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SENSITIVITY RANGE DETERMINATION OF SURFACE TDR PROBES

Water causes serious problems in building exploitation. It appears at external barriers from many sources, e.g. ground or rainfalls and even sanitary system fails, causing disintegration of building materials and the worsening of the indoor air parameters. To minimize the water influence on buildings many measuring methods were developed. One of them is the TDR moisture determination based on surface TDR probes.

The application of the surface TDR probes is a new approach and requires many investigations to make it a complete, fully useful method. In this paper, we estimate the range of TDR surface probe sensitivity.

1. INTRODUCTION

Porous building materials are prone to water influence. Water influence is significantly considered in the building materials which are destroyed when exposed on it. Many newly built and historical buildings suffer from water capillary rise from the ground, rainfalls or even from the water vapor condensation inside the barriers.

Measurement of water content in above mentioned environments, materials or structures is very important and required issue which would allow to keep the appro-

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priate water conditions. During the years many measurement methods have been developed. These methods can be generally divided into direct and indirect methods.

Direct methods are very precise, and give the best readouts of moisture. The biggest frailty of them is the necessity of sampling. They are strongly invasive and water content can be only determined in the laboratory after sample processing. The most popular direct method is a gravimetric method which determines water content by comparison of weights of the sampled and dry material. This method does not allow constant monitoring of an object and in case of small objects can be the reason of their destruction.

Indirect methods rely on determination of the indirect parameters values which are dependent on water content. The most popular among them are the electrical methods. The most popular electrical methods assume that water is good current conductor and its presence in the porous medium increases its conductivity. Meters utilizing this method work mainly in low frequency electromagnetic field and are called resistance methods. They offer quick moisture readouts, sometimes with acceptable precision but they are prone to salinity, and in case of the building materials with significant dissolved salts concentration falsify measured values. Another possibility of indirect, electrical moisture determination is offered by the TDR (Time Domain Reflectometry) method. This method functions in high frequencies and is relatively free of salinity influence, it also offers quick and precise water content readouts and has a very strong monitoring potential both in natural and artificial porous materials (NOBORIO 2001, O'CONNOR and DOWDING 1999, TOPP et al. 1980).

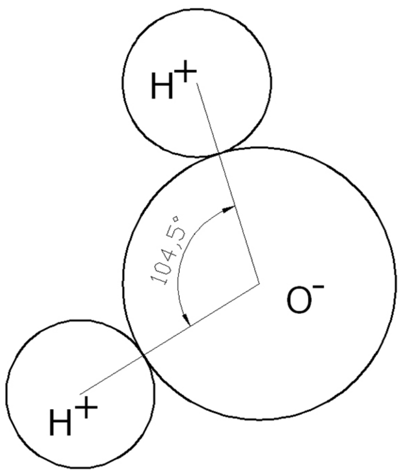

Fig. 1. Asymmetric character of water molecule

Porous materials considered consist of at least three phases: solid, gaseous and liquid. From the electrical point of view they can be treated as weak conductors and water has the greatest influence on their behavior in presence of electromagnetic field. This is caused by high dielectric permittivity of water caused by the fact that water molecule is a dipole (Figure 1) with dipole moment value equal $6{,}216 \cdot 10^{-30}$ C·m (SKIERUCHA and MALICKI 2004).

TDR technique, which is a high-frequency electrical method, offers the possibility of determination of a relative dielectric permittivity ε, being a measure of the material particles interaction with the external, alternate electric field induction. Due to the alternate field influence water molecules rotate according to the input field to follow its direction and cause energy storage, which is released after the external field disappears. This water dipoles energy can be expressed as the real part of the dielectric constant ε' and states the base for TDR moisture measurements of porous materials. Imaginary part ε'' of the dielectric permittivity represents energy loses caused by ionic conductivity dependent on the salts concentration. Dielectric permittivity of such medium with non-zero electric conductivity is described by the following formula:

$$\varepsilon_{\omega} = \varepsilon'_{\omega} - i\left(\varepsilon''_{\omega} + \frac{\sigma_0}{\varepsilon_0 \omega}\right) \tag{1}$$

where:

ε'_{ω} – real part of dielectric permittivity of medium in relevant frequency ω,

ε''_{ω} – imaginary part of dielectric permittivity of medium in relevant frequency ω,

i = imaginary unit,

σ_0 = electrical conductivity,

ε_0 = dielectric permittivity of vacuum (ε_0 = 8.85•10–12 F/m),

ω = angular frequency of the external electric field.

