

# Dielectric mixing models for water content determination in woody biomass

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**Abstract** The aim of this study is to determine the dielectric constant of woody biomass at different water contents and describe its behavior with a dielectric mixing model. The use of the model for determination of water content is also verified. Dielectric constants were calculated from the travel times of electromagnetic waves with a center frequency of 555 MHz through collected biomass samples. The power law, Maxwell–Garnett, and Polder van Santen mixing models were applied to the experimental data. In the models, biomass was considered as a mixture of three phases: a solid solution composed of wood cellular material and bound water, free water, and air. The experimental data was found to be better described by the Maxwell–Garnett model. The use of this model along with an independent validation set for the determination of volumetric water content resulted in a root mean square error of prediction of 0.03 within the investigated volumetric water content range of 0.07–0.29.

## Introduction

Woody biomass is used as feedstock in several industrial processes, such as production of paper and construction materials. It is also used as biofuel for combustion in both heating and combined heat and power plants, and can become an important feedstock for ethanol and gas production in the future (Hendriks and Zeeman 2009). The water content of woody biomass can vary to a large degree, and therefore becomes an important parameter in processes where this feedstock is

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utilized. This raised the need for the development of sensors for water content measurement in woody biomass (Nyström and Dahlquist 2004). Electromagnetic aquametry, the measurement of water content using electromagnetic waves, is most adequate for the development of such sensors as it allows for non-destructive, instantaneous, and subsurface measurement. It has a wide range of applications in areas ranging from agriculture (Nelson 2006) to civil engineering (Sun 2008), as well as many in other areas of industry and science (Kupfer 2005).

A method for measuring water content in a bulk of woody biomass with radio frequency waves (RF) was developed by Nyström (Nyström 2006). This is a laboratory-scale method meant to be further developed into an in-line application. The method predicts water content from a measured parameter, the reflection coefficient, using a model built with multivariate data analysis (Nyström et al. 2005). However, parameters such as the reflection coefficient are a function not only of the characteristics of the material but also of the measurement setup and the amount of material. A prediction model based on such parameters cannot be generalized to different measurement conditions.

In order to develop generalized models for water content prediction, the dielectric properties, which characterize the interaction of the electromagnetic waves with the material, should be used. An example of an empirical model using dielectric properties is the Topp's equation (Topp et al. 1980). This model has been found to give accurate results, and it is still used to predict water content in soil and other porous materials (Turesson 2006; Vallone et al. 2007). The knowledge of the dielectric properties is also of great interest as it can improve the understanding of the material. Examples of such contributions are the study of the influence of temperature on the amount of bound water in porous materials by Jones and Or (2003), and the study of the structure and properties of chemically treated wood by Sugiyama and Norimoto (2003), which are done by analyzing the dielectric properties.

Although relevant, the dielectric properties of woody biomass have not been previously determined. In this paper, a dielectric property of woody biomass, the dielectric constant, is presented for the first time. The dielectric constant at RF is determined for different types of woody biomass with varying water content.

This paper also attempts to understand the relation between the dielectric constant and the characteristics of the material. Dielectric mixing models are used for this purpose. Dielectric mixing models are physically based models that relate the dielectric properties of a mixture with the dielectric properties of the mixture's individual components, their volumetric fraction, and geometry (Robinson et al. 2003). Different dielectric mixing models have been used with success to model the dielectric constant of mixtures: the power law model has been applied to soil and granular materials (Vallone et al. 2007; Mironov et al. 2004; Heimovaara et al. 1994), the Maxwell–Garnett model (MG) has been applied to soil (Dirksen and Dasberg 1993; van Dam et al. 2005), and the Polder van Santen model (PS) to snow and sea ice (Sihvola 1999). These three models are used in this paper, assuming woody biomass as being a mixture of a solid solution constituted by wood cellular material and bound water, free water, and air. An estimation of the dielectric constant of the solid solution is also given for the first time. The use of the best explanatory model for the determination of water content is also investigated.

