

DIELECTRIC DETERMINATION OF MOISTURE OF CEREALS GRAIN USING TIME DOMAIN REFLECTOMETRY*

M.A. Malicki, J. Kotliński

Institute of Agrophysics, Polish Academy of Sciences, Doświadczalna 4, 20-290 Lublin 27, P.O.Box 201, Poland

Accepted May 18, 1998

A b s t r a c t. The usefulness of time domain reflectometry, TDR, for moisture of cereal grain was examined. TDR was applied to determine the moisture dependent relative dielectric constant, ϵ , of the samples. A relationship between gravimetric moisture on wet basis, θ , and relative dielectric constant was investigated for wheat, rape, vetch, barley, Triticale and maize. Obtained results showed a linear $\theta(\sqrt{\epsilon})$ relationship, with intercept and slope varying from one species to another. Fitting a regression line to the $\theta(\sqrt{\epsilon})$ data set for each particular species resulted in a coefficient of regression $R = 0.9959$ and standard deviation $SD = 0.0097$ at best, and $R = 0.9795$ and $SD = 0.0211$ at worst case. Fitting the regression line to the aggregated $\theta(\sqrt{\epsilon})$ data set, comprising all species together, resulted in $R = 0.9595$ and $SD = 0.0289$. Thus, it was concluded that TDR could be a convenient technique to estimate the gravimetric moisture of grain with no specific calibration needed if readings of moderate accuracy were sufficient.

K e y w o r d s: time domain reflectometry, TDR, cereal grain moisture determination

VARIABLES AND SYMBOLS

- TDR - time domain reflectometry
 ϵ - relative dielectric constant
 θ - gravimetric moisture on wet basis (g g^{-1})
 θ_{TDR} - moisture on wet basis determined using TDR (g g^{-1})
 R - regression coefficient
 SD - standard deviation
 σ - electrical conductivity (S m^{-1})
 sg - specific gravity (g cm^3)

- pH - acidity
 $ecEs:1$ - el. cond. of water extract, 5 parts of water to 1 part of grain by mass (S m^{-1})
 a - longest intercept (mm)
 b - longest intercept normal to a (mm)
 c - longest intercept normal to a and b (mm)
 sph - sphericity = $(abc)^{1/3}/a$ (mm mm^{-1})
 η - porosity ($\text{cm}^3 \text{cm}^{-3}$)
 ρ - bulk density (g cm^{-3})

INTRODUCTION

Moisture, besides temperature, is the crucial physical parameter which determines conditions of storage of cereal grain. Monitoring the moisture of the cereal grain involves a moisture sensing device. Taking into account that only electrically read sensors can be integrated in modern data acquisition systems, it became clear that the incorporated meter for grain moisture has to be electrical.

Limitations of electrical meters of moisture of cereals grain

Electrical moisture meters for cereal grain are primarily of two types: conductance-type and capacitance-type. The conductance-type meters utilize the grain electrical conductivity as

*Paper presented at 6 ICA.

This work was supported by the State Committee for Scientific Research, Poland, under Grant No. 5 S306 009 06.

influenced by moisture. The calibration of the method rests in the determination of θ versus σ conversion equation.

Application of the conductance-type meters for moisture of cereal grain is troublesome for the following reasons:

- $\sigma(\theta)$ relation is specific for a given species on account of great dependence on the distribution of the moisture within the material [17,19,20];
- $\sigma(\theta)$ relation is not stable, on account of greatly varying surface electrical conductivity of the grain [18];
- σ is, besides temperature (easy to account for), strongly affected by compactness of the sample under measurement [18];
- σ little changes with moisture at low water contents due to tight bounding of water in grain at low moisture level. At moisture levels close to full water capacity increase of water content results in only a slight increase in grain conductivity. Thus the conductance-type meter is inaccurate at either low and high moisture levels [19,20];
- σ is strongly affected by grains salt content resulting from fertilizers [8].