Energy loses caused by ionic conductivity (imaginary part of dielectric permittivity) have big influence in low frequency measurements (resistance or capacitance methods). For the frequencies applied in the TDR technique (1 GHz and higher) they do not influence the value of dielectric permittivity read and during measurements can be neglected.

Due to the polar character of the water molecule its dielectric permittivity essentially differs from the dielectric permittivity of solid and gaseous phase. For water it equals about 80, for the air 1, and for the solid phase varies between 4 and 8 or sometimes even more depending on material (CURTIS and DEFANDORF 1929). Dielectric permittivity depends on some other parameters like temperature or electromagnetic field frequency but in the range of frequencies used by the TDR technique dielectric permittivity of materials is almost constant, that's why in many papers it is called dielectric constant (MOJID and CHO 2002, NOBORIO 2001, O'CONNOR and DOWDING 1999).

Porous materials with low water content are formed of the two main phases – the solid and the gaseous one and the relative dielectric permittivity of such medium is rather small. On the other hand moist or saturated materials show high values of dielectric permittivity. TDR technique enables the determination of the relative dielectric permittivity of such a two or three phase system and thus estimation of porous materials moisture.

In the TDR device the pulser generates a signal which propagates along the wave-guide and receiver collects the echo of the initially generated signal. Interpretation of this enables the determination of the electrical parameters of the examined medium. This technique has been previously used in electrics and electronics to detect the disturbances in long electric cables. The electromagnetic signal was emitted with constant velocity, and when the echo was collected it was possible to find where the conduit was broken (O'CONNOR and DOWDING 1999).

Signal emitted by a pulser is prone to the dielectric parameters of the surrounding environment. Dielectric permittivity is then calculated from the following equation (NOBORIO 2001):

$$\varepsilon = \varepsilon_{\omega} = \left(\frac{c \cdot t_p}{2 \cdot L} \right)^2 \tag{2}$$

where:

c – light velocity in a vacuum ($3 \cdot 10^8$ m·s^{-1}),

t_p – time of signal propagation along the wave-guide (s),

L – length of the wave-guide installed in a material (2 in numerator means that the signal travels in two sides, m)

For moisture determination in porous materials the TDR technology was first applied for soils (TOPP et al. 1980). It was connected with the construction of the probes and the loosy character of the soils. During the years the method was improved. New probes constructions were used, more advanced electronics were applied, but the main idea remained the same. The TDR method proved its potential in agriculture, hydrology and many sciences connected with the soils. Unfortunately it is hard to apply for water content determinations in rocks and building materials which differ from the soils in structure. They are hard and the simple installation of the probes is not possible which significantly limited the application of the methodology in these fields.

2. MATERIALS AND METHODS

Application of the TDR surface probes (SOBCZUK 2008, SUCHORAB et al. 2008) presented on Figure 2 is the attempt to eliminate all above described limitations and it may allow to use the TDR technique in hard materials like rocky soils, rocks or even hard building materials like concrete. Surface probes do not require invasive installation of the wave guides (rods of the probes) inside the investigated material. Measurement elements are only put onto the surface of material and in that position the measurement is done. Pictures below present two prototypes of TDR probes which differ in length.