## Materials and methods

### The dielectric constant

The dielectric properties of a material characterize its interaction with the electromagnetic waves. Non-magnetic materials are characterized by permittivity,  $\varepsilon$ , which is a measure of the polarization in the material when an electromagnetic field is applied.  $\varepsilon$  includes both energy storage and energy dissipation effects, and is therefore represented as a complex number:  $\varepsilon = \varepsilon' - j\varepsilon''$ , where  $\varepsilon'$  is the real part, or dielectric constant, describing the energy storage,  $j$  is the square root of  $-1$ , and  $\varepsilon''$  is the imaginary part, or loss factor, describing the energy dissipation (Ulaby 2007). When  $\varepsilon''$  is much smaller than  $\varepsilon'$  the medium can be considered low-loss and  $\varepsilon'$  can be calculated using Eq. 1, where  $c$  is the velocity of electromagnetic waves in free space,  $v$  is the velocity of electromagnetic waves in the sample, and  $\varepsilon'$  is the dielectric constant relative to that of free space.

$$\varepsilon' = \left(\frac{c}{v}\right)^2 \quad (1)$$

The effects of  $\varepsilon''$ , even if not measurable, may be present in the estimation of  $\varepsilon'$  with Eq. 1, this  $\varepsilon'$  has therefore been called apparent dielectric constant (Topp et al. 1980).  $\varepsilon'$  calculated with Eq. 1 may be overestimated for higher water contents, when effects of dielectric losses are higher (Topp et al. 2000). At radio and microwaves frequencies, the  $\varepsilon'$  of water is much larger than that of solid materials, and therefore the  $\varepsilon'$  of a mixture increases with increasing water content. Besides water content,  $\varepsilon'$  can be influenced by other factors such as density and temperature. Density is likely to have a minor influence in moist substances because the  $\varepsilon'$  of solids is close to that of air. The influence of temperature in the range between 1 and 63°C has been shown not to influence the electromagnetic measurements of woody biomass (Paz et al. 2006).

### Woody biomass

The material considered in this study consisted of different types of biomass derived from forest products, comprised mainly of wood, but also of treetops and bark. These materials can be considered as a mixture of three components: air, water, and solid woody material. Water in mixtures with a solid phase can either be found in free form or bound to the solids. In woody biomass, water is bound by hydrogen forces to the hydroxyl groups in wood and is found in the cell wall, while free water is held in the cell wall cavity (Skaar 1988; Torgovnikov 1992; Berry and Roderick 2005). The integrated mixture of cell wall material and bound water has been recognized as a distinct phase called solid solution (Berry and Roderick 2005). The mass of water bound in wood is generally accepted to be up to 30% of the mass of dry matter, and this level is often named the fiber saturation point (Berry and Roderick 2005). Bound water molecules are less free to participate in polarization phenomena, decreasing the  $\varepsilon'$  of bound water in relation to that of free water. However, the dielectric properties of bound water are complex and not fully

**Table 1** Distribution of the measurements of different woody biomass types between calibration and validation sets and respective  $\theta_w$  and  $\rho$  span

Material	Calibration			Validation		
	Measurements	$\theta_w$ (vol vol <sup>-1</sup> )	$\rho$ (g cm <sup>-3</sup> )	Measurements	$\theta_w$ (vol vol <sup>-1</sup> )	$\rho$ (g cm <sup>-3</sup> )
SD	188	0.07–0.29	0.13–0.18	12	0.11–0.27	0.11–0.18
TN	42	0.08–0.15	0.16–0.19	16	0.09–0.21	0.15–0.20
RW	19	0.08–0.24	0.16–0.18	11	0.08–0.23	0.15–0.18

understood, as they vary with the degree of the bound water and show a wide spectrum of relaxation frequencies (Torgovnikov 1992).

Structurally, wood consists of hollow tubular cells of earlywood and latewood parallel to the wood branch, and ray cells perpendicular to those tubular cells. As a result of this cellular structure and also the arrangement of cell wall components, wood exhibits dielectric anisotropy (Torgovnikov 1992; Koponen 2005). Values for  $\epsilon'$  of wood are often presented for the electrical field parallel to the tubular cells, named longitudinal or transversal  $\epsilon'$ , and for the electrical field perpendicular to the tubular cells, named tangential  $\epsilon'$ . The woody biomass used in this study is made up of randomly oriented wood pieces and it can therefore be considered an isotropic mixture.

