Simple constitutive methods to represent the tensile response of a laboratory-aged nonwoven geotextile

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Abstract. Simple constitutive models (polynomial and hyperbolic-based) were used to represent the tensile response of a nonwoven polypropylene geotextile. The model parameters were defined for a virgin sample and for samples submitted to two degradation mechanisms: thermo-oxidation and artificial weathering. Thermo-oxidation tests were carried out by the oven-ageing method (exposure in air, 110 ºC, in the dark during 56 and 112 days). The artificial weathering tests were performed in a laboratory weatherometer with exposure to ultraviolet radiation and water spraying. The virgin and laboratory-aged samples were characterised by tensile tests. The laboratory-aged samples exhibited some changes in their tensile properties. The best constitutive model to approximate the response of the geotextile (virgin and laboratory-aged samples) was the polynomial (order 6). However, the model parameters have no physical meaning. The hyperbolic-based model fitted well the experimental data. Model parameters *a* and *b* have physical meaning as they were related to tensile properties. The fit improved by using correction factors. Hyperbolic-based model parameters for the laboratory-aged samples were adequately estimated from tensile properties of the virgin sample and reduction factors for the laboratory ageing induced. This latter approach for estimating model of aged samples is promising and should be explored further.

1 Introduction

The design of geosynthetics is based on the definition of tensile properties (e.g., tensile strength and elongation at break) taking into account relevant aspects related to durability. To analyse the behaviour of geosynthetics, numerical models are often adopted, implemented using finite elements or finite differences methods. In those models, a geosynthetic is often

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represented with a simple linear-elastic constitutive model, i.e., a stiffness (and sometimes a tensile strength). This can be a very crude simplification. In the literature, proposals for simple constitutive models can be found to represent the tensile force *versus* elongation response of geosynthetics [1,2]. In most cases, such models represent the tensile response of virgin geosynthetics, ignoring aspects related to their durability. However, durability is a crucial aspect to take into account when designing with geosynthetics, as the functional properties of these materials can be significantly altered by degradation mechanisms [3]. Herein, simple constitutive models were used to represent the tensile response of a geotextile before and after laboratory ageing.

2 Materials and methods

2.1 Geotextile

This work studied a polypropylene (PP) geotextile (nonwoven type) with a mass per unit area of 300 g/m^2. The geotextile was commercially available on the market and, according to the manufacturer, had protection against thermal and photodegradation (the composition of the stabilisation package was not available in the product's technical data sheet).

The sampling and preparation of test specimens (for the characterization and degradation tests) was carried out according to EN ISO 9862 [4]. Four sample conditions (different ageing states) were considered in the work plan: (1) virgin sample (as received, without laboratory ageing); (2) TO-56D sample (exposed to 56 days of thermo-oxidation); (3) TO-112D sample (exposed to 112 days of thermo-oxidation); and (4) weathered sample (exposed to ultraviolet (UV) radiation and water spraying in a laboratory weatherometer).

2.2 Degradation tests

The geotextile was submitted to two different laboratory degradation tests: thermo-oxidation and artificial weathering.

The thermo-oxidation tests (oven-ageing method) consisted of exposing the geotextile to high temperature (110 ºC) in an oven (*Heraeus Instruments*, model T6120) with a normal oxygen atmosphere (21% O_2) and without forced air circulation. The exposure periods were 56 and 112 days (samples TO-56D and TO-112D, respectively). These time intervals were longer than those prescribed in EN ISO 13438 [5] for PP geotextiles. The option for longer exposure periods was intended to make the degradation conditions more severe and therefore enhance the effects of thermo-oxidation.

The artificial weathering test was performed in a laboratory weatherometer – the QUV Weathering Tester (*Q-Panel Lab Products*, model QUV/spray). In this test, the geotextile was exposed to alternating cycles of UV radiation (duration of 5 hours at 50 ºC) and water spray (duration of 10 minutes; water at room temperature with a flow of 5 L/min). The total duration of the test was 362 hours (about 15 days), which corresponded to approximately 70 weathering cycles under the previous conditions. Fluorescent UVA-340 lamps operating with an irradiance of 0.68 W/m^2 at 340 nm were used as the UV radiation source. The accumulated UV radiant exposure (290-400 nm) during the entire test was 50 MJ/m^2, corresponding to the value defined in EN 12224 [6].

