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MOISTURE OF POROUS MATERIALS DETERMINED BY REFLECTOMETRIC METHOD

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A b s t r a c t: Water content in porous materials determines the propagation velocity of electromagnetic wave in it. Measurement of this velocity enables to determine dielectric constant and indirectly moisture of the tested material. Measurement of the attenuation of electromagnetic wave as it travels along the TDR sensor inserted into the tested porous material enables to determine its electrical conductivity. These data are obtained simultaneously by the same TDR probe.

The study presents the applied measurement technique, the main components of the TDR meter and the relation between water content and dielectric constant of soil, wood as well as cereal grain. Similar relations can be obtained for other porous materials used in food and building industry. The application of reflectometric technique in other than agriculture areas of human activity is possible.

K e y w o r d s: moisture, porous materials, TDR method, time reflectometry.

INTRODUCTION

Water particle is a dipole and therefore water as compared to solid as well as gas phases of the soil has much higher value of dielectric constant, ε. In room temperature ε = 81 for water, while for soil solid phase is 3-5 and 1 for gas phase. Therefore water content in the soil is the main reason determining its bulk dielectric constant. However, dielectric constant is a complex value that can be presented as:

$$\varepsilon = \varepsilon' - j\left(\varepsilon'' + \frac{\sigma}{2\pi f \varepsilon_0}\right) \qquad (1)$$

where: ε' stands for susceptibility of particles to polarize in the electric field, ε'' represents dielectric loss connected to dielectric polarization process, σ is soil electrical conductivity, f is frequency of applied electric field, ε_0 is dielectric constant of vacuum.

The real, ε', and imaginary, ε'', parts of the complex dielectric constant for water are presented by Cole-Cole formula [1]. Both components of the complex dielectric constant (1) can be represented by loss angle, δ, tangens of which is the ratio of the imaginary to real part.

The frequency dispersion of the real part, ε', of the complex dielectric constant and the loss angle, δ, for the electrolyte having different conductivity values are presented in Fig. 1. The figure, based on the Cole-Cole formulas, takes into account the electrical conductivity of the electrolyte ($\sigma/2\pi f\varepsilon_0$ from Eq.(1)). For the defined frequency range, dependent on the electrical conductivity, σ_e, of the applied electrolyte, the loss angle decreases approaching zero. Therefore for the frequency close to 1 GHz the complex dielectric constant of electrolyte reduces to its real part, ε', only when the tested material does not have too high electrical conductivity.

The time-domain reflectometry as applied to the measurement of moisture and salinity of porous materials implements the property described above.

MEASUREMENT OF MOISTURE AND ELECTRICAL CONDUCTIVITY BY TDR METHOD

The idea of TDR measurement of moisture and electrical conductivity of porous materials is presented in Fig. 2.

The probe consists of two waveguides connected together: a coaxial one, called the feeder, and a parallel one, called the sensor, made of two parallel metal

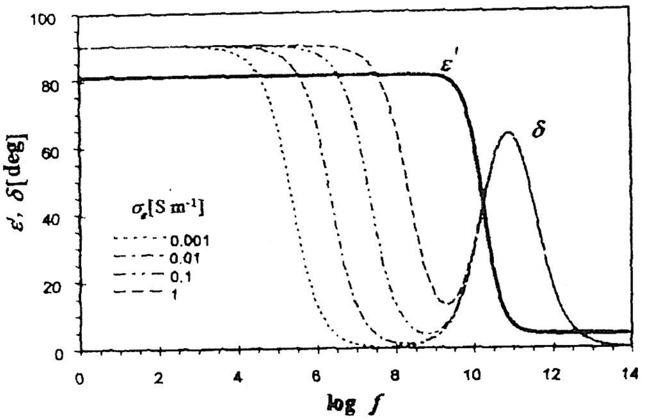


Fig. 1. Frequency dispersion of the real part, ε', of the complex dielectric constant and the loss angle, δ, for the electrolyte for its various electrical conductivities, σ_e