The data in this study is comprised of measurements of 89 different samples of the following woody biomass types: sawdust (SD), mixture of treetops and needles (TN), and residual woodchips (RW) obtained from pallets and building materials. For each sample, three repetition measurements were taken in which the sample holder was emptied and filled again with the same sample. Measurements of the same sample with different densities were also included. The total data set was divided into a calibration set and a validation set without common samples. Repeated measurements of the same sample were included in the calibration set, while in the validation set only one measurement for each sample was used. The calibration set included 249 measurements of 50 different samples, and the validation set included 39 measurements of 39 samples.

The volumetric water content,  $\theta_w$ , varied between 0.07 and 0.29, and the percentage of water as a fraction of the mass of dry material was between 46 and 206%, which means that all samples were above the fiber saturation point. The density,  $\rho$ , ranged from 0.11 to 0.2 g cm<sup>-3</sup>. Measurements were taken with samples at a temperature of  $20 \pm 1^\circ\text{C}$ . The water content of the samples was determined by the standard gravimetric oven method. The distribution of the different biomass types between the calibration and validation sets and respective  $\theta_w$  and  $\rho$  can be seen in Table 1.

### Measurement system

The system used to perform the biomass measurements was developed and is described in detail by Nyström (2006). The system is composed of two linked steel drums, one acting as a sample holder and the other protecting the antenna from the

environment. The two linked drums act as a wave guide with a short circuit at the far end. The sample holder has a diameter of 0.6 m, and the sample depth varied between 0.4 and 0.5 m. A network analyzer and a log periodic antenna were used to emit a sweep of frequencies between 310 and 800 MHz. The waves are sent by the antenna, travel through the material, and are reflected back to the antenna at the bottom of the sample holder. The reflection coefficient was calibrated with a short-open-offset calibration and transformed into the time domain. The calibration corrects systematic errors related to antenna mismatch and frequency response; if the error correction is not applied, reflections within the cables and multiple reflections within the system are present, and it can be difficult to identify reflection from the surface of the biomass and from the bottom of the container. The data treatment includes windowing, resulting in a centre frequency of 555 MHz and transformation into time-domain.

The travel time through the sample was obtained by calculating the difference between the times of the reflections at the bottom and at the biomass surface. The velocity of the electromagnetic waves in the biomass can be calculated using the travel time and the height of the sample, and  $\varepsilon'$  is calculated using Eq. 1.

### Dielectric mixing models

Three different mixing approaches were used to study the behavior of the dielectric constant of biomass: a semi-physical model—the power law model and two theoretical models—the MG and PS models. It was assumed that the woody biomass consists of three components: air, a solid solution of wood cellular material and bound water, and free water.

Dielectric mixing theory holds that the  $\varepsilon'$  of mixtures depends not only on the  $\varepsilon'$  and volumetric fractions of the constituents but also on their geometry. In the power law model, this is taken into account by an empirical constant, the geometric factor  $\beta$  that compensates for the shape of the components and their orientation relative to the applied electric field (Ferre and Topp 2000). The power law model is a generalization of the Birchak and Looyenga models that use a specified power term (Sihvola 1999). This model is based on the simple principle of averaging a power of permittivity by the volumetric fractions of the constituents of the mixture. A power law model with three components is presented in Eq. 2, where  $\theta$  is the volumetric content, and the subscripts  $m$  stand for mixture,  $fw$  for free water,  $a$  for air, and  $s$  for solid solution.

$$\varepsilon_m^{\prime\beta} = \theta_{fw} \times \varepsilon_{fw}^{\prime\beta} + \theta_a \times \varepsilon_a^{\prime\beta} + \theta_s \times \varepsilon_s^{\prime\beta} \quad (2)$$

Both the MG and the PS models are theoretical models derived from the Maxwell equations that explain the interactions of the electromagnetic fields with matter. The mixing theory on which these models are based assumes inclusions of a determined shape distributed in an environment phase: the host or matrix. In the case of woody biomass, air is the host, while free water and the solid solution are the two inclusion fractions.