For the above $\sigma(\theta)$ changes from one variety to another and determined once for a given grain material does not hold for long time. Therefore the conductance-based readings of moisture of cereal grain need frequent recalibration, which makes the method inconvenient.

The capacitance-type meters utilize the relation between the grain dielectric constant and moisture. Dielectric properties of moist grain are predominantly determined by water, because the dielectric constant of free water is about 20-fold greater than that of the grain solid; - relative dielectric constant of water is 81 (in 20°C) whereas that of starch and protein matter is around 4 [6]. The calibration of the method rests in the determination of θ versus ϵ conversion equation.

The capacitance method for moisture of cereal grain is believed to be more prospective because under a high frequency alternated electrical field the electrical current related to dielectric polarization (the displacement

current) dominates that related to direct electrical conductivity (the conductance current). Thus, the electroconductive moist grain behaves as if it was an insulator and therefore all disturbances coming from electrical conductivity of the sample become immaterial.

Thus, regarding a given variety (or even a given species) of grain, the capacitance based readings are expected to be less subject to area-to-area and/or season-to-season variations. However, in practice it appears that despite the above qualities the capacitance method also needs species-specific calibration.

Abilities of time domain reflectometry (TDR)

Since TDR proved as a method for measuring the dielectric properties of matter [1,2] its applicability was widely examined to measure the moisture of soil [3,11,16]. Efforts were also undertaken to apply TDR for determining the moisture of agricultural materials other than soil [7], like plant tissue, plant seeds or even insects (in order to find optimum frequency for selective dielectric heating them off).

TDR operates with a pulse edge of which consists of frequencies ranged from 0.5 GHz to 5 GHz. At such high frequencies the electrical current, due to dielectric polarization, dominates the parasite conductance current making the latter negligible [10]. Thus, because TDR has proven its applicability for electroconductive materials, such as the soil, and because solid matter of the soil as well as solid matter of plant tissue do not differ remarkably regarding their relative dielectric constants (ranging for both from 2 to 5 [6,12]), it was assumed that TDR should suit well for the determination of moisture of cereal grain.

MATERIALS AND METHODS

Materials

Samples of wheat, rape, vetch, barley, Triticale and maize were investigated. The characteristics of the investigated grain are

shown in Table 1, 2 and 3. Chosen biochemical properties are listed in Table 1. Table 2 contains intercept grain size, a , b , c , sphericity, sph [14], and specific gravity, sg . Table 3 illustrates porosity and bulk density of the samples as influenced by water content, because porosity, as well as bulk density of grain linearly depend

on moisture. Therefore columns 2 and 3 of Table 3 contain respective reregression equations.

Methods

Samples of the grain material having moisture differentiated from dryness up to saturation were prepared. The investigated

Table 1. Chosen biochemical characteristics of the investigated grain

Species	pH^*	$ecE_{5.1}^*$ ($dS\ m^{-1}$)	Carbohydrates	Protein	Fat	Cellulose	Storch	Salts
Wheat	5.01	1.18	79	14	2	2.5	65	1.8
Rape	5.94	1.09	19	20	45	6	0	4.5
Vetch	5.95	2.42	nd	30	4	17	0	nd
Barley	5.41	1.21	67	13.4	1.9	5.6	55	2.5
Triticale	4.84	1.15	nd	13	nd	nd	67	nd
Maize	5.45	0.19	67	12.1	3.6	2.4	70	1.3

*for water extract obtained from mixture of 1 part of grain and 5 parts of water by mass, nd - not determined.

Table 2. Intercept grain size, a , b , c , sphericity, sph , and specific gravity, sg , of the investigated grain

Species	a	b	c	sph	limits of sg	sg mean
Wheat	5.9	3.5	3.0	0.671	1.30+1.51	1.42
Rape	2.1	1.9	1.6	0.883	1.05+1.18	1.12
Vetch	4.6	4.3	3.6	0.901	1.33+1.45	1.40
Barley	10.5	3	3	0.434	1.36+1.56	1.47
Triticale	7.6	3.7	2.9	0.571	1.26+1.43	1.34
Maize	9.5	8.3	5.5	0.797	1.21+1.65	1.40

a - longest intercept, b - longest intercept normal to a , c - longest intercept normal to a and b , $sph = (abc)^{1/3}/a$, sg - specific gravity.