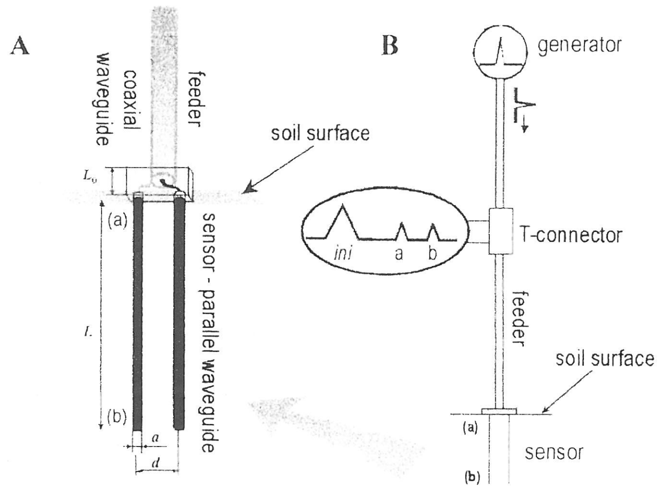


Fig. 2. Application of TDR method for simultaneous measurement of soil moisture and salinity. A - TDR probe (not to scale). Typical dimensions of used sensors: α=0.8÷5 mm, d=5÷60 mm, L=50÷600 mm, L_0=5÷50 mm, B - principle of operation.

rods inserted into the measured medium.

The initial needle pulse, *ini*, travels from the generator by the feeder towards the sensor. This pulse is registered by the recorder as it passes T-connector. In the connector, between the feeder and the sensor, there is an impedance discontinuity, introduced by rapid change in geometry of the electromagnetic wave travel path. The feeder impedance, z_0, is constant and depends only on the type of the used coaxial cable. However the impedance of the sensor, z, built from two parallel metal rods inserted into the medium, depends on its dielectric constant, $\varepsilon(\theta)$ which primary depends on water content, θ, of this medium.

Three reflectograms (voltage as a function of time at the chosen point in the feeder) are presented in Fig. 3. They represent cases when the sensor was placed in dry (*), moist (**) and water saturated soil (***). The time, t, necessary for the pulse to cover the distance equal to the double length of metal rods in the soil increases with the soil dielectric constant, thus moisture. This time is measured from the registered reflectogram.

The velocity of propagation, v, of electromagnetic waves (EM) in the soil is calculated from the propagation time, t, and the length, L, of the sensor rods:

$$v = \frac{2L}{t} = \frac{c}{\sqrt{\varepsilon}} = \frac{c}{n} \quad (2)$$

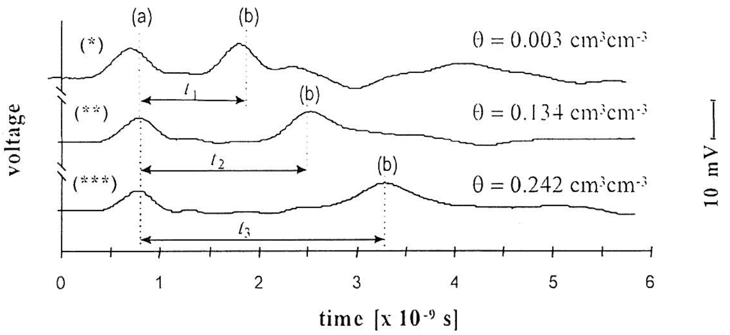


Fig. 3. Reflectograms from TDR sensors inserted in dry (*), moist (**) and water saturated (***) sandy loam. The maxima (a) and (b) represent the reflection from the beginning and end of the TDR sensor.

where: c is EM velocity of propagation in free space, n is the EM refractive index.

The EM velocity of propagation in the medium, for example in the soil, can be presented by equation (2) which takes into account the fact that the dielectric constant of the soil reduces to its real part for the frequencies of 10^9 Hz. If the refractive index, n, is known it is possible to determine soil volumetric water content, θ, from the empirical relation $n(\theta)$ or $\varepsilon(\theta)$, where:

$$\varepsilon(\theta) = [n(\theta)]^2 = \left(\frac{c}{2L}t\right)^2 . \tag{3}$$

The electrical conductivity of the material can be determined from amplitude measurements of the received reflectogram. The value of pulse voltage, U_{in}, entering into the soil is decreased during its travel along metal rods in the soil. The attenuated signal has the amplitude U_{out}. The ratio of these two amplitudes determines the electrical conductivity of the soil, σ [2]:

$$\sigma = \frac{1}{120\pi L} \ln\left(\frac{U_{in}}{U_{out}}\right)\sqrt{\varepsilon} \tag{4}$$

where: ε is the relative dielectric constant of the soil, σ is its electrical conductivity [S m^{-1}].

