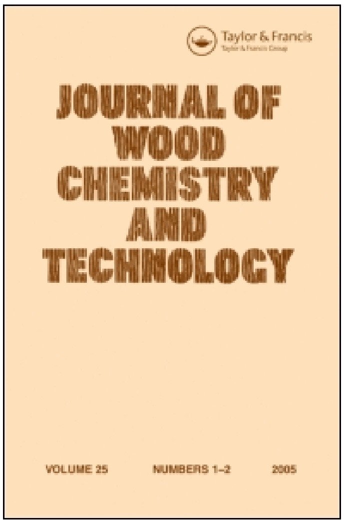

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Françoise Hugot[a]; Gilles Cazaurang[b]
[a] Université de Limoges, ENSIL, Limoges, France [b] Université Bordeaux, LGM^{2}B, Gradignan, France

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Mechanical Properties of an Extruded Wood Plastic Composite: Analytical Modeling

Françoise Hugot[1,2] **and Gilles Cazaurang**[3]
[1]Université de Limoges, ENSIL, Limoges, France
[2]INRA UAR 911, Cestas, France
[3]Université Bordeaux, LGM^{2}B, IUT Bordeaux 1, Gradignan, France

Abstract: The focus of this study has been to predict wood plastic composite (WPC) properties using analytical models dedicated to reinforced composites and to define their limits. Experiment tests have been realized to characterize mechanical properties of a commercial WPC. On one hand, good compressive and three points bending performances were observed in agreement with application requirements for this decking product. On the other hand, lower tensile performance and failure appearances revealed a lack of interfacial bonding between wood fiber and matrix despite the presence of a coupling agent in the composite formulation.

Keywords: Analytical modeling, HDPE, mechanical properties, polymer-matrix composites, wood fiber, WPC

INTRODUCTION

In recent years, wood plastic composites (WPC) have attracted great interest in composite science and commercial developments. In North America WPC decking represents 65% of WPC market with a 15% share of the global decking market.[1,2] The European WPC market is small compared to the North American one but growing despite a lack of commercial leadership.[3] The replacement of petroleum-based products by renewable materials is an economic and environmental issue. Wood fibers have the advantage to be recyclable and abundant.

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Address correspondence to Françoise Hugot, Université de Limoges, ENSIL, 16 rue Atlantis Parc ESTER Technopole, BP, 6804 87068 Limoges, France. E-mail: hugot@ensil.unilim.fr

Studies deal with WPC properties: different attempts were made with various raw materials (natural fibers and virgin or recycled polymers) and different morphology.[4–8] Problematic issues like interfacial adhesion are outlined and solutions (coupling agent, surface treatments) are discussed comparing mechanical properties of WPC formulations.[9–12] Also, some works show the nonlinear behavior of Wood Plastic Composites.[13,14]

The main purpose of this article is to describe different analytical mechanical models for determining elastic modulus. Experimental tests (tensile, compressive, three points bending, and shear tests) of Wood Plastic Composites that are manufactured using an extrusion process were carried out in order to determine mechanical properties.

MATERIALS

A commercial WPC dedicated to decking applications was used for this study. This product is made by twin screw extrusion processing of 60% wood, 30% HDPE (High Density Polyethylene) polymer, and 10% of additives. HDPE Lacqtene® (MFI = 2.5 g/10 min) polymer granulates are from ATOFINA and additives contain coupling and dispersive agents, lubricant, stabilizers, and talc (the percentages of their components are confidential).

The wood was softwood sawdust with morphological characteristics described in Figure 1. Optical scanning of fiber is used to determine size