The depolarization factor is used to define the geometry of the inclusions. In a mixture where the inclusions are defined by the semi-axes in the orthogonal

directions  $x$ ,  $y$ , and  $z$ , the depolarization factor of the inclusion  $i$  in the direction of the semi-axis  $k$  is  $D_{i,k}$ . The depolarization factor can be calculated from the semi-axes  $a_x$ ,  $a_y$ , and  $a_z$  according to equations presented in Sihvola (1999). The three depolarization factors for any ellipsoid satisfy  $D_x + D_y + D_z = 1$ . Equations for the MG and PS models with a host and two inclusions are presented in (3) and (4), respectively (Sihvola and Kong 1988):

$$\varepsilon'_m = \varepsilon'_e + \varepsilon'_e \sum_{i=1}^2 \frac{\frac{\theta_i}{3} \sum_{k=x,y,z} \frac{\varepsilon'_i - \varepsilon'_e}{\varepsilon'_e + D_{i,k}(\varepsilon'_i - \varepsilon'_e)}}{1 - \frac{\theta_i}{3} \sum_{k=x,y,z} \frac{D_{i,k}(\varepsilon'_i - \varepsilon'_e)}{\varepsilon'_e + D_{i,k}(\varepsilon'_i - \varepsilon'_e)}} \quad (3)$$

$$\varepsilon'_m = \varepsilon'_e + \sum_{i=1}^2 \frac{\theta_i}{3} (\varepsilon'_i - \varepsilon'_e) \sum_{k=x,y,z} \frac{\varepsilon'_m}{\varepsilon'_m + D_{i,k}(\varepsilon'_i - \varepsilon'_m)} \quad (4)$$

The conceptual difference in the derivation of the MG and PS models is that the MG model measures the polarization of the inclusions against the host medium,  $\varepsilon'_e$ , while in the PS model the polarization of the inclusions is measured against the homogenized mixture,  $\varepsilon'_m$ . As a result, the MG model is more suitable for sparse concentration mixtures where  $\varepsilon'$  of the surrounding of the inclusion can be considered to be equal to  $\varepsilon'_e$  (Sihvola 1999).

The power law, MG and PS model are applied to the experimental data, and the geometric factors that result in a best fit are identified. To do this evaluation, the root mean square error, RMSE, is calculated according to Eq. 5, where  $N$  is the total number of samples,  $y_{meas}$  is the measured parameter, and  $y_{mod}$  is the parameter calculated with the model.

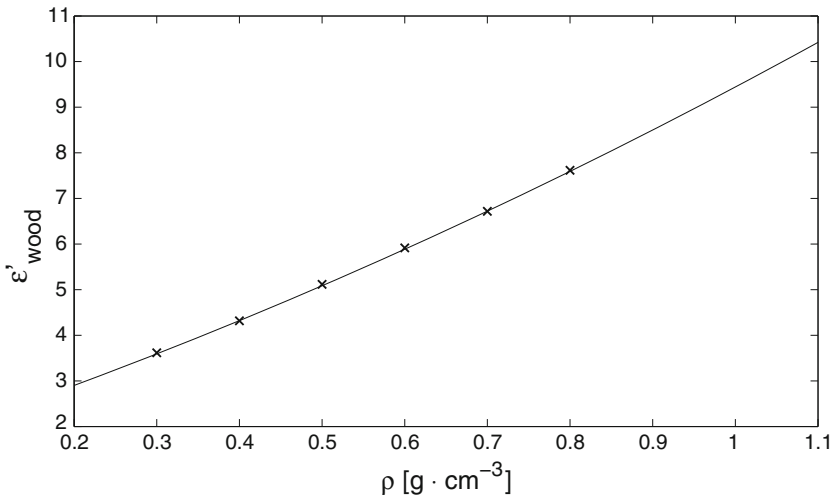
$$RMSE = \sqrt{\sum_{n=1}^N \frac{(y_{meas} - y_{mod})^2}{N}} \quad (5)$$

#### Parameters used in mixing models

The  $\varepsilon'$  and  $\theta$  of the three phases (air, free water, and solid solution) are required for the application of the models.  $\varepsilon'_a$  can be considered to be 1, as the absolute value of  $\varepsilon'_a$  is very close to that of the free space (Ulaby 2007).  $\varepsilon'_{fw}$  can be calculated from the Debye equation (Nyfors and Vainikainen 1994) and is 80 at 20°C. The main difficulty was in assigning the value for  $\varepsilon'_s$  as there are no references for its value or for the value of the  $\varepsilon'$  of bound water in wood.

