as photolysis degradation, is discussed in Section 2.3. Ultraviolet rays of the incoming solar radiation degrade the properties of engineered fabrics. According to the World Health and International Commission on Non-Ionizing Radiation [16], UV radiation is represented by a global solar UV index, which follows the worldwide consistency measurement, ranging from 1 (i.e., low UV radiation) to 11 or higher (i.e., extreme UV radiation). Figure 1 shows the distribution of the average global UV index from 1996 to 2002 [17]. The focus of this study area was in the Asia region, specifically Malaysia, with an average UV index of above 10 [18,19].

Several factors have been identified that influence UV radiation. These include cloud cover, time of day, land cover, geographical latitude, earth's surface characteristics, seasons, altitude, and ozone concentration [11,15]. Malaysia is located close to the equator with minimal seasonal variation and is subjected to consistent UV radiation throughout the year. Therefore, it is important to assess the degradation of engineered fabrics based on the outdoor UV weathering test, which considers the geographical location and environmental factors as a basis for the holistic assessment. This proves the necessity and importance of field UV weathering in assessing the durability performance of engineered fabrics.



Figure 1. Global UV index map from 1996 to 2002.

2.3. Photolysis and Photo-Oxidation Degradation

Photolysis degradation involves the energy from incoming solar radiation, which causes adverse changes in the molecular structure and bonding of polymers [20]. Theoretical explanations for the photolysis degradation of engineered fabrics can be found in the quantum mechanics of electromagnetic excitation [11]. Light photons from incoming solar radiation interact with individual electrons of the polymer bonds. Higher energy photons than the polymer's bonding strength allow the electron to dislodge from its orbit. The high-energy photons simulate a series of chemical reactions to produce free radicals (unstable atoms

with high reactivity) responsible for chain scission (i.e., bond breaking) and crosslinking (i.e., bond formation) [21]. Unstable engineered fabric is characterized by chain scission dominance over crosslinking. Again, the energy required for the polymer chain scission is related to Planck's radiation law, where the energy is directly (inversely) proportional to its frequency (wavelength). Planck's radiation law is expressed in Equation (1), where the terms h, c, f, and w represent Planck's constant, speed of light, frequency of the light spectrum, and wavelength of light, respectively. Engineered fabrics under a freely-exposed condition with greater oxygen availability further simulate photo-oxidation degradation. The photo-oxidation reaction of polymers, specifically for PE and PP, can be described by the chemical reaction expressed in Equation (2); where RH denotes the polymer chain, O_2 denotes oxygen, and *R*, *ROO*, *RO*-, and *OH* denote free radicals [22].

$$E = hf = h \cdot \left(\frac{c}{w}\right) \tag{1}$$

$$RH + O_2 + hf \rightarrow R \cdot + RO \cdot + ROO \cdot + OH$$
(2)

2.4. Durability of Engineered Fabrics

The long-term performance of engineered fabrics under extreme weather conditions is related to their durability [23]. The lifetime of engineered fabrics can be estimated from the weathering test under the conditions of either being covered or exposed. Weathering tests under covered conditions shield the UV radiation from reaching into the amorphous phase of the materials. Nevertheless, engineered fabrics placed in an exposed environment are prone to UV exposure, thereby facilitating material degradation. Engineered fabrics placed under exposed conditions are more susceptible to UV degradation. Discrepancy between the covered and exposed conditions during the weathering test of engineered fabrics is subjected to the presence of (i) UV radiation, (ii) a full oxidative environment, and (iii) an elevated temperature [12]. The presence of pollutants and contaminants, such as heavy metal ions, further exacerbates the degradation of engineered fabrics in an exposed environment [24]. According to Koerner [12], the lifetime performance of the engineered fabrics can be estimated by following three stages as follows:

- 1. Incubation of representative engineered fabrics at different temperatures, with test specimens being tensile tested on a regular basis.
- 2. Data analysis through the extrapolation of results from high-temperature tests to lower temperatures.
- 3. Data analysis via the conversion of laboratory half-life (time to reach 50% reduction in the initial strength) data into field-predicted durations at particular locations.