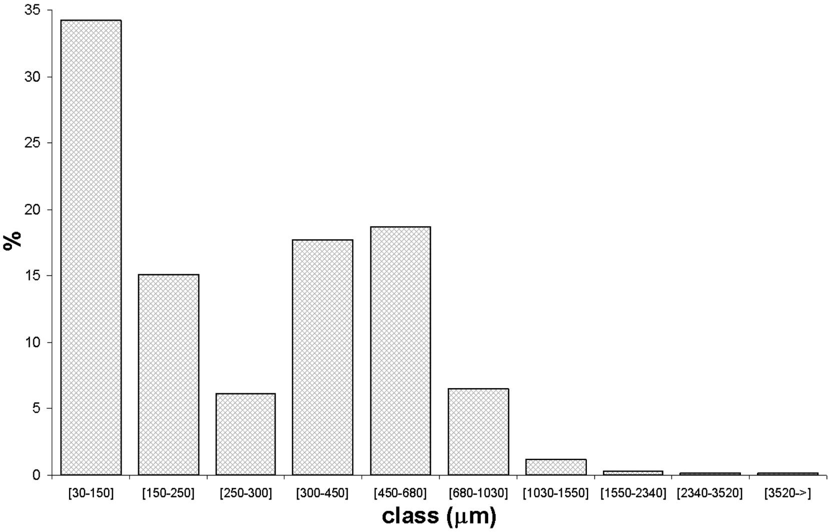


Figure 1. Morphological characteristics of wood fibers.

Table 1. Raw material properties

Properties (MPa)		Tension		Compression		Bending		Shear	
		Long.	Trans.	Long.	Trans.	Long.	Trans.	Long.	Trans.
Pine wood[1]	MOE	12 000	800	12 000	800	11 200	800	750	80
	$\sigma_{\max}$	51	3.2	25	25	20	—	6.5	—
HDPE[2]	MOE	1 250	1 250	1 250	1 250	1 250	1 250	250	250
	$\sigma_{\max}$	25	25	20	20	20	—	—	—

MOE modulus of elasticity, $\sigma_{\max}$: maximum stress.

[1] Data from literature: wood (as whole) properties are used as fiber properties.[15]

[2] Experimental data from HDPE compression molding tests.

distribution in frequency of wood fibers. A MorFi LB01 system from Techpap allowed these morphological characteristic measurements of wood elements. Frequency distribution does not take into account the very small elements (length $< 30\ \mu$m), called fines, which represent about 90% in total length and 20% of the total surface of all elements analyzed.

HDPE polymer specimens are produced, in laboratory conditions, by compression molding at 180°C in order to have a set of mechanical properties.

All properties of raw material are summarized in Table 1.

EXPERIMENTAL METHODS

Based on standard guides, different appropriated test methods are chosen for evaluating mechanical properties of WPC product. Mechanical characterization was carried out onto a set of 20 specimens for each test using a universal testing machine device (ADAMEL, MTS).

Conditioning

Prior to testing, all specimens were conditioned to a temperature of 20°C ± 2 and a relative humidity of 65% ± 3 for several weeks in order to reach equilibrium state.

Tensile and Three Points Bending Tests

Tensile and three points bending properties were tested according to the standards dedicated for plastics and reinforced plastics composites, NF EN ISO 527-1-4 and NF EN ISO 178-1, respectively. The thickness of the tensile "rectangular dog bone" sample was 3 mm. Bending specimen size was 4 × 10 × 67 mm^3. Tensile and three points bending speeds were 0.5 $mm.min^{-1}$ and 1 $mm.min^{-1}$, respectively.

Compressive and Shear Tests

Compressive and shear tests are carried out according to standards dedicated for wood specimens, ASTM D143. Compressive specimen size is 20 × 20 × 60 mm^3. Shear specimen size is 25 × 25 × 35 mm^3 with a notched corner of 10 × 10 mm^2. Compressive and shear test speeds are 0.3 $mm.min^{-1}$ and 1 $mm.min^{-1}$, respectively.

Fitting Curve Method

The Curve Fitting Toolbox of MATLAB® software was used to create fitting curves of the WPC stress-strain behavior. The nonlinear relationship is described by Zawlocki[14] using a hyperbolic tangent function [Eq. (1)].

$$\sigma = a \tanh(b\varepsilon) \tag{1}$$

where a, b are fitting parameters estimated by statistical analysis.

EXPERIMENTAL RESULTS

Longitudinal direction (Long.) refers to extrusion process directional flow (wood fiber orientation) whereas transversal direction (Trans.) takes into account the transversal behavior of this material. The maximum stress ($\sigma_{\max}$) is selected in order to compare different tests.

WPC Behavior

WPC stress-strain curves present a global nonlinear behavior, which is closer to thermoplastic behavior than the usual wood brittle linear one. Indeed, WPC exhibit a constant accumulation of residual strain that can be well described using a hyperbolic tangent function as suggested by Zawlocki.[14] Tensile and three points bending curves (Figures 2 and 3, respectively) do not exhibit a distinct point suitable to determine yield point.