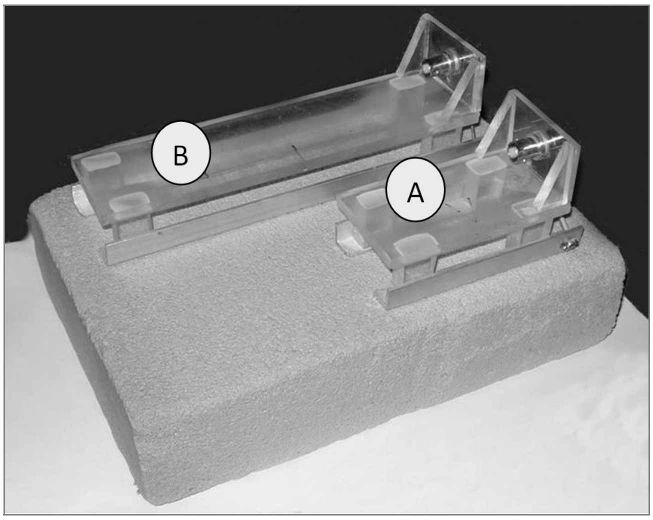

Fig. 2. TDR surface probes used in experiment. A – short probe (measure elements 10 cm long), B – long probe (measurement elements 20 cm long)

Measurement elements in the form of the aluminum angle bars with the following dimensions: 12 × 12 × 2 mm (200 mm long for longer probe and 100 mm for the shorter one) are put on the examined porous material. The ambient air influence is always constant and after suitable empirical probe calibration can be neglected.

TDR method using surface probe is still being developed to improve the reliability of the measurements. New probe prototypes are designed which offer moisture determinations in more complicated, uneven surfaces like sculptures, columns and rocks.

In this paper we consider a very important aspect of application of the indirect methods in moisture measurements – the range of influence of the surface TDR probes. This problem is very important in *in situ* measurements because it gives necessary information about making the experiments and also is very important in determination of the size of materials samples for empirical calibration.

Determination of the influence range was conducted for two presented in Figure 2 TDR surface probes. For that purpose 20 samples of porous material were prepared. For the experiment the autoclaved aerated concrete was chosen because it offered the best possibilities for assumed sample geometry (Figure 3):

- 10 samples with dimensions: 13 × 8 × 1 cm (for short probe),
- 10 samples with dimensions: 23 × 8 × 1 cm (for long probe).

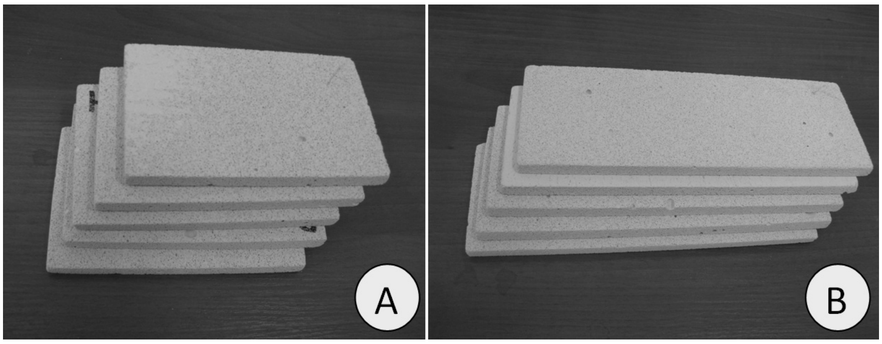

Fig. 3. Samples of autoclaved aerated concrete used in experiment
(A – samples for short probe, B – samples prepared for the long probe)

Samples presented above were slowly put to the water to remove the air from the pores and then sunk until no mass growth was observed and the state of saturation was obtained (volumetric water content equal 35% vol). Application of the saturated aerated concrete samples allowed to distinguish dielectric porous material parameters from dielectric parameters of the air.

To conduct the experiment the following assumptions were made: TDR readout of the echo returning from the probe depends on the dielectric parameters of the wet sample (high value of dielectric permittivity) and the ambient air (directly covering the bars and the sample from the other side, low value of dielectric permittivity – 1). Share of the air which covers the TDR probe bars is constant and for the regular measurements can be compensated in calibration formula. But the influence of the air below the sample cannot be neglected and this strongly depends on the sample width.

If the sample is too thin the air influence is high and the measurement cannot be correct because the resultant dielectric properties will depend both of the wet sample and the air behind it. When the sample width grows the influence of the air decreases and the readouts become more reliable. Finally there is a critical sample width where no behind air influence is relevant. This width is equal to the range of influence of the surface TDR probe.