Table 3. Porosity and bulk density of the investigated grain versus water content

Species	Porosity, η		Bulk density, ρ	
	(cm cm ⁻³)		(g cm ⁻³)	
Wheat	$\eta=0.491+0.332\theta$	R=0.95683	$\rho=0.713-1.070\theta$	R=0.97742
Rape	$\eta=0.387+0.300\theta$	R=0.90212	$\rho=0.656-0.749\theta$	R=0.99151
Vetch	$\eta=0.420+0.190\theta$	R=0.87566	$\rho=0.813-1.029\theta$	R=0.99575
Barley	$\eta=0.552+0.130\theta$	R=0.70590	$\rho=0.646-0.744\theta$	R=0.99307
Triticale	$\eta=0.501+0.167\theta$	R=0.80841	$\rho=0.659-0.797\theta$	R=0.98800
Maize	$\eta=0.545-0.188\theta$	R=0.56433	$\rho=0.712-0.951\theta$	R=0.99484

θ - gravimetric moisture on wet basis.

samples were moistened in 5 steps by mixing dry grain with a respective amount of water in sealed containers. To equilibrate a rotary mixer was applied set at 30 rpm. The mixer was agitated for 15 min 24 times over 1 day [13] at an ambient temperature of $20 \pm 3^\circ\text{C}$. Measurements of water content on wet basis, θ , and relative dielectric constant, ϵ , were made. Also the basic characteristics listed in Tables 1, 2 and 3 were determined using standard methods.

To find the relative dielectric constant of the sample TDR was applied [2,15], using a Hewlett-Packard HP54120B sampling oscilloscope provided with a Hewlett-Packard HP 54121A TDR head [5], as shown in Fig. 1. A special sample container-sensor (Fig. 2) of known volume and mass, comprising an open-end section of a 600 mm long coaxial transmission line was applied. The sensor was filled with a chosen sample then weighted. To compact the sample material, the side wall of the container was tapped with a wooden hammer. After having the container-sensor filled with the sample, its top was covered with

0.05 mm polyethylene wrap, to protect the sample against evaporation.

After having the sample relative dielectric constant, ϵ , known, the container was emptied and the moisture of the sample was determined gravimetrically. Bulk density, ρ , was calculated using the samples gravimetric water content, mass and volume. Porosity was determined using a modified [4] porosimeter of Loebell [9]. The procedure was repeated threefold for each sample.

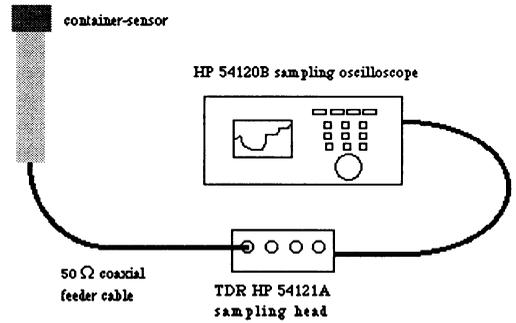


Fig. 1. The TDR stand applied for the determination of dielectric constant of the investigated cereals grain.