The method used to estimate  $\varepsilon'_s$  consisted of calculating the  $\rho_d$  of the solid solution and take the corresponding value from the curve of  $\varepsilon'$  of wood at the fiber saturation point with varying  $\rho_d$ . This curve can be seen in Fig. 1 obtained with values published by Torgovnikov (1992).

To calculate the density of the solid solution, it is assumed that its volume can be calculated as in Eq. 6, where  $M_d$  is the mass of wood cellular material,  $\rho_d$  is density of wood cellular material,  $M_{bw}$  is the mass of bound water, and  $\rho_w$  the density of water. The calculation with Eq. 6 is possible because all woody biomass samples are above the fiber saturation point, and the density of bound water can be



**Fig. 1**  $\epsilon'$  of wood at fiber saturation point as function of its density. The values are published by Torgovnikov (1992) for the electric field transverse to the wood tubular cells, at frequency of  $10^8$  Hz, and a temperature of 20°C. The continuous line is a quadratic fit of the data

considered equal to that of free water (Berry and Roderick 2005). Considering  $\rho_d = 1.53 \text{ g cm}^{-3}$ ,  $\rho_w = 1 \text{ g cm}^{-3}$ , and the fiber saturation point as 30% of  $M_d$  (Torgovnikov 1992; Berry and Roderick 2005), the density of the solid solution,  $M_d/V_s$ , can be calculated with Eq. 6, and the value obtained is  $1.05 \text{ g cm}^{-3}$ .

$$V_s = \frac{M_d}{\rho_d} + \frac{M_{bw}}{\rho_w} = \frac{M_d}{1.53} + 0.3M_d \quad (6)$$

The solid solution can be interpreted as a piece of wood at the fiber saturation point where there is no air fraction. In this manner, the curve in Fig. 1 can be interpolated for a density of  $1.05 \text{ g cm}^{-3}$  resulting in an estimate of  $\epsilon'_s = 10$ .

During the experiments, the total volume,  $V_t$ , total mass,  $M_t$ , and the gravimetric water content,  $M_w/M_t$ , of the samples were monitored, allowing the calculation of all necessary parameters. A summary of the parameters, equations and values used is presented in Table 2. The subscript *fw* stands for free water, *a* for air, *s* for solid solution, *bw* for bound water, *d* for the dry wood cellular material, *w* for total water phase, and *t* for the total sample.  $\theta$  stands for volumetric content,  $\rho$  for density,  $M$  for mass, and  $V$  for volume.

## Results and discussion

The variation of  $\epsilon'$  with  $\theta_w$  for the different types of woody biomass is presented in Fig. 2. In this figure, all measurements included in calibration and validation set are shown. As expected  $\epsilon'$  increases with  $\theta_w$ , but it is notable that different values of  $\epsilon'$  are obtained for the same  $\theta_w$ . This occurs even for samples of the same woody biomass type. Such variation can be due to errors inherent to the measurement

**Table 2** Summary of the values and equations used in the mixing models parameters

Parameter	Value	References	Parameter	Equation
$\varepsilon'_{fw}$	80	(Nyfors and Vainikainen 1994)	$\rho$	$M_d/V_t$
$\varepsilon'_s$	10		$M_d$	$M_t - M_w$
$\varepsilon'_a$	1	(Ulaby 2007)	$M_{bw}$	$0.3M_d$
$\rho_w$	1 g cm <sup>-3</sup>	(Torgovnikov 1992)	$\theta_{fw}$	$V_{fw}/V_t = (M_w - M_{bw})/(\rho_w \times V_t)$
$\rho_d$	$M_d/V_d = 1.53$ g cm <sup>-3</sup>	(Torgovnikov 1992)	$\theta_s$	$V_s/V_t = (M_d/\rho_d + M_{bw}/\rho_w)/V_t$
			$\theta_a$	$V_a/V_t = 1 - (\theta_{fw} + \theta_s)$