Reinforcement created by fiber orientation due to the extrusion process induces a higher longitudinal stress response (up to two times the transversal one) at a same strain for both tensile and three points bending curves. Hyperbolic

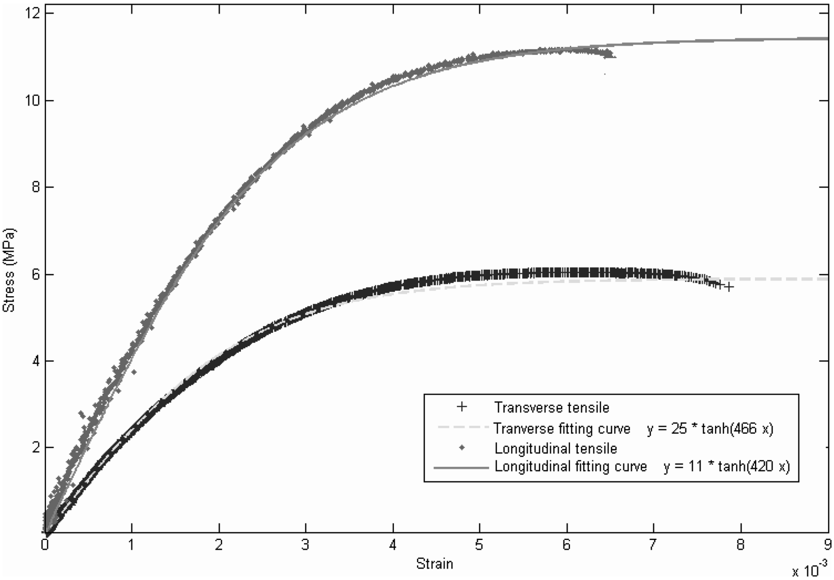


Figure 2. Experimental and fitted tension stress strain curves.

tangent functions show R^2 above 0.99 for three points bending fitting curves and above 0.85 for tensile fitting curves.

Tensile and three points bending wood, plastic, and WPC stress-strain relationships are reported in Figure 4. Wood behavior presents a higher tensile

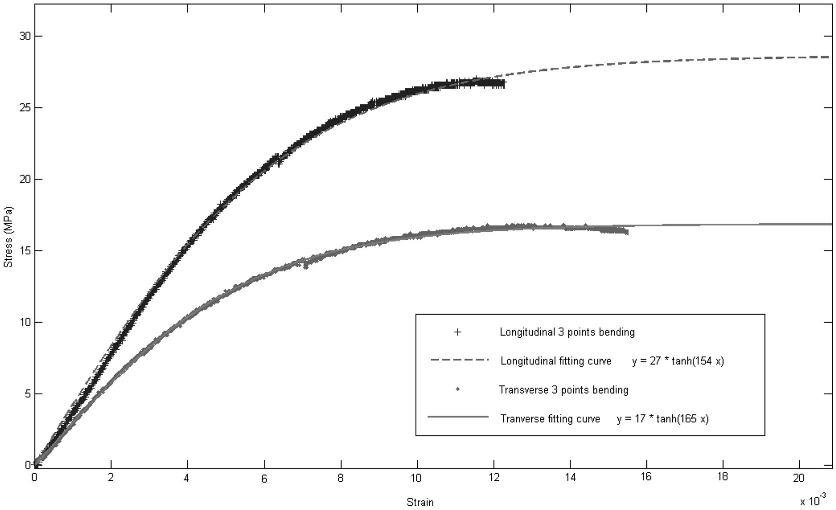


Figure 3. Experimental and fitted bending stress strain curves.

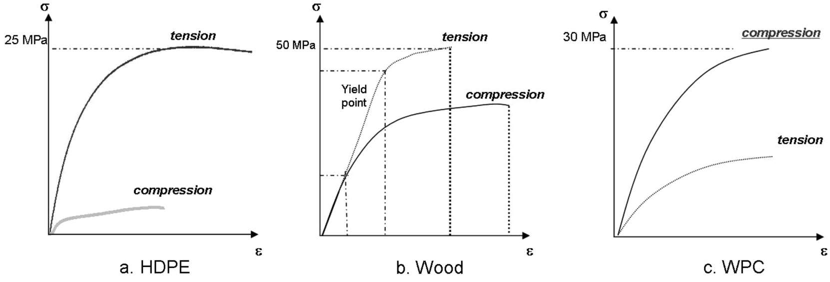


Figure 4. Comparison of HDPE, wood, and WPC mechanical behaviors in tension and compression.

than compressive resistance. Tensile failure is brittle whereas compressive failure tends to be more ductile. HDPE polymer tested shows a higher tensile than compressive strength.