The described experiment idea was to collect the TDR reflectograms of electromagnetic impulse propagating in the surface probes and to compare the results for the samples of various width and basing on the obtained data to establish the sensitivity ranges.

For that aim a set of previously described (Figure 3), thin (1 cm thick) samples were prepared. In the first step one sample was used and the measurement was done (Figure 4). Then another 1cm wide sample of material was added to form one 2 cm thick homogenous sample and the TDR measurement was repeated. Experiments were conducted until 10 thin samples formed one 10 cm sample of saturated aerated concrete. Each step was repeated three times. Experiments were performed for short version of the probe and for the long one.

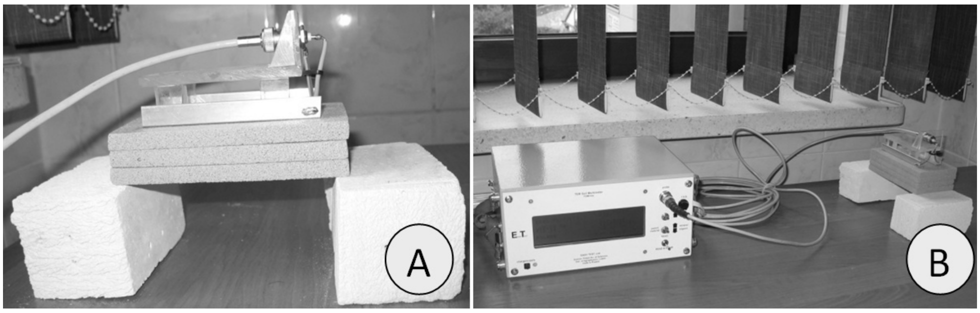

Fig. 4. Experimental setup
(A – short surface probe on the samples, B – TDR meter during measurement)

3. RESULTS AND DISCUSSION

Experiments proved the influence of sample thickness on the results obtained. Figures 5 and 6 present the relevant fragments of TDR traces and their change with different sample dimensions (for the long and the short probe respectively). The first peaks on each diagram represent the echo of the electromagnetic signal [mV] from the probe beginning and the second from its end. The horizontal axis represents the time covered by pulse [ps]. Time between two peaks is essential in moisture determination and is the base in dielectric permittivity estimation with the application of Equation (2).

It can be assumed that the first peaks are constant. The small shifts observed can be caused by the differences of reflected pulse energy. On the other hand the second peaks are shifted respectively to the sample thickness. For the long surface probe (Figure 5) it is clearly visible that in a case of 1 cm thick sample the signal propagates faster and the return time is the shortest (second peak shifted to the left). In case of thicker samples the second peaks are moved to the right which means slower signal propagation and longer time of echo return. In a case of a short probe (Figure 6) all above described dependencies are also visible, only the signal travel time is shorter which is caused by the shorter wave-guide dimension.

For the samples 1 cm thick the electromagnetic field strongly depends on the below air influence which is observed in the TDR readouts. Air dielectric permittivity is small which results in decreasing the value of effective dielectric permittivity which is expressed by shorter time of signal propagation. In a case of thicker samples the influence of ambient air on the sample is reduced and the effective dielectric conductivity depends only on the sample dielectric properties which is expressed in longer signal propagation and the increased value of effective, measured with the TDR technique, dielectric permittivity.