2.3 Tensile tests

The tests used to assess the tensile behaviour of the geotextile (virgin and laboratory-aged samples) followed the procedures of ISO 9073-3 [7]. These tests were conducted on a *Lloyd*

Instruments (model LR 50K) tensile machine. The specimens had the following dimensions: length of 200 mm (between jaws) and width of 50 mm (specimens prepared and tested in the machine direction of production). The test speed was 100 mm/min.

The parameters determined in the tensile tests (average values of 5 specimens) included tensile strength (T_{max}, in kN/m), elongation at tensile strength (ε_{Tmax}, in %), secant stiffness at 2% elongation ($J_{s2\%}$, in kN/m) and secant stiffness at 5% elongation ($J_{s5\%}$, in kN/m). The tensile results are presented with 95% confidence intervals.

2.4 Constitutive models

In this work, two types of constitutive models were used to approximate the tensile force (T) *versus* elongation (ε) curves of the geotextile for the different samples studied: order 6 polynomial model (T_{6p}, Equation 1) and hyperbolic model (T_{hy}, Equation 2). The model parameters are coefficients a_i, for the order 6 polynomial model, and a, b and α, for the hyperbolic-based model. Herein, this last model will be shortly designated as hyperbolic.

$$T_{6p} = a_0 + a_1\varepsilon + a_2\varepsilon^2 + a_3\varepsilon^3 + a_4\varepsilon^4 + a_5\varepsilon^5 + a_6\varepsilon^6 \quad (1)$$

$$T_{hy} = \frac{\varepsilon}{a+2b\varepsilon} + \frac{1}{2b} \cdot e^{-\alpha(\varepsilon-\varepsilon_{max})^2} \quad (2)$$

The tensile force *versus* elongation curves were fitted with the chosen equations using the software DataGraph 5.4. The fitting exercise was done per specimen, i.e., the tensile force *versus* elongation curve for each specimen was approximated by a constitutive equation. The corresponding model parameters were estimated. Then, average model parameters were calculated to represent average estimated tensile force *versus* elongation response.

3 Results and discussion

3.1 Tensile behaviour: experimental data

The degradation tests (both thermo-oxidation and artificial weathering) caused some changes in the tensile behaviour of the geotextile. The tensile properties of the virgin and laboratory-aged samples can be found in Table 1. Additionally, Figure 1 shows representative tensile force *versus* elongation curves obtained for the different samples. These curves correspond to the curve of the specimen (one for each sample) with the tensile behaviour closest to the average behaviour of the 5 specimens tested in each sample.

Table 1. Tensile properties of the geotextile (virgin and laboratory-aged samples).

Sample	T_{max} (kN/m)	ε_{Tmax} (%)	$J_{s2\%}$ (kN/m)	$J_{s5\%}$ (kN/m)
Virgin	12.10 ± 0.72	60.9 ± 3.1	12.89 ± 2.52	13.48 ± 1.85
TO-56D	9.74 ± 0.71	58.1 ± 2.8	11.92 ± 1.78	11.89 ± 1.47
TO-112D	8.81 ± 0.98	54.8 ± 6.9	10.32 ± 2.60	11.87 ± 1.87
Weathered	9.18 ± 0.61	52.6 ± 3.5	12.07 ± 1.39	12.33 ± 0.89

As can be seen in Table 1, the tensile strength of the geotextile decreased after 56 days of thermo-oxidation – reduction of 19.5%. Increasing the exposure time to 112 days resulted in a more pronounced reduction relative to the virgin sample, namely of 27.2%. The corresponding elongations also tended to decrease, but on a smaller scale (in percentage terms). In fact, taking into account the 95% confidence intervals, the elongation at tensile strength found for the TO-56D and TO-112D samples was not very different from that obtained for the virgin sample. With regard to secant stiffness, both at 2 and 5% elongation, the values obtained for the samples exposed to thermo-oxidation tended to be lower than those found for the virgin sample. However, and again, the 95% confidence intervals were relatively wide.