3. Experimental

3.1. Materials

Materials used in this experimental study were woven and composite-engineered fabrics provided by TenCate Geosynthetics Asia Sdn Bhd. Both raw materials are used in the manufacture of Geotube[®]. Polypropylene is used as the base polymer for woven fabric. The composite-engineered fabric is fabricated from woven polypropylene coarse crimped fibres and overlaid by a layer of non-woven polypropylene. Polypropylene fibre, with the characteristic of low density, provides superior buoyancy qualities, making it appropriate for the application of marine-related construction. The characteristics of the engineered fabrics used in this study are presented in Table 1.

110	Ven	Composite		
MD	CD	MD	CD	
130	130	70	60	
10	10	10	10	
90		90		
1.5		6.3		
535		1200		
	MD 130 10 9(1. 53	MD CD 130 130 10 10 90 1.5 535	MD CD MD 130 130 70 10 10 10 90 90 90 1.5 6. 535	

Table 1. Properties of woven and composite-engineered fabrics.

3.2. Exposure Procedure

This research focused on the standard outdoor UV weathering of engineered fabrics. Engineered fabrics were first exposed to sunlight for a five-month duration. At the end of each month, these engineered fabrics were cut into specimens and subjected to a series of laboratory tests to monitor the extent of degradation. The engineered fabrics were placed in an open and uncovered area to maximise UV exposure (see Figure 2). The experimental setup was constructed at Petaling Jaya, Selangor, Malaysia. Environmental factors that could have potentially biased the test results were recorded. These included maximum (T_{max}) and minimum (T_{min}) air temperature, humidity (HUM), cloud cover (CC), UV index (UVI), precipitation (P), and air quality index (AQI). This meteorological data was useful in assessing the degradation of engineered fabrics. The correlation between the degradation of the engineered fabric (see later part to quantify the material degradation) and meteorological data was considered.



Figure 2. Outdoor UV weathering test for woven (black) and composite (yellow) (Courtesy: Tencate Geosynthetics Asia).

3.3. Equipment

3.3.1. Tensile Testing

A constant rate of extension (CRE) tensile testing machine (Shimadzu AGX series) with a 600 kN load cell was adopted to study the tensile properties of engineered fabrics. The tensile test was conducted in accordance with ISO 13934-1 [25]. This test method determined the maximum force and its corresponding elongation by using the strip method. According to ISO 13934-1, the strip method required the full width of the test sample to be gripped within the jaws of the tensile testing machine. The test samples were 50 mm wide and 200 mm in gauge length, as specified in the test method. Test samples were mounted with a pretension of 0.5 N and subjected to an extension rate of 100 mm/min in the CRE tensile testing machine. A modification to the test method, ISO 13934-1, was necessary due to the constraints in the experimental study. Limited space available for outdoor UV weathering generally reduced the number of samples per test. At each level of exposure time, the number of samples was reduced from five, as required by ISO 13934-1, to three samples in both machine (MD) and cross-machine (CD) directions to check the consistency of the results.

3.3.2. Fourier-Transformed Infrared (FTIR) Spectroscopy

Fourier transform infrared (FT-IR) spectroscopy is a common analytical technique that is used to study polymer degradation due to photo-oxidation. FTIR spectra analysis identifies the chemical structure alteration of polymers via the functional groups corresponding to distinct bands in the mid-infrared (MIR) range from 4000 to 400 cm⁻¹. This technique validated the results from the tensile testing. FTIR spectra analysis was conducted using a Nicolet iS10 (Thermo Fisher Scientific, Waltham, MA, USA) with a universal attenuated total reflection (ATR) sampling technique. The absorbance spectra were recorded at a resolution of 4 cm⁻¹ with 64 scans. These selected parameters were based on a consideration of the accuracy in spectra analysis (i.e., a high signal-to-noise ratio) [26]. In general, the higher number of scans simulated a greater signal-to-noise ratio and the higher resolution improved the accuracy with which the narrow spectra bands were easily distinguished. These standard parameters can be accessed by the majority of FTIR spectrometers. All the spectra were processed and analyzed using Omnic software (Thermo Fisher Scientific Inc.).