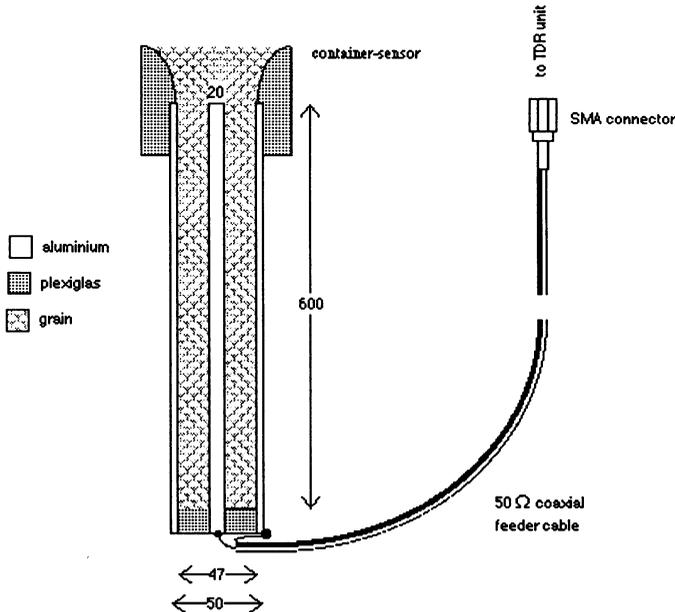


Fig. 2. Details of the TDR probe applied for the determination of dielectric constant of the investigated cereals grain (dimensions in mm).