The propagation time of EM along the TDR sensor rods is very short (about 10^{-9} s), therefore it can be measured after application of the stroboscope technique used in the wide-bandwidth stroboscope oscilloscopes [3]. The appropriate meter has been developed and built in the Institute of Agrophysics Polish Academy of Sciences in Lublin [4].

CALIBRATION

The relation $n=f(\theta)$, representing the refractive index, n (where $n=\sqrt{\varepsilon}$) as a function of moisture of tested material, measured by reflectometric technique is defined as the calibration curve for the given material. The reference method for moisture determination of tested material is thermogravimetric method. The calibration curve for typical Polish mineral and organic soils as well as laboratory prepared mixtures of sand and peat (so as to achieve soil samples with evenly spread bulk densities) is presented in Fig. 4.

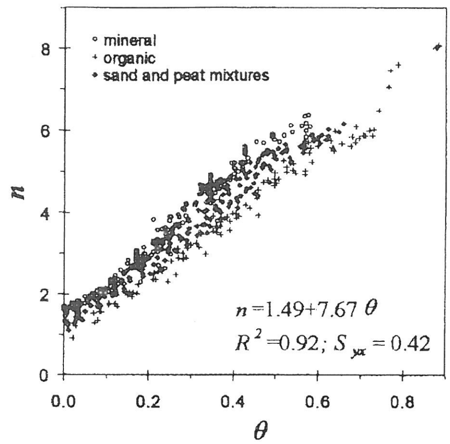


Fig. 4. Relation between the refractive index, n, and moisture, θ[cm^3 cm^{-3}], for samples of mineral, organic soils and their mixtures.

The linear function $n(\theta)$:

$$n = 1.49 + 7.67\theta \qquad (5)$$

is a trend line fitted to the experimental data. Statistical parameters used in Fig. 4 are: R - correlation coefficient, S_{yx} - standard deviation from regression line.

The statistical analysis showed that regression parameters calculated separately for each soil sample were better than for all soil samples. After correction for soil bulk density, ρ, the regression parameters of the calibration curve $n(\theta)$ were drastically better. Taking this into account, the linear function of the calibration curve (5) had been modified so as to present its slope and shift as linear function of soil bulk density, ρ. The values of appropriate coefficients were determined using the least square method and finally the new density corrected calibration curve was as follows:

$$n = 0.573 + 0.582\rho + (755+0.792\rho)\theta \, . \qquad (6)$$

The relation (6) is a new calibration curve $n(\theta,\rho)$ accounting for the influence of the solid phase, represented by soil bulk density, ρ, on the velocity of EM propagation in the soil. The comparison of refractive indexes: n_{TDR} - measured by the TDR - meter and calculated from the formula (3), $n(\theta)$ - calculated directly on the base of regression (5) and $n(\theta,\rho)$ - accounting for the soil bulk density and calculated from the formula (6) is presented in Fig. 5.