3.3.3. Scanning Electron Microscope (SEM)

The non-conductive engineered fabrics were first gold-coated using a rotary pumped sputter coater (Quorum Q150R S) to enhance the imaging under SEM. The gold-coated specimens were then subjected to a variable pressure scanning electron microscope (Hitachi S3400N-II) to observe the surface characteristics. All the SEM micrographs were observed at a magnification of $\times 30, \times 300, \times 7000, \times 15,000$, and $\times 27,000$ at 5 kV.

4. Results and Discussions

4.1. Meteorological Data

Figure 3 depicts the meteorological data collected during the outdoor weathering test from November 2021 to March 2022. This test was carried out in conjunction with the northeastern monsoon season, which typically occurs from early November to the end of March [27]. During this period, Malaysia is subjected to higher rainfall and an active cold surge. The statistical correlation matrix that was used to study the relationship between the meteorological data is shown in Figure 4. A strong positive correlation ($R \ge 0.8$) was identified between the T_{max} -UVI and UVI-AQI, and a negative correlation ($R \le -0.8$) was identified between the CC- T_{max} and UVI-CC.



Figure 3. Meteorological data collected from 21 November to 22 March 2022 at Petaling Jaya, Selangor, Malaysia.



Figure 4. Statistical correlation matrix between the collected meteorological data from 21 November to 22 March 2022.

4.2. Tensile Properties Degradation

The extent of photo-oxidation degradation was monitored through the tensile behaviour of geotextiles under various exposure levels. Table 2 summarizes the tensile test results of woven and composite-engineered fabrics in both machine direction (MD) and cross-machine direction (CD). The tensile test results were reported based on the arithmetic mean of three specimens. A comparison between engineered fabrics indicated that woven geotextiles had greater tensile strength and strain compared to composite geotextiles. The introduction of non-woven geotextiles as part of the composite geotextiles decreased the tensile properties of the individual woven geotextiles. The variability of tensile test results was studied based on the statistical analysis of the coefficient of variation (henceforth referred to as CV). Tensile test results in Table 2 show CV values ranging from 0.10% to 11.83% and 0.32% to 11.15% for woven and composite fabrics, respectively. Such a remarkably high CV value for geotextiles reveals a high degree of non-uniformity in the fabric structure.

Geotextiles	Months	Machine Direction			Cross-Machine Direction				
		T _{max} [kN/m]	ε _{max} [%]	CV (T _{max}) [%]	CV (ε _{max}) [%]	T _{max} [kN/m]	ε _{max} [%]	CV (T _{max}) [%]	CV (ε _{max}) [%]
Woven	0	136.87 (±0.32)	10.76 (±0.33)	0.21	2.74	133.65 (±0.15)	8.33 (±0.15)	0.10	7.13
	1	127.67 (±1.46)	10.85 (±0.79)	1.01	6.39	123.11 (±4.21)	8.29 (±4.21)	3.02	8.87
	2	124.99 (±3.20)	9.56 (±1.28)	2.26	11.83	122.65 (±8.90)	7.48 (±8.90)	6.41	5.51
	3	119.03 (±11.47)	9.84 (±0.09)	8.52	0.79	114.72 (±2.33)	6.89 (±2.33)	1.80	4.50
	4	106.65 (±6.64)	9.82 (±0.64)	5.50	5.76	102.98 (±2.21)	6.70 (±2.21)	1.89	4.22
	5	101.36 (±1.03)	9.80 (±0.16)	0.89	1.46	92.95 (±2.86)	6.72 (±2.86)	2.72	10.98
Composite	0	60.95 (±5.04)	8.13 (±0.91)	7.30	9.94	52.91 (±3.49)	6.24 (±0.11)	5.83	1.52
	1	61.76 (±0.22)	8.37 (±0.12)	0.32	1.27	52.84 (±0.49)	5.92 (±0.30)	0.82	4.54
	2	65.75 (±3.99)	8.26 (±0.60)	5.37	6.41	59.91 (±1.77)	6.40 (±0.06)	2.61	0.87
	3	65.72 (±3.32)	8.89 (±0.95)	4.47	9.44	64.11 (±0.89)	6.79 (±0.13)	1.22	1.71
	4	54.00 (±0.80)	9.24 (±1.17)	1.32	11.15	63.38 (±5.77)	6.38 (±0.36)	8.04	4.96
	5	57.41 (±0.98)	8.19 (±0.90)	1.51	9.76	60.16 (±1.40)	$5.15(\pm 0.30)$	2.06	5.12

Table 2. Tensile properties of woven and composite geotextiles at various months of UV exposure.