Like the thermo-oxidation tests, the artificial weathering test also caused a decrease in the tensile strength of the geotextile – reduction of 24.1%. The elongation at tensile strength also experienced a decrease (from 60.9% in the virgin sample to 52.6% in the weathered sample). The secant stiffness at 2 and 5% elongation tended to decrease, although to a lesser extent than the reductions observed in the samples exposed to thermo-oxidation. Given the 95% confidence intervals, these variations in secant stiffness may be of little significance.

Overall, although there were some changes in tensile behaviour, the geotextile proved to have some resistance to thermo-oxidation and artificial weathering. This is concordant with the presence of chemical stabilisers in the geotextile, as stated by the manufacturer. Indeed, an unstabilised PP geotextile would have been destroyed if submitted to the degradation tests conducted in this work.

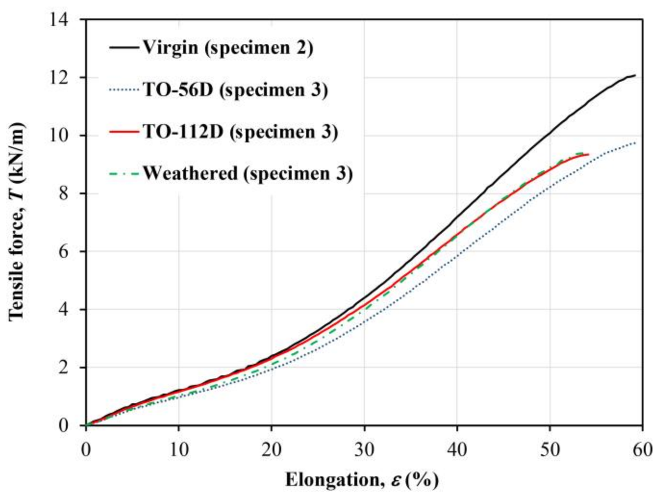

Fig. 1. Tensile force *versus* elongation curves of the geotextile (virgin and laboratory-aged samples) for representative specimens.

3.2 Constitutive models

The model parameters obtained from the curve fitting exercise are summarised in Tables 2 and 3 for the order 6 polynomial model and the hyperbolic model, respectively. The corresponding 95% confidence intervals and coefficients of determination (R^2) are shown. Figure 2 illustrates different tensile force *versus* elongation curves obtained for representative specimens: experimental data and fitted curves using both order 6 polynomial and hyperbolic equations. The secant (J_s) and tangent (J_t) stiffness values were estimated using the different models and compared to the experimental data (Table 4). In Table 4, $J_{t0\%}$, $J_{t2\%}$, $J_{t5\%}$ correspond to tangent stiffness obtained at, respectively, 0%, 2% and 5% elongation.