WPC behavior is different of its component behaviors (HDPE and wood fiber) (Figure 4c). Compressive strength is higher than the tensile one. The contrary effect emphasizes a lack of reinforcement expected from wood fibers. It seems that in tension, wood fibers behave like an inclusion, whereas in compression, they act like an encapsulated filler. Despite low interfacial bonding, a mechanical interlocking on the surface of wood fibers and HDPE polymer occurs to allow taking benefit during the compressive test. In fact, fines elements without aspect ratio effect should increase WPC compressive properties.

Mechanical Properties

Due to the global nonlinear behavior of WPC, mechanical properties such as MOE are difficult to obtain. Indeed, standard guide recommendations are often not suitable for this composite. Therefore, we decided to evaluate the MOE using the specifications for reinforced plastic standard (MOE_{norm} taken between 5×10^{-4} and 2.5×10^{-3} of strain) and to define a tangent modulus of elasticity based on the first derivate of hyperbolic tangent function ($\text{MOE}_{\text{tangent}}$). The latter one is the more appropriate to calculate tensile elastic modulus. Difference between MOE_{norm} and $\text{MOE}_{\text{tangent}}$ confirms an underestimation of MOE standard method due to the nonlinear behavior. Results are summarized in Table 2.

Tensile and three points bending values of transversal MOE confirm the anisotropic behavior of an extruded WPC.

Tensile and three points bending transversal stresses (σ_{max}) are up to two times smaller than longitudinal values. Compressive and shear maximal stresses are almost unaffected by directional consideration.

Table 2. Mechanical properties of WPC product

WPC properties (MPa)	Tension		Compression		Bending		Shear	
	Long.	Trans.	Long.	Trans.	Long.	Trans.	Long.	Trans.
MOE_{norm}	3000 (340)	1500 (150)	3700 (215)	1980 (150)	4100 (235)	2660 (190)	240 (35)	220 (25)
$MOE_{tangent}$	4700 (550)	2540 (460)	—	—	4300 (470)	2800 (185)	—	—
σ_{max}	11.6 (1.0)	5.3 (0.5)	28.1 (0.7)	25.4 (0.8)	26.1 (1.0)	16.7 (0.5)	8.1 (0.4)	7.1 (0.3)

$MOE_{tangent}$: Modulus of elasticity taken as the tangent at $x = 0$ of the hyperbolic tangential function fitted onto experimental values for each sample test. ( ): standard deviation.

Tensile maximal stress is far lower for WPC ($\sigma_{tl} = 11.6$ MPa) than HDPE ($\sigma_{tl} = 25$ MPa) and wood ($\sigma_{tl} = 50$ MPa), which leads us to conclude that somehow wood elements act more like a filler, even like an inclusion, than a real reinforcement. For instance, interfacial adhesion plays a main role in load transfer from the matrix to the fiber. Compressive and three points bending properties are less dependent on adhesion quality than tensile ones.

Fracture Appearance

Material composite failure modes can be initiated by fiber breakage, fiber/matrix interfacial debonding, fiber pull-out, or matrix plastic deformation and cracking. Mechanical function of reinforced composite can only be efficient if stresses are transferred from the matrix to the fiber. Load transfer depends on the mechanical response of the interface zone between the fiber and the matrix.

Observations of WPC tensile failure with optical microscope (Figure 5) present evidence of fiber pull-out, which is characteristic of poor interfacial adhesion. The same trends of failure behavior are observed for different applied loads. Weak interfacial bonding is a well-known problem of WPC due to incompatibility of both components. Coupling agent incorporated in this commercial product may not be efficient enough and additional improvements should be done to link wood fiber to thermoplastics in order to prevent the fiber pull-out leading to a better load transfer. Interfacial bonding quality is a key point of mechanical performance for WPC.