Geotextiles, after each month of weathering tests, were studied for their respective tensile strength and retained strain percentages. Figure 5 shows the plot of maximum tensile strength and its corresponding retained strain percentage against various exposure levels for both geotextiles in MD and CD. The tensile properties retained were calculated based on the tensile properties of the exposed specimens divided by the unexposed specimens and multiplied by 100%. Figure 5a shows that the woven geotextile progressively lost its maximum tensile strength under prolonged UV exposure. Such degradation was associated with retained strength percentages of 74.06% and 69.55% in the final month of UV exposure in the MD and CD, respectively. The retained strength percentage for woven geotextiles after each month of outdoor exposure was relatively consistent and

well controlled in both directions, despite the anisotropic properties of geotextiles that indicated up to 8.66%. The tensile strength of the composite fabric was of particular importance, with an anisotropy of up to 15.58%. No strength losses were observed in the CD, while minimal strength losses in the MD began after the fourth month and were associated with a retained strength percentage of 94.19% following the last months of outdoor UV exposure. Overall, degradation was more pronounced in woven geotextiles, which had a lower retained strength percentage after five months of weathering testing than in composite geotextiles.

The corresponding retained strain percentage in Figure 5b reveals a higher degree of non-uniformity compared to the plot of maximum strength retained percentage. Woven fabrics started to show significant strain reduction only after the second month of outdoor exposure. Inconsistency of retained strain percentages began to emerge in the third month, when woven geotextiles showed a higher (lower) retained strain percentage in the MD (CD) than the preceding month. The strain reduction for the remaining months remained steady in both MD and CD, with 91.08% and 80.74% of the strain being retained in the final months, respectively. The anisotropy of the strain retained was determined to be up to 37.77%. For the composite fabric, no strain losses were observed in the MD after five months of outdoor exposure. However, initial strain reduction occurred in CD after the first month and disappeared for the following months until the final month of outdoor UV exposure, which depicted a retained strain percentage of 82.63%. Accordingly, the emerging difference contributed to an anisotropy of up to 45.46%. Overall, the composite fabric showed a greater retained strain percentage after the final month of outdoor exposure compared to the woven fabric.

The tensile strength and strain loss that engineered fabrics underwent gave a better indication of the photo-oxidation degradation that takes place during the outdoor weathering test. A comparison between both engineered fabrics indicated that woven geotextiles were subjected to a higher degradation rate than composite fabrics, which were associated with the least tensile strength and retained strain percentages after the five months of outdoor exposure. This suggested that the non-woven geotextile layer in the composite fabrics provided excellent protection for the primary load-bearing woven geotextile from photo-oxidation degradation. Moreover, the aforementioned findings show that, after several months of outdoor weathering tests, composite geotextiles exhibited higher strength and strain than virgin samples, contradicting the hypothesis made earlier. This phenomenon can be attributed to the deposition of particulate matter and pollutants in the polymer matrix, which is evidenced by the plot of retained strength percentage for composites that indicated a similar trend to the air quality index (see purple colour series in Figure 3). Notably, the deposition of dust and small dirt particles was further subjected to change by the rainfall that flushed them out. The geotextile samples were collected immediately after the rain event for 1 month (medium intensity), 2 months (medium intensity), and 4 months (high intensity). The deposition of particulate matter and pollutants was identified and attributed to an increase in tensile properties. A similar phenomenon was found by recent studies, which was mostly attributed to the sample mass per unit area increasing after the deposition of dust and microscopic dirt particles in the non-woven polymer matrix [1,7,9]. Moreover, Valentin et al. [7] claimed that the randomly positioned fibres in the non-woven geotextile might undergo a certain extent of fibre realignment after the outdoor UV weathering test that provides additional tensile strength and strain resistance from the interactions between fibres. Once again, this phenomenon was not observed in woven fabrics that underwent degradation associated with the disintegration of damaged fibres, which resulted in a considerable loss of sample mass that was more dominant than the increased mass supplied by dust and dirt particle deposition.