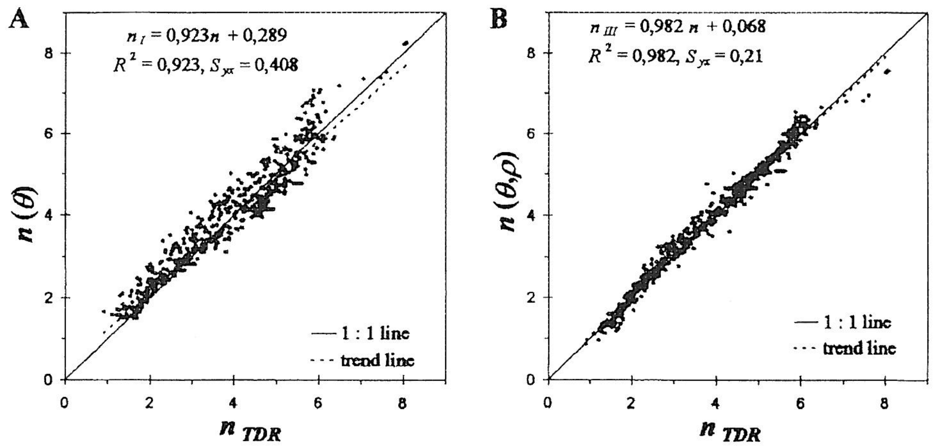


Fig. 5. Comparison of refractive indexes: n_{TDR} - measured by the TDR meter and calculated from the formula (3), $n(\theta)$ - calculated directly on the base of regression from the formula (5) A and $n(\theta,\rho)$ - accounting for the soil bulk density and calculated from the formula (6) B.

This figure shows that the introduction of correction parameter, i.e., soil bulk density, ρ, representing soil solid phase significantly improved the statistical parameters (R^2 increased from 0.923 to 0.982 and standard deviation from regression line representing scatter of data decreased from 0.408 to 0.21).

On the basis of presented models: $n(\theta)$ and $n(\theta,\rho)$ it is possible to calculate soil moisture. Rewriting the formulas (5) and (6) the conversion functions can be obtained: $\theta(n)$ and $\theta(n,\rho)$:

$$\theta(n)=0.134n - 0.182 \tag{7}$$

$$\theta(n,\rho) = \frac{n - 0.573 - 0.582\rho}{7.755 + 0,792\rho}. \tag{8}$$

The comparison of volumetric water content values produced by formulas (7) and (8) with the ones, θ, measured by the reference thermogravimetric method is presented in Fig. 6. Again it is evident that soil solid phase significantly influences the TDR readout of soil moisture. If the user of TDR moisture meter is not satisfied by its accuracy he can increase it by using correction for the soil bulk density, according to formula (8). Unfortunately the application of this correction is burdened by the knowledge of bulk density of the measured soil.

The solutions that are successful in the soil moisture measurement should be effective in measurement of other biological materials of less than soil differentiated

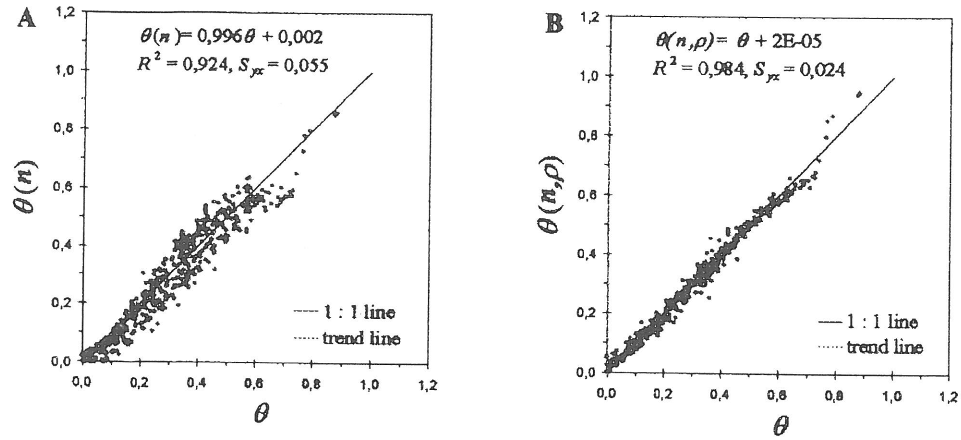
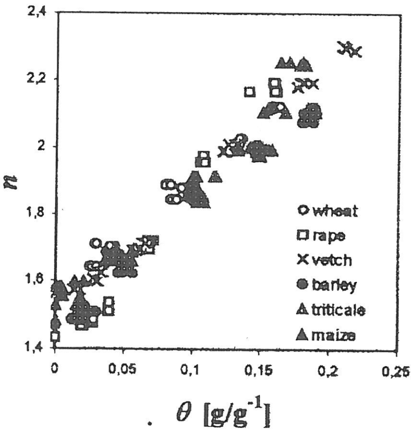


Fig. 6. Comparison of volumertic moisture values produced by formulas (7) - θ(n) A and (8) - θ(n,) with the real values, θ B, measured by the reference thermogravimetric method.

structure, i.e., plant or building materials. Below (Fig. 7) there is a relation between the refractive index, n, and moisture, θ, for some varieties of cereal grain [6].