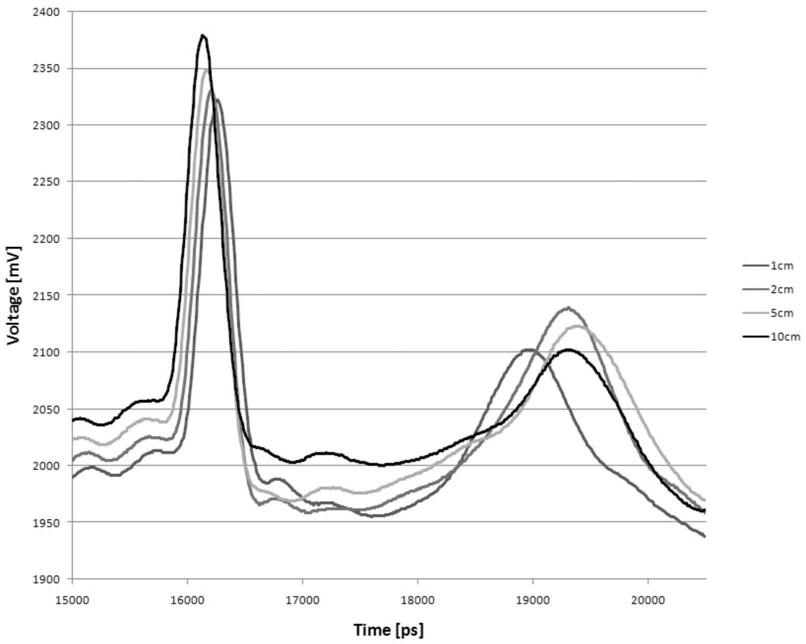

Fig. 5. The fragments of the TDR reflectograms collected from the long surface probes

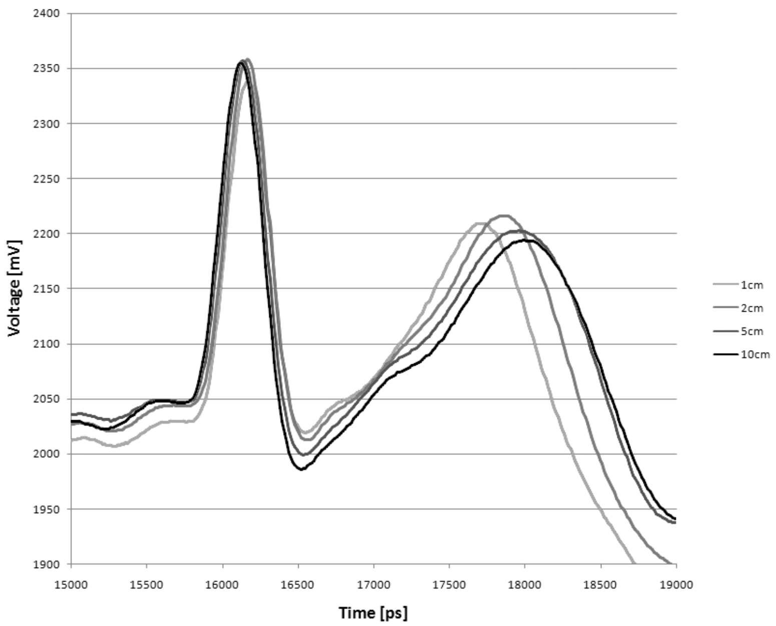

Fig. 6. The fragments of the TDR reflectograms collected from the short surface probes

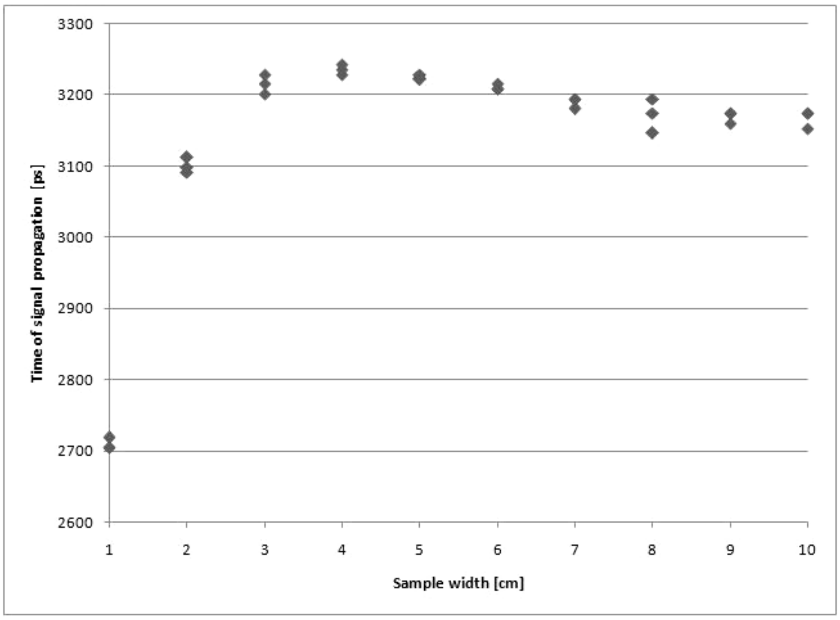

Fig. 7. Dependences between sample width and the time of propagation measured in long (20 cm) surface probe