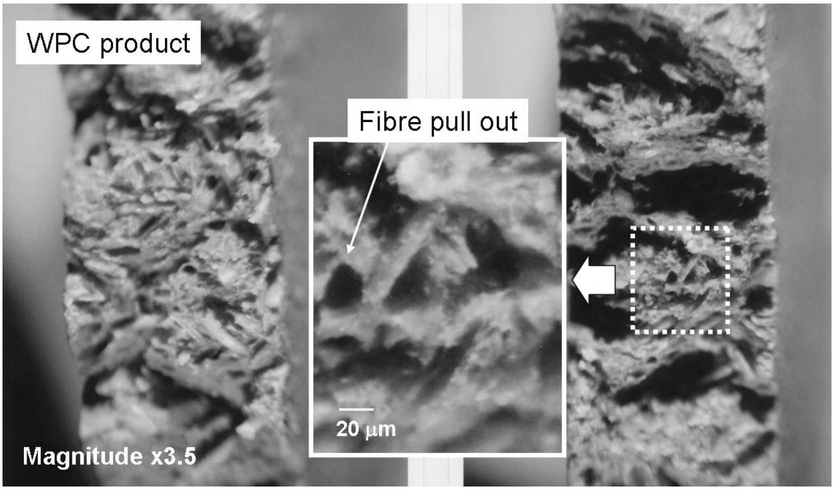


Figure 5. Failure appearance of WPC.

ANALYTICAL MODELS

Analytical models that predict elastic properties of two discontinuous phases can be found in the literature: these can be applied to short, orientated fiber-reinforced composites. Selected models are series, parallel, Hirsch, Cox/Bigg/Kelly, and Halpin/Tsai models.[16–19] Bonding between fiber and matrix is supposed to be perfect: it is a first modeling approach from an engineering point of view.

Composite properties depend on individual components. M and V are, respectively, elastic moduli (longitudinal or transversal moduli) and volume fraction. The c, m, and f subscripts represent, respectively, composite, matrix, and fiber.

Hirsch Model

The Hirsch model [Eq. (2)] proposes an elastic modulus relation based on weighed average of simplest models, that is, parallel (Voigt or upper bound) and series (Reuss or lower bound) equations. Composite microstructure is represented as a unit cell: uniform strain and uniform stress, respectively, are used in these expressions. Parameters x and $(1 - x)$ are the relative proportion of material conforming to the upper and lower bound solutions. x is determined mainly by fiber orientation, fiber length, and stress concentration effect near fiber reinforcement.

$$M_c = x(M_m V_m + M_f V_f) + (1 - x)\frac{M_m M_f}{M_m V_f + M_f V_m} \tag{2}$$

In order to take into account fiber partial orientation in longitudinal direction due to the extrusion process, x factor was chosen as a vector instead of a scalar value. A dichotomy method allows to fit x parameter to experimental values.

Cox/Kelly/Bigg Model (CKB)

Cox/Kelly/Bigg equations have been established with only one fiber factor [Eq. (3)]. η can have different values and in case of random fiber reinforcement, η is equal to 1/3.

$$M_c = M_f V_f \eta + M_m(1 - V_f) \tag{3}$$

In order to take into account fiber partial orientation due to the extrusion process, the CKB model is modified:

- Longitudinal modulus is estimated with longitudinal moduli of WPC components and η, which is dependant on fiber orientation range in longitudinal direction. η is assumed to follow a uniform probability density function in the [–θ, θ] range [Eq. (4)].

$$\eta = \eta * \times \left(\frac{1}{1 - \nu^2}\right)\eta^* = \frac{1}{2\theta}\int_{-\theta}^{\theta} \cos^4(\alpha)\, d\alpha \quad \text{for partially oriented materials} \tag{4}$$

- Transverse modulus is estimated with longitudinal moduli of WPC components. Indeed, wood transverse properties are more than ten times smaller than in longitudinal direction. So, η is dependant on complementary fiber orientation range:

$$[-(\pi - \theta), (\pi - \theta)].$$

Experimental longitudinal tensile modulus is used to calculate θ by fitting η with the CKB equation.