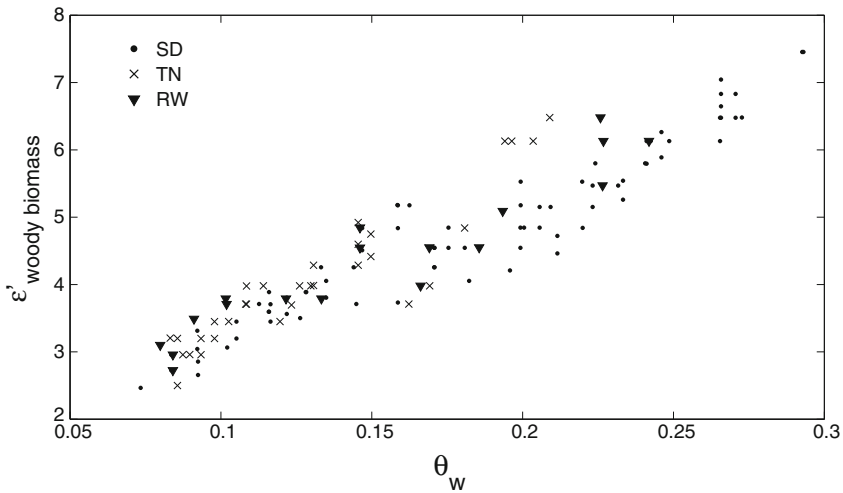
Values taken from references are identified

method or to density variation between samples. The influence of these latest variations can be verified with the application of the dielectric mixing models.

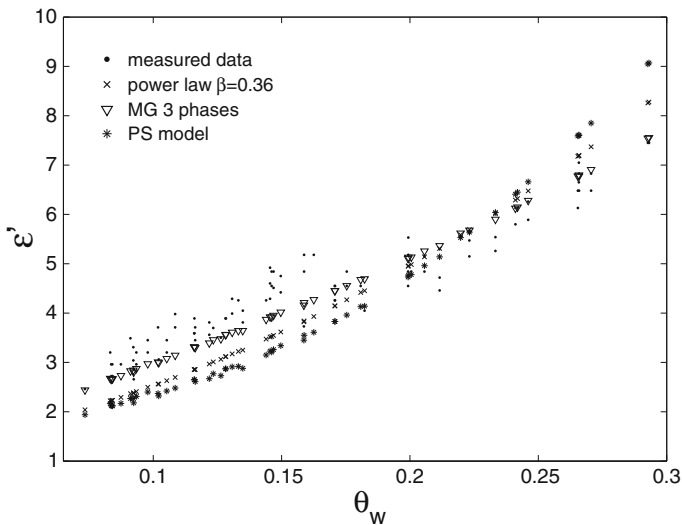
It can also be noted that the variation of  $\varepsilon'$  with  $\theta_w$  is not linear. Looking at the SD samples, which occur in large number in the entire  $\theta_w$  range, a discontinuity for a  $\theta_w$  of about 0.16 can be seen. Differences in the variation of  $\varepsilon'$  with  $\theta_w$  have been noted to occur in soil at the fraction of maximum bound water (Mironov et al. 2004). However, in this study, all the samples are above the fiber saturation point. Even though, it can be pointed out, that the mode of the sample's density is 0.16 g cm<sup>-3</sup>, which means that the point where their mass of water is 100% of their dry mass is at  $\theta_w = 0.16$ . It is possible that at such point, there are differences in how water is held by wood which influence how this fraction scatters the electric field. Such a phenomenon has been noted for snow, where increasing water content is thought to influence the geometry of the water inclusions (Hallikainen et al. 1984; Fig. 2).