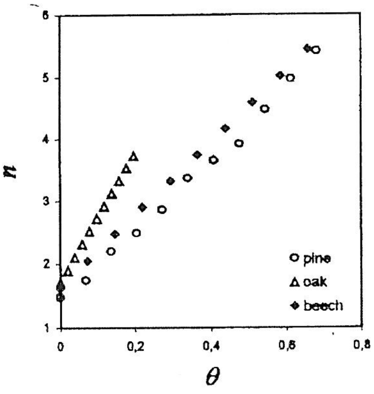
For each cereal grain variety, n and θ are strongly correlated but the regression parameters of n(θ) relations are different. This means that there is no universal calibration curve for cereal grain.

The same calibration procedure was performed for wood, i.e. pine, beech and oak [6]. Each wood type was characterized by individual calibration curves, with different slope and shift (Fig. 8).



	R^2	S_{yx}
wheat n=1,56+3,36θ	0,99	0,02
rape n=1,37+5,11θ	0,99	0,04
vetch n=1,52+3,67θ	0,99	0,03
barley n=1,44+3,68θ	0,99	0,02
triticale N=1,46+3,55θ	0,99	0,02
maize n=1,52+3,61θ	0,98	0,05

Fig. 7. Calibration relations in TDR moisture measurement in cereal grain and the corresponding regression parameters.



	R^2	S_{yx}
pine $n=1{,}36+5{,}75\theta$	0,99	0,09
oak $n=1{,}70+10{,}3\theta$	0,98	0,08
beech $n=1{,}62+5{,}80\theta$	0,99	0,06

Fig. 8. Calibration relations in TDR moisture measurement for wood and the corresponding regression parameters.

It is reported [6] that if the porosity of the sample is known, then the TDR method as applied to electrical measurement of moisture in the discussed here varieties of wood is selective, i.e., it does not need additional and individual calibration for each wood variety.

Calibration of the reflectometric method as applied to the measurement of soil conductivity was performed by the measurement of attenuation of electromagnetic pulse in soil solutions of known electrical conductivities. This relation is linear in the range applicable in soils ($\sigma=0\div0{,}4$ S m^{-1}) [5].

CONCLUSIONS

The presented TDR method for the determination of moisture and electrical conductivity was positively verified for soils. The application of this method in the measurement of other than soil porous materials also gives positive results. The influence of solid phase on calibration curves is different for different materials. This measurement technique gives fast and accurate results and becomes increasingly popular in agriculture. The hardware development will decrease its price and increase accuracy. Further research is necessary to apply it in other than agriculture areas of human activity where the information about water and salt content in the media of interest is important.

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POMIAR WILGOTNOŚCI MATERIAŁÓW POROWATYCH METODĄ REFLEKTOMETRII CZASOWEJ

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S t r e s z c z e n i e. Zawartość wody w materiale porowatym determinuje prędkość propagacji fal elektromagnetycznych w tym materiale. Mierząc tę prędkość można wyznaczyć przenikalność dielektryczną materiału i oszacować jego wilgotność. Technika reflektometryczna umożliwia pomiar prędkości propagacji impulsu wzdłuż linii przesyłowej (czujnika), utworzonej z dwóch równoległych, metalowych prętów, umieszczonych w badanym materiale. Mierząc amplitudę sygnału powracającego z czujnika można wyznaczyć tłumienie stosowanego impulsu elektromagnetycznego, skąd można obliczyć elektryczną konduktywność materiału i jego zasolenie. Pomiar tych dwóch wielkości realizowany jest jednocześnie, przy użyciu tej samej sondy. W pracy przedstawiono stosowaną technikę pomiaru, budowę przyrządu oraz zależność przenikalności dielektrycznej gleby, drewna oraz ziarna od wilgotności objętościowej.

S ł o w a k l u c z o w e: wilgotność, przenikalność dielektryczna, reflektometria czasowa, TDR, materiały porowate.