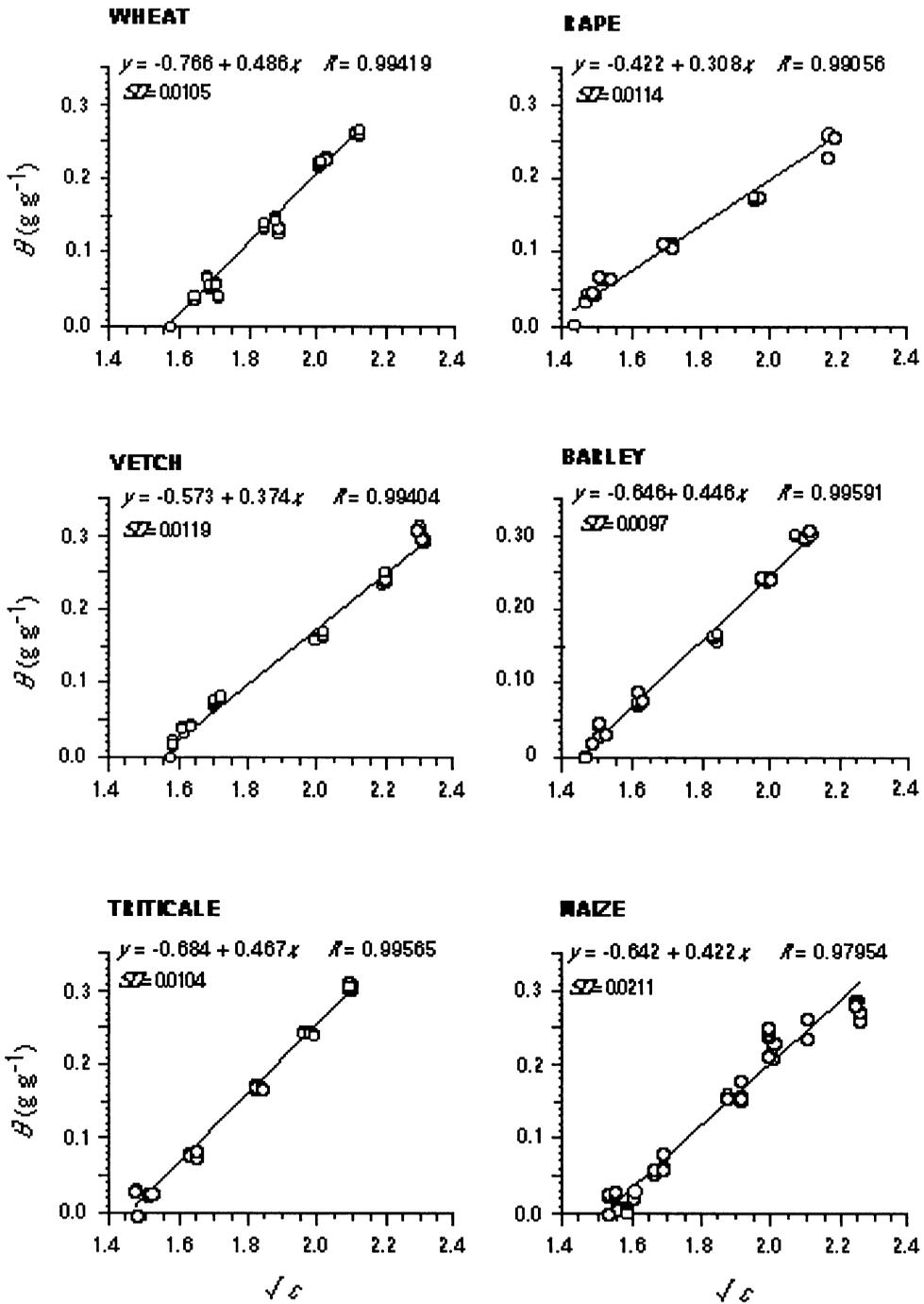


Fig. 3. Relations between relative dielectric constant, ϵ , and gravimetric water content on wet basis, θ , and calibration equations for the investigated cereals grain.

RESULTS AND DISCUSSION

Obtained results (Fig. 3) show a linear $\theta(\sqrt{\epsilon})$ relationship, specific for each of the investigated grains, with intercept varying from -0.766 to -0.422 and slope varying from 0.308 to 0.486, respectively. Coefficient of regression, R , varied from 0.99056 to 0.99591 and standard deviation, SD , ranged from 0.0097 to 0.0211. Fitting a regression line to the whole data set, resulted in intercept -0.567 and slope 0.387 with $R=0.9595$ and $SD = 0.0289$, as shown in Fig. 4.

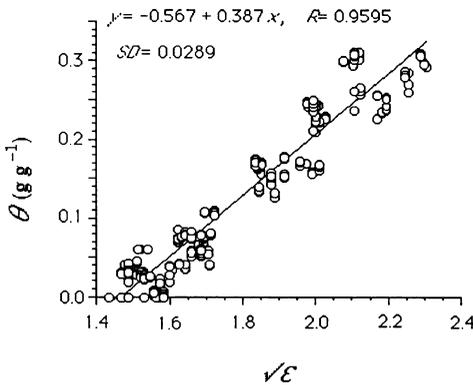


Fig. 4. Aggregated relation between relative dielectric constant, ϵ , and gravimetric water content on wet basis, θ , and calibration equation for the data set comprising all investigated cereals grain together.

The relation from Fig. 4 was applied as the calibration equation, common for all investigated grain materials, in order to verify the TDR technology as applied to the determination of cereal grain moisture:

$$\theta_{TDR} = -0.567 + 0.387\sqrt{\epsilon} .$$

Obtained results are shown in Fig. 5. It can be seen that for the price of slightly lower accuracy TDR can be used to determine the moisture of all investigated grain materials with no grain-specific calibration needed.

The above shows that TDR makes it possible to electrically determine moisture of cereals grain with no grain-specific calibration needed if moderate accuracy is sufficient. For best accuracy the grain-specific calibration is recommended.

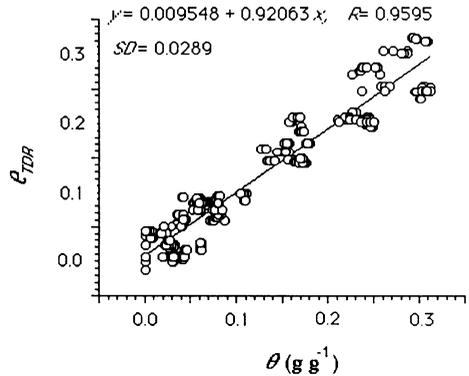


Fig. 5. TDR-determined moisture of grain, θ_{TDR} , versus that determined gravimetrically, θ , using oven-drying method.