In Fig. 3, the results obtained with the power law, the MG model, and the PS model are shown. The best fitting geometric factor,  $\beta$ , found for the power law model was 0.36, but it can be noted that this model is not able to explain the experimental data, because  $\varepsilon'$  is underestimated for lower  $\theta_w$  values and overestimated for higher  $\theta_w$  values. The same scenario occurs with the PS model, which is not able to explain the data in the entire  $\theta_w$  range. The MG model gives a better fitting of the experimental data resulting in a RMSE for  $\varepsilon'$  of 0.4. That the MG model obtained better results than the PS model can be explained by the fact that woody biomass is a sparse concentration mixture, as the mean value for  $\theta_a$  was of 0.73 vol vol<sup>-1</sup>. The depolarization factors that resulted in the best fit were  $D = [1 \ 0 \ 0]$  for the solid solution inclusions, and  $D = [0.9 \ 0.05 \ 0.05]$  for the free water. These depolarization factors correspond to disc-like geometries. It is difficult to justify the results obtained for the inclusion geometries. The structure of wood indicates tubular cells in which walls the water is bound, and with free water kept in the cell cavities. This structure suggests needle-like geometries. Although, woody biomass is composed by pieces of wood in an air host and the geometry that the solid solution and free water inclusions show to the electrical field in such mixture can be that of disc-like inclusions.



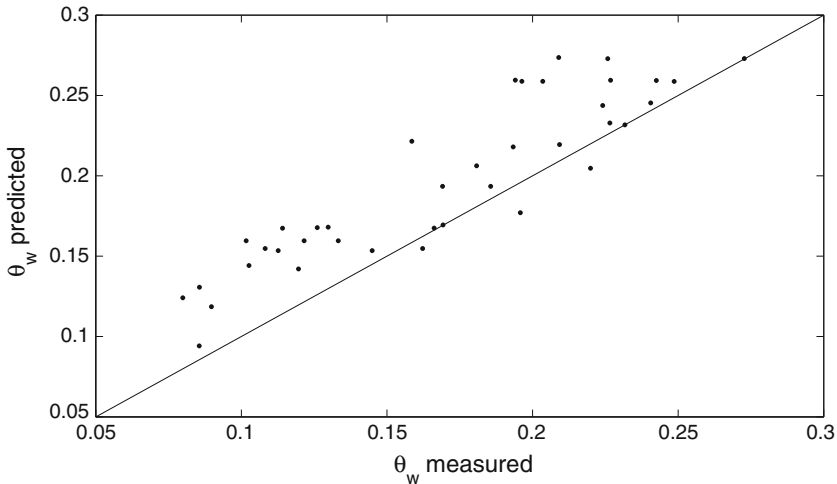


**Fig. 2**  $\epsilon'$  as a function of the volumetric water content for the different types of woody biomass. *SD* sawdust, *TN* tops and needles, and *RW* residual woodchips



**Fig. 3** Different dielectric mixing models applied to the measured data

A closer analysis of the MG model shown in Fig. 3 shows that this model estimates closely the measured data at higher  $\theta_w$ , but underestimates most data values for lower  $\theta_w$ . This behavior indicates the possibility that the value of  $\epsilon'_s = 10$ , which dominates at lower  $\theta_w$ , is underestimated. It can also be noted that, with the MG model, variations in  $\rho$  do not result in large variations of  $\epsilon'$  for the same  $\theta_w$ .



**Fig. 4** Measured  $\theta_w$  versus  $\theta_w$  predicted with the MG model

This means that there is a large variation in  $\varepsilon'$  that is not explained by known characteristics of the woody biomass samples.

The MG model was used to predict water content with an independent test set with 39 biomass samples. The prediction results are shown in Fig. 4. It can be noted that the points are well distributed along the 1:1 line, although, the model tends to overestimate  $\theta_w$ . A RMSE of prediction of  $0.03 \text{ vol vol}^{-1}$  was obtained. This result might not be enough for accurate water content measurement applications, where a different calibration model might be needed.

## Conclusion

The different types of woody biomass show similar variation of  $\varepsilon'$  with  $\theta_w$ .  $\varepsilon'$  increases with  $\theta_w$  but the variation is not linear. A discontinuity occurs at about  $\theta_w = 0.16$ , which corresponds to the point where the mass of water equals the mass of dry material.

It was found that the power law model and the PS models were unable to explain the experimental data, underestimating  $\varepsilon'$  for lower  $\theta_w$  and overestimating for higher  $\theta_w$ .

The MG model, most adequate for sparse-concentration mixtures, showed better agreement with experimental data. Although, this model still underestimated most of the data at lower  $\theta_w$ , which may be caused by an underestimation of  $\varepsilon'_s$ .

The use of the MG model as a prediction model with an independent test set resulted in a RMSE of prediction of 0.03.

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