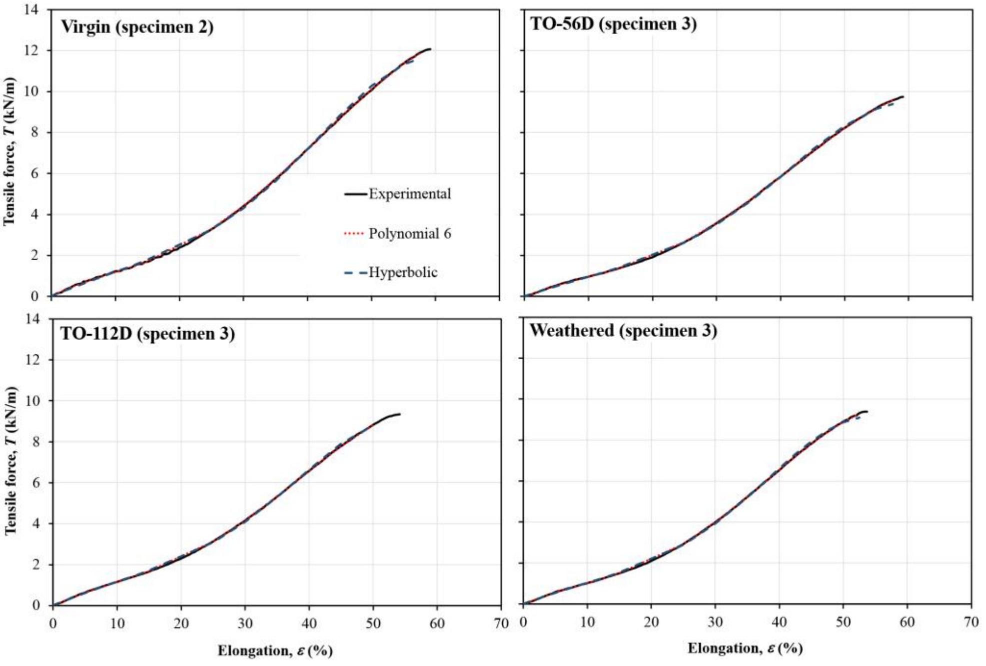

Fig. 2. Tensile force *versus* elongation curves of the geotextile (virgin and laboratory-aged samples) for representative specimens: experimental curves and corresponding fitted curves with order 6 polynomial and hyperbolic equations.

Table 2. Polynomial 6 model parameters (a_i) for virgin and laboratory-aged samples.

T_{6p}	Virgin	TO-56D	TO-112D	Weathered
a_6	-4.12E-10 ± 3.38E-10	-3.62E-10 ± 4.07E-10	-4.85E-10 ± 1.34E-09	-1.22E-12 ± 3.33E-10
a_5	1.02E-07 ± 6.97E-08	7.76E-08 ± 6.48E-08	6.76E-08 ± 1.67E-07	2.15E-08 ± 4.14E-08
a_4	-1.15E-05 ± 5.34E-06	-8.64E-06 ± 3.84E-06	-6.58E-06 ± 8.34E-06	-5.95E-06 ± 2.27E-06
a_3	6.07E-04 ± 1.70E-04	4.76E-04 ± 1.04E-04	3.81E-04 ± 2.10E-04	4.19E-04 ± 5.82E-05
a_2	-1.16E-02 ± 1.82E-03	-9.46E-03 ± 1.28E-03	-7.97E-03 ± 2.55E-03	-8.44E-03 ± 7.33E-04
a_1	1.85E-01 ± 1.32E-02	1.62E-01 ± 1.54E-02	1.61E-01 ± 2.10E-02	1.61E-01 ± 8.94E-03
a_0	-3.49E-02 ± 4.05E-02	-3.38E-02 ± 8.88E-03	-5.74E-02 ± 1.59E-02	-2.04E-02 ± 3.42E-02
R^2	1.000 ± 0.000	1.000 ± 0.000	1.000 ± 0.000	1.000 ± 0.000

Table 3. Hyperbolic model parameters (*a, b, α*) for virgin and laboratory-aged samples.

T_{hy}	Virgin	TO-56D	TO-112D	Weathered
a	9.00E+00 ± 1.19E+00	9.19E+00 ± 1.47E+00	8.29E+00 ± 2.09E+00	8.27E+00 ± 1.06E+00
b	6.19E-02 ± 4.01E-03	7.91E-02 ± 7.66E-03	9.06E-02 ± 1.16E-02	8.56E-02 ± 7.50E-03
α	1.53E-03 ± 2.21E-04	1.81E-03 ± 2.78E-04	2.21E-03 ± 9.45E-04	2.24E-03 ± 4.66E-04
R^2	0.999 ± 0.000	0.999 ± 0.000	0.999 ± 0.001	0.999 ± 0.000

Table 4. Secant and tangent stiffness for virgin and laboratory-aged samples.