Figure 5. (a) Tensile retained strength percentage of woven and composite geotextiles in both machine (MD) and cross-machine directions (CD); (b) retained strain percentage of woven and composite geotextiles in both machine (MD) and cross-machine directions (CD).

4.3. Microstructure Analysis

Visual inspection of the surface morphology of the engineered fabrics was essential. Prior to the SEM, the colour of composite fabric subjected to outdoor weathering was observed (by the naked eye) to be brown colour (originally yellow). However, the woven fabric was observed to exhibit no change in colour (originally black). The change in colour observed in the composite fabric was mainly contributed by the accumulation of dust on the polymer surfaces. This statement warrants further studies through SEM micrographs. Aside from the aforementioned, there was no discernible difference visible to the human eye.

Figures 6 and 7 depict SEM micrographs of engineered fabrics at various exposure levels. Figure 6a indicates the SEM micrograph of an unexposed woven fabric with an even and smooth surface morphology. All fibres were positioned in a closely packed and well-aligned interlaced structure. The virgin sample showed no signs of degradation. After the first month of outdoor weathering tests, significant white spots with a rough surface texture were observed on the polymer surface under a magnification of $\times 3000$. Such white spots were also observed in the remaining months of the weathering test (not shown here). Additionally, SEM micrographs captured at $\times 30$ magnification indicated a minimum extent of degradation through the loosening of fibres at the edges after the first month, as shown in Figure 6b. For the remaining months of weathering tests, SEM micrographs captured at $\times 30$ magnification through significant changes in the polymer structure, specifically its fibre alignment. Where the fibres tended to spread apart from each other and become loose, this effect was more significant under prolonged UV exposure. In general, the fibres in UV-degraded woven fabrics showed a loose structural alignment after prolonged UV exposure.

Figure 7a–f depicts the surface microstructure behaviour of composite samples. Similar to woven samples, the unexposed composite sample shown in Figure 7a indicates a smooth and even surface appearance with no degradation. The significant white spots were also present in the composite fabrics (see Figure 7b) after the first month, and subsequently decreased in the remaining months (see Figure 7c–f), which was associated with the formation of greater microcracks width. No degradation was observed at the end of the first month of UV exposure. Unlike woven fabric, the degradation mechanism was shown by the presence of microcracks (in the transverse fibre direction) that were observed after the second month of weathering testing. These microcracks continued to develop with a significant increase in width. At the end of the second month of exposure, microcracks with a maximum width of 165 nm were observed, and progressively increased to 478 nm after the final month.

Geotextiles placed in the outdoor environment were subjected to ambient air conditions that consisted of particulate matter (i.e., PM10 and PM2.5) responsible for air quality regulatory purposes. Both PM10 and PM2.5 (i.e., particulate matter with diameters of 10 microns and 2.5 microns or less, respectively) were considered to be a part of the indicators in assessing the air quality index (AQI) of this research study. Other indicators comprising the AQI include gaseous pollutants such as ozone, sulfur dioxide, and nitrogen dioxide. Both engineered fabrics indicated a significant number of white spots on the polymer surface after outdoor weathering, which is attributed to the deposition of atmospheric particulate matter. This supports the preliminary visual observation. Such conditions under the outdoor weathering test have been supported by an experimental study previously conducted [28]. The degradation observed from the SEM micrographs of woven fabric was relatively consistent with the tensile test findings, where the loosening of fibre alignment caused a progressive reduction in tensile properties after each month of outdoor exposure. For composite fabrics, the presence of microcracks on the polymer surface after the second month provided a shorter pathway for UV penetration, which accelerated polymer degradation through the evidence of greater microcracks formed thereafter. The substantial development of microcracks were observed on the surface of composite fabrics, which was not well supported by significant tensile strength loss. The tensile strength was primarily governed by the load-carrying component (i.e., woven fabric). In this case, the non-woven geotextile overlay, which acted as a sacrificial layer, protected the woven geotextiles in composite fabrics to the extent of minimal to no damage. UV radiation has thus been identified to cause engineered fabric degradation that is associated with tensile property loss.