Halpin/Tsai Model (HT)

Halpin/Tsai equations have been established for an oriented short fiber ply. Longitudinal stiffness of an oriented short fiber composite is a function of the aspect ratio [Eqs. (5) and (6)]:

$$M_c = M_m\left(\frac{1 + A\eta V_f}{1 - \eta V_f}\right) \tag{5}$$

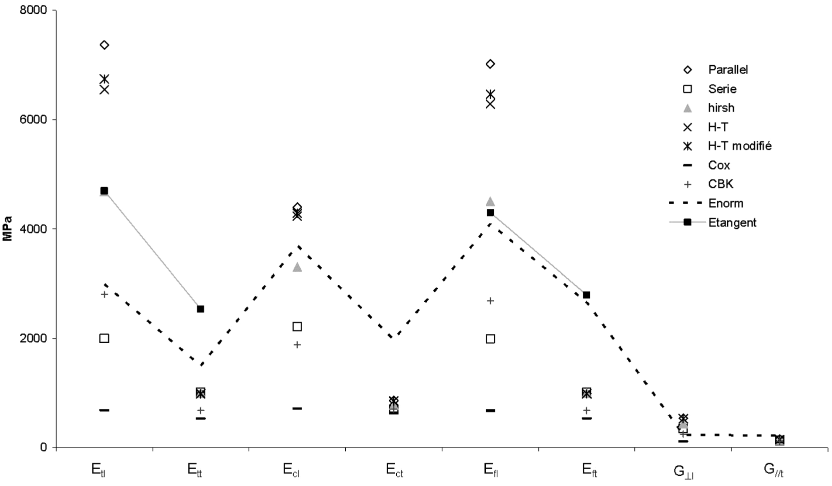
$$\eta = \frac{M_f/M_m - 1}{M_f/M_m + A} \tag{6}$$

A is a factor determined by fiber geometry, fiber distribution, and fiber volume fraction ($A = 22$). η accounts for fiber and matrix elastic moduli.

ANALYTICAL RESULTS

Analytical MOE are compared to experimental ones (tensile, compressive, three points bending and shear). Results are presented in Figure 6.

Modified Hirsh model has shown reasonable agreement with experimental data. Hirsh vector x is equal to 0.45, 0.15, respectively, in longitudinal and transverse directions. The factor x is strongly related to the reinforcement role.



E_{md}: elastic modulus with m mode of solicitation (tension, compression, flexion) and d direction (longitudinal or transverse)
$G_{\perp d}$ and $G_{//d}$: shear modulus perpendicular or parallel to the direction

Figure 6. Evaluation of analytical models compared to experimental values for MOE.

The Cox/Kelly/Bigg model shows similar observations. Fitting theoretical modulus with experimental longitudinal tensile modulus gives a $\eta^* = 0.69$ corresponding to a fiber orientation distribution in the $[-\pi/4, \pi/4]$ range. η^* is equal to 0.27 for transversal direction. Estimated MOE with modified CBK are closed to experimental values validating the assumption of a partial orientation of wood fibers.

A complete fiber orientation in longitudinal direction could give a good estimation of MOE with Halpin/Tsaï model. Overestimation is a consequence of both morphological aspects of wood elements and partial fiber orientation. In fact, wood fiber aspect ratio is irrelevant for the fines, which represent at least 90% of wood fibers in frequency. Series, parallel models underestimate transversal moduli, confirming the impact of anisotropic fiber distribution.

CONCLUSION

Tensile, compressive, three points bending and shear tests are realized for the WPC product. Experimental results point out that Wood Plastic Composite has a good potential for compressive and three points bending uses, which are decking main properties requirements. Extrusion process creates anisotropic behavior. Fiber pull-out observations indicate a lack of adhesion between wood fibers and HDPE polymer although a coupling agent is present. Mechanical performance of fiber-reinforced composites strongly depends on the load transfer between the matrix and the fibers.[20]

Modified Hirsh and Cox/Bigg/Kelly models are in good agreement with experimental data and emphasize anisotropic distribution of wood fibers. Nevertheless, WPC tensile performances are lower than both wood and HDPE polymer performances, showing inefficiency of fiber reinforcement. This explains analytical modeling limitations. Further development of numerical homogenization methods will permit one to incorporate the real nonlinear anisotropic behavior and interfacial problems such as sliding and friction, which are not included in the previous models presented.[21,22]

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