Sample		$J_{s2\%}$ (kN/m)	$J_{s5\%}$ (kN/m)	$J_{t0\%}$ (kN/m)	$J_{t2\%}$ (kN/m)	$J_{t5\%}$ (kN/m)
Experimental data	Virgin	12.89 ± 2.52	13.48 ± 1.85	-	-	-
	TO-56D	11.92 ± 1.78	11.89 ± 1.47	-	-	-
	TO-112D	10.32 ± 2.60	11.87 ± 1.87	-	-	-
	Weathered	12.07 ± 1.39	12.33 ± 0.89	-	-	-
Polynomial 6	Virgin	14.67 ± 2.78	13.38 ± 1.43	18.51 ± 1.32	14.55 ± 0.92	10.91 ± 0.74
	TO-56D	12.79 ± 1.67	11.87 ± 1.35	16.19 ± 1.54	12.95 ± 1.29	9.89 ± 1.10
	TO-112D	11.80 ± 2.43	11.86 ± 1.80	16.11 ± 2.10	13.36 ± 1.61	10.70 ± 1.51
	Weathered	13.56 ± 2.47	12.46 ± 1.37	16.11 ± 0.89	13.22 ± 0.71	10.52 ± 0.64
Hyperbolic	Virgin	13.17 ± 1.61	11.98 ± 1.28	11.78 ± 1.37	11.39 ± 1.23	11.03 ± 1.09
	TO-56D	11.81 ± 1.67	10.96 ± 1.53	11.37 ± 1.99	10.76 ± 1.65	10.09 ± 1.26
	TO-112D	12.81 ± 2.59	11.83 ± 2.34	12.73 ± 3.15	11.76 ± 2.53	10.66 ± 1.89
	Weathered	12.83 ± 1.24	11.88 ± 1.10	12.53 ± 1.54	11.71 ± 1.22	10.83 ± 0.86

3.2.1 Order 6 polynomial model

The order 6 polynomial equations approximated the experimental data very well (R^2 = 1.000) and were able to capture the shape of the experimental curves (Figure 2). These polynomial equations allow estimating the tangent stiffness for different values of elongation, as needed. The coefficients a_i obtained were low, particularly for monomials a_4 to a_6.

The model parameters (the polynomial coefficients, a_i) have no physical meaning and cannot be estimated unless a curve fitting exercise is conducted, for both virgin and aged samples.

3.2.2 Hyperbolic model

The hyperbolic model was able to approximate the experimental data very well, as evident from the coefficient of determination (R^2) of 0.999 for all types of samples studied, and from Figure 2. The model parameters a and b changed after ageing, reflecting the changes observed for the experimental data. The model parameter α increased after ageing.

As in previous studies [8], model parameters a and b were estimated using equations from the literature to assess their physical meaning (Equations 3 and 4), illustrated in Figure 3. Then, correction factors were included (C_J and C_T in Equations 5 and 6) [8]; the resulting curve fitting and the correction factors are illustrated, respectively in Figure 3 and Table 5.

$$a = \frac{1}{J_i} \tag{3}$$

$$b = \frac{1}{T_{max}} \tag{4}$$

$$a = \frac{C_J}{J_i} \tag{5}$$

$$b = \frac{C_T}{T_{max}} \tag{6}$$

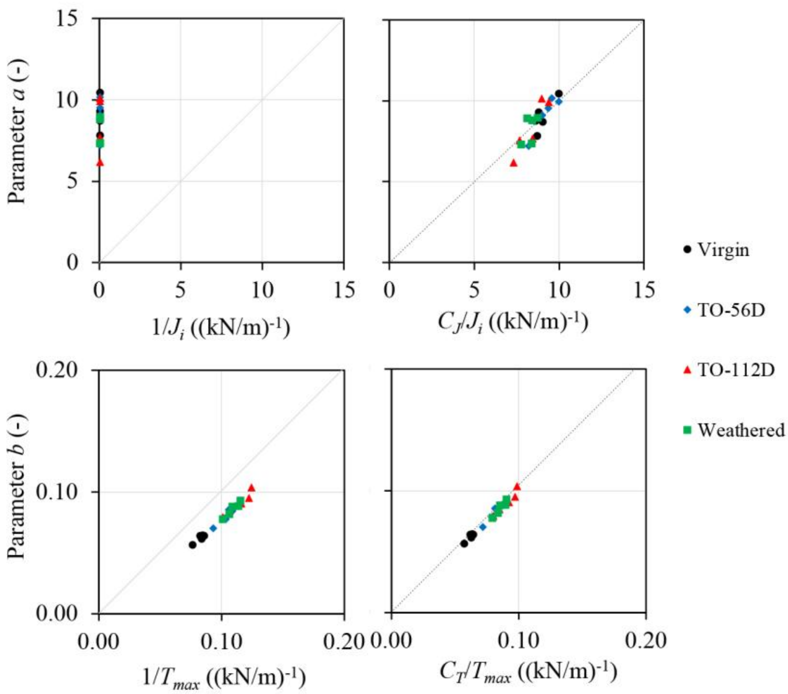

Fig. 3. Physical meaning of hyperbolic model parameters a and b.