Figure 6. SEM micrographs of woven fabrics at (**a**) Month 1, (**b**) Month 2, (**c**) Month 3, (**d**) Month 4, (**e**) Month 5, and (**f**) Month 6 of exposure.



Figure 7. SEM micrograph of composite fabrics at (**a**) Month 1, (**b**) Month 2, (**c**) Month 3, (**d**) Month 4, (**e**) Month 5, and (**f**) Month 6 of exposure.

4.4. Tensile Properties Degradation

The UV degradation suffered by engineered fabrics was further evidenced through FTIR spectrum dissolution. Figure 8 shows the FTIR spectra of the engineered fabrics under various UV exposure levels. The IR spectra are presented in the plot of absorbance against wavenumbers. The spectra of virgin samples were initially compared to reference spectra stored in the OMNIC software library databases to verify their polymer type. The spectral databases included a wide variety of reference spectral collections with detailed information which aimed to provide a more accurate comparison. Results indicated that the FTIR spectra of both samples closely resembled the characteristics of polypropylene atactic with a similarity of 87.84% (woven) and 86.81% (composite), in accordance with the Hummel polymer FTIR spectral library. The spectra similarity was characterized based on the reference absorption bands of polypropylene shown in Table 3 [26,29–32].

With reference to Figure 8, the FTIR spectra were sensitive towards the climatic elements that generally altered throughout the time of day or month under the outdoor environment. Accordingly, during the sunshine hours, the FTIR spectrum closely approached the upper limit of 1, which indicated a maximum absorption of solar radiation. Conversely, during the raining hours and night-time, the spectra intensity approached the lower limit of 0, which indicated a minimal absorbance of solar radiation. However, this behaviour of spectrum intensity was not clear evidence for the UV degradation of polypropylene under long-term exposure. Polypropylene subjected to UV radiation undergoes a series of chain scissions in its macromolecules through the multi-stage complex reactions. Scheme 1 illustrates the simplified photo-oxidation process of polypropylene. The preliminary stage of photo-oxidation involves the formation of hydroperoxides (2), after which it undergoes homolysis by the UV radiation under the conditions of oxygen availability to produce alkoxyl and hydroxyl radicals (3). Subsequently, reaction of alkoxyl radicals occurs through β -scission to produce ketones and primary radicals (4). These intermediate photoproducts, including free radicals, undergo further chain scissions which bring about deterioration towards the mechanical properties, such as tensile, shear, puncture resistance, etc. The final stage of degradation involves the photoproducts known as acetic acids in the form of solid and gas (i.e., volatile) phases. The formation of intermediate and final photoproducts from Scheme 1 can be tracked in the FTIR spectra (see Figure 8) through the corresponding absorption bands formed. In this research, the hydroxyl (O-H) and carbonyl (C=O) functional groups were used to monitor the extent of polypropylene degradation in conjunction with its chemical structural alteration, as shown in Scheme 1.



Scheme 1. Photo-oxidation degradation of polypropylene.

Figure 8a shows that the hydroxyl group ($3800-3000 \text{ cm}^{-1}$) formed a broad peak after the first month of outdoor exposure. The absorption peak in this region became notable under prolonged UV exposure. The development of a peak, indicating the presence of a hydroxyl group, served as evidence of the formation of hydroperoxides as the photoproduct in the early stage of photo-oxidation degradation (stage 2 in Scheme 1). Later, a significant peak was also observed due to the presence of a carbonyl group (1850–1650 cm^{-1}) after the third month. This absorption band, specifically located at a wavenumber of 1713 cm^{-1} , was identified in Scheme 1 as acetic acid [33,34]. This photoproduct appeared to be increasing under prolonged UV exposure, which was observed through its remarkable peak formed after the final month. The formation of acetic acids was further supported by the absorption peaks formed due to the presence of the CO bands $(1300-1000 \text{ cm}^{-1})$ which characterized the C-O stretching vibration of the acetic acids. Unlike woven fabrics, the hydroxyl and carbonyl groups belonged to the composite samples (see Figure 8b), which appeared to remain unchanged after several months of UV exposure. No peaks were observed after the final month of outdoor exposure. This result alone suggested that composite samples had not undergone any photo-oxidation degradation.