CONCLUSIONS

1. Linearity of the $\theta(\sqrt{\epsilon})$ conversion equation makes TDR equally sensitive over full range of changes of moisture of cereals grain.
2. TDR suits the dielectric determination of moisture of cereals grain, especially in electrical systems of data acquisition.
3. Using TDR no grain-specific calibration is needed if moderate accuracy suffices.

REFERENCES

1. Chudobiak W.J., Syrett B.A., Hafez H.M.: Recent advances in broad-band VHF and UHF transmission line methods for moisture content and dielectric constant measurement. IEEE Trans. on Instrumentation and measurement, IM-28, 4, 284-289, 1979.
2. Fellner-Feldegg H.: The measurement of dielectrics in the time domain. J. Phys. Chem., 73, 3, 616-623, 1969.
3. Gardner C.M.K., Bell J.P., Cooper J.D., Dean T.J., Hodnett M.G.: Soil water content. In: Soil Analysis: Physical Methods (Eds C.E. Mullins & K.A. Smith), Marcel Dekker, New York, 1-73, 1991.
4. Gawlik J.: A modified porosimeter of Loebell and its usefulness for air-properties of soils (in Polish). Roczn. Glebozn., 28, 1, 59-69, 1977.
5. Hewlett Packard.: TDR fundamentals for use with HP 54120T digitizing oscilloscope and TDR. Application Note 62, April 1988.
6. Hunt W.H.: Problems associated with moisture determination in grain and related crops. In: Humidity and Moisture. Reinhold Publishing Corporation, New York, 11, 123, 1965.
7. Kwok B.P., Nelson S.O., Bahar E.: Time-domain measurements for determination of dielectric properties of agricultural materials. IEEE Transactions on

- Instrumentation and Measurement, IM-28, 2, June, 109-112, 1979.
8. **Leroy R.P.:** Moisture measurement by high-frequency currents. In: Humidity and Moisture. Reinhold Publishing Corporation, New York, 4, 135, 1965.
 9. **Loebell R.:** Barometerfreie Luftpyknometer. Zeitschrift für Pflanzenernährung, Düngung und Bodenkunde, 60, 172-181, 1953.
 10. **Malicki M.A.:** Influence of soil physical properties on electrical parameters of electrodes-soil system in aspect of the determination of soil moisture and salinity (in Polish). Acta Agrophysica, 1993.
 11. **Malicki M.:** Electric measurement of soil moisture and salinity using time domain reflectometry method (in Polish). Zesz. Probl. Post. Nauk Roln., 429, 215-221, 1996.
 12. **Malicki M.A., Plagge R., Roth C.H.:** Improving the calibration of dielectric TDR soil moisture determination taking into account the solid soil. European J. Soil Sci., 47, 357-366, 1996.
 13. **Milner M., Shellenberger J.A.:** Physical properties of weathered wheat in relation to internal fissuring detected radiographically. Cereal Chemistry, 30, 202-212, 1963.
 14. **Mohsenin N.N.:** Physical Properties of Plant and Animal Materials. Gordon and Breach, Science Publishers, Inc. New York, 59, 1978.
 15. **Oliver B.M., Cage J.M.:** Electronic Measurements and Instrumentation. Inter-university Electronics Series, McGraw-Hill Book Company, USA, 12, 61-64, 1971.
 16. **Topp G.C., Davis J.L., Annan A.P.:** Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resour. Res., 3, 574-582, 1980.
 17. U.S. Department of Agriculture: Comparison of various moisture meter with the oven method in determining moisture content of grain Bulletin AMS-511. Standardization and Testing Branch of the Grain Division. Agricultural Marketing Service, Washington, DC, 1963.
 18. **Young J.H.:** Moisture. In: Instrumentation and measurement for environmental sciences. American Society of Agric. Eng., Special Publication, 05-91, 7-01-7-11, June, 1991.
 19. **Zeleny L.:** Methods for grain moisture measurement. Agric. Eng., 35, 4, 252-258, 1954.
 20. **Zeleny L.:** Moisture measurements in the grain industry. Cereal Science Today 5, 130-136, 1960.