The experimental data showed that Equations 3 and 4 cannot be used to estimate the model parameters, particularly for model parameter a and its relation to the initial stiffness J_i. Nevertheless, by including the correction factors C_J and C_T, the hyperbolic model parameters could be estimated more accurately; this was observed for all types of samples studied (virgin geotextile and after laboratory ageing). C_J is not constant, and it depends on the type of sample studied; for the conditions analysed herein, this correction factor decreased after laboratory ageing. C_T is similar to a failure ratio and ranged between 75% (virgin sample) and 79% (after thermo-oxidation for 112 days); this factor increased after ageing. The quality of the fitting exercise to derive these correction factors is represented by the corresponding coefficients of determination (R^2), shown in Table 5.

Table 5. Correction factors C_J and C_T for virgin and laboratory-aged samples.

Sample	C_J	R^2 for C_J	C_T	R^2 for C_T
Virgin	166.37	0.9966	0.748	0.9993
TO-56D	148.47	0.9968	0.769	0.9992
TO-112D	133.35	0.9903	0.794	0.9991
Weathered	132.99	0.9938	0.785	0.9994

3.2.3 Estimates of model parameters after laboratory ageing

An approach similar to that adopted by Carneiro *et al.* [8] was used to estimate the hyperbolic model parameters for laboratory-aged samples ($a_{a,e}$ and $b_{a,e}$). For that, simple relations between tensile properties of virgin and laboratory-aged samples and the model parameters for the virgin sample (a_v and b_v) were adopted. This approach uses the concept of reduction factors (Equation 7) for tensile properties linked to the physical meaning of model parameters a and b (RF_{Ji} and RF_T). Such reduction factor (RF_X) is the ratio of property X for the virgin sample to that for the laboratory-aged sample.

$$RF_X = \frac{X_{virgin}}{X_{aged}} \quad (7)$$

Different relations were analysed; the best approximation of model parameters for the aged samples (a_a and b_a) was obtained by using Equations 8 and 9, as illustrated in Figure 4. The estimates were particularly good for model parameter b.

$$a_a \sim a_{a,e} = a_v \times RF_{Ji} \quad (8)$$

$$b_a \sim ab_{a,e} = b_v \times RF_T \quad (9)$$

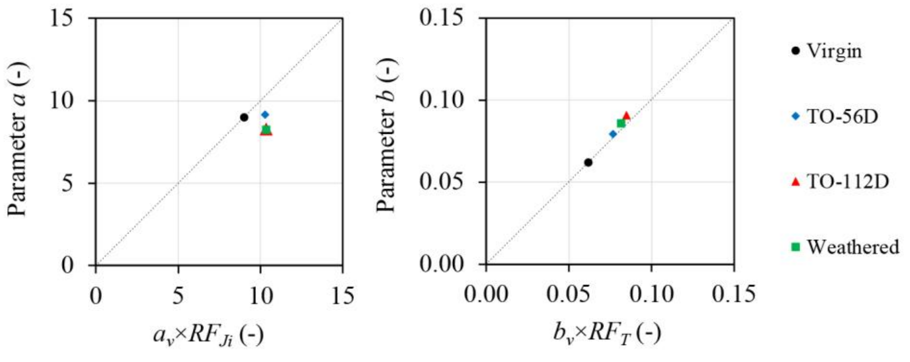

Fig. 4. Hyperbolic model parameters a and b and their estimates after laboratory-ageing.

Then, tensile force *versus* elongation curves were generated using the estimated hyperbolic model parameters a_a and b_a, and the model parameter α obtained for the virgin sample. These average curves are represented in Figure 5. From the figure it is clear that the approximation obtained was adequate; this response was also within the range of responses observed for the five specimens tested per sample (exception for the laboratory weathered sample). The estimates are particularly good for smaller values of elongation, up to 7%.