Figure 8. (a) FTIR spectra of PP120S fabric under various UV exposure levels; (b) FTIR spectra of TC120 fabric under various UV exposure levels.

The abovementioned results clearly describe the behaviour of engineered fabrics under photo-oxidation degradation through their chemical structure changes. Studies between these engineered fabrics indicated that woven samples were subjected to an accelerated photo-oxidation degradation compared to composite samples. Despite the significant microcracks that were observed in the SEM micrographs of composite fabrics, the FTIR spectra showed no evidence of chemical structural change. These micro-scale findings were aligned with the tensile test results that were well supported by the lowest tensile strength and retained strain percentages in woven fabrics, as well as composite fabrics that exhibited minimum to no degradation after five months of outdoor UV weathering tests. As a result, the additional layer of non-woven fabrics found in composite fabrics served as a sacrificial layer for the woven fabric to protect it from rapid degradation.

Wavenumber (cm $^{-1}$)	Vibration	Assignment	
2955, 2952, 2949	Asymmetrical stretching	CH_3	
2916	Asymmetrical stretching	CH_2	
2867	Stretching	CH_3	
2838	Symmetrical stretching	CH ₂	
1456	Symmetrical bending	CH_2	
1436	Bending	CH_2	
1375	Symmetrical bending	CH_3	
997, 972	Rocking, stretching	СН3, С-С	
840	Rocking	C-H	
809	Stretching	C-C	

Table 3. FTIR absorption bands of polypropylene.

5. Conclusions

Prolonged exposure of woven geotextile to UV radiation revealed the greatest extent of degradation through minimum tensile strength and retained strain percentages of 69.55% and 80.74%, respectively, after five-months of outdoor exposure. The woven geotextile showed a more brittle behaviour under prolonged UV exposure. SEM micrographs of woven fabrics revealed considerable loosening in fibre structures that were originally densely packed and well-aligned. Disruption of fibre-to-fibre interactions and alignment most likely contributed to the tensile property degradation. Such evidence was further supported by the FT-IR analysis, which revealed a chemical structure change of the polypropylene after the outdoor weathering test via the formation of acetic acids as a by-product, which was seen in the absorbance peak created at a wavenumber of 1713 cm⁻¹. The formation of an absorbance peak became notable for its extended period of UV exposure.

Surface micrographs of composite fabrics indicated significant microcracks with increased dimension following prolonged UV exposure. These observed microcracks on the non-woven geotextile, however, did not significantly contribute towards the loss of tensile properties. On the other hand, FTIR analysis detected that no chemical structure alteration occurred in the polymer matrix after five months of UV exposure. This suggested that the non-woven geotextiles acted as a sacrificial layer and protected the underlying primary load-bearing woven fabrics from rapid degradation. Therefore, the additional layers of non-woven geotextile successfully proved their effectiveness in protecting the woven fabrics from being used alone. As a matter of fact, the short study period of five months adopted in this study was insufficient to adequately evaluate the tensile behaviour of composite fabrics under UV exposure. Accordingly, in future studies, it is recommended that the outdoor UV weathering test be extended until the half-life (i.e., 50% retained) of the tensile properties is achieved. Moreover, it is recommended that the deposition of dust and microscopic dirt particles in the polymer matrix that potentially affected the tensile behaviour of composite fabrics under prolonged outdoor UV weathering be investigated.

Overall, this study provides clear evidence on the UV degradation of engineered fabrics in outdoor UV weathering tests, which greatly supports the earlier hypothesis

made that the degradation of engineered fabrics will exacerbate with prolonged UV exposure. Laboratory experimental tests from this study also indicated a close agreement in supporting engineered fabric degradation.

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