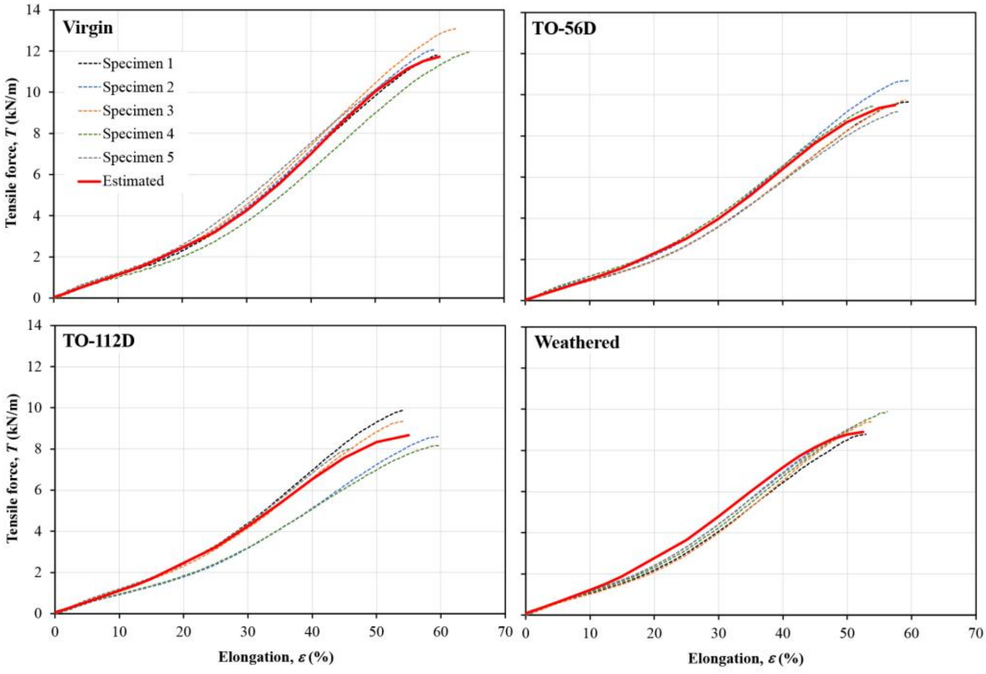

Fig. 5. Tensile force *versus* elongation curves obtained for the geotextile (virgin and laboratory-aged samples): experimental (5 specimens) and estimated by hyperbolic equations (parameters a_a, b_a, α).

4 Conclusions

Four different samples of a nonwoven PP geotextile (in different ageing states) were studied: virgin sample (as received, without laboratory ageing); sample exposed to 56 days of thermo-oxidation in laboratory; sample exposed to 112 days of thermo-oxidation in laboratory; and weathered sample (exposed to UV radiation and water spraying in laboratory). The tensile force *versus* elongation response of these samples was assessed experimentally. Then, two different constitutive models were used to fit the experimental data: order 6 polynomial and hyperbolic-based models. The data generated was used to estimate model parameters after laboratory ageing. The main conclusions of this study are:

- The laboratory-aged samples exhibited some changes in their tensile properties.
- The best constitutive model to approximate the tensile force *versus* elongation response of the geotextile (virgin and laboratory-aged samples) was the order 6 polynomial. However, its model parameters have no physical meaning.
- The hyperbolic-based model fitted well the experimental data and the model parameters *a* and *b* have physical meaning, as they can be related to tensile properties of the samples (fit improved by the use of correction factors).

- The hyperbolic-based model parameters (*a* and *b*) for the laboratory-aged samples were adequately estimated from the tensile properties of the virgin sample and the reduction factors for the laboratory ageing induced.
- This latter approach for estimating model parameters and the tensile force *versus* elongation response of aged samples is promising and should be explored further for other geosynthetics and degradation conditions.

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Data Availability Statement: Some or all data or models that support the findings of this study are available from the corresponding author upon reasonable request.

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