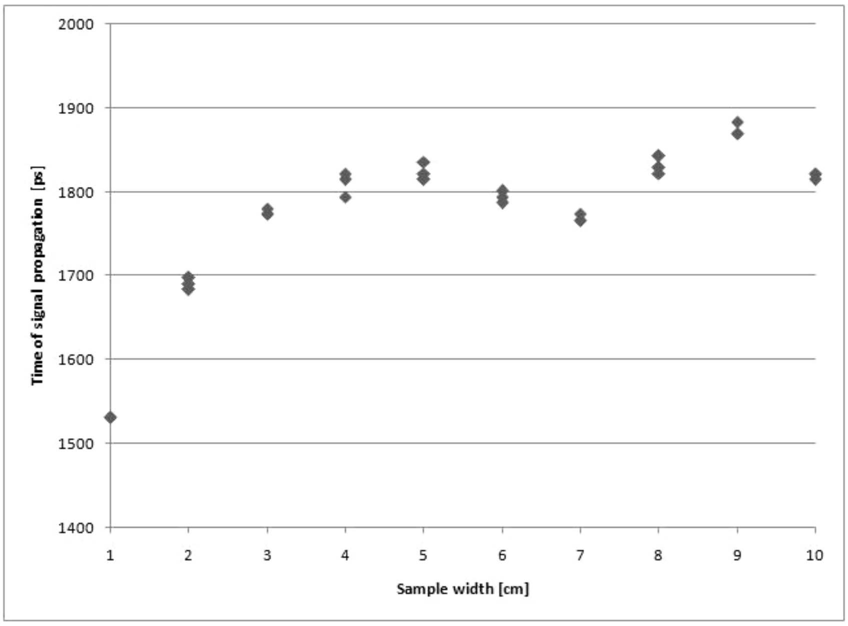

Fig. 8. Dependences between sample width and the time of propagation measured in short (10 cm) surface probe

Figures 7 and 8 show the calculated dependences between the sample thickness and the time of electromagnetic signal travel along the wave-guides of the probe. The interpretation of the results obtained is not simple. It is visible that for small sample dimensions the time increases together with sample thickness increase and the maximum values are obtained for the following sample dimensions: 4 cm in case of long probe and 5cm in case of short probe. These readouts indicate the highest propagation time and the effective dielectric permittivity calculated from the Equation 2 would be the maximal. Following values (4 cm for the long probe and 5 cm for the short one) should be treated as sensitivity range for the probes of above described constructions.

Diagrams presented on Figures 6 and 7 show that time of signal propagation along waive-guide decreases after reaching the maximal points. This may be caused by the structure of the examined samples because the electromagnetic field propagation in layered medium is rather complicated and should be further investigated.

4. CONCLUSIONS

Experiment presented above confirms that TDR meter shows the best results in case of samples 4 cm wide in case of long probe and 5 cm in case of short probe.

This, empirically determined values should be treated as the sensitivity range of the probe of presented construction. This information is significant for the surface TDR probes development, especially from the point of view of the calibration procedures.

Sensitivity range determines the minimal thickness of the TDR samples used for calibration. Application of thinner samples would give wrong results because influence of dielectric parameters or the ambient air behind the sample. From the other point of view the thicker samples are also not the best option because it may be difficult to obtain the homogenous sample with constant water distribution across its width.

Information about the surface TDR probes sensitivity range is also important for *in-situ* measurements. Moisture readouts made with this probes are reliable only at the depth of 4 or 5 centimeters respectively and water content of further parts of the rock or building structure may differ and if necessary they require the application of a different (perhaps invasive) method of determination.

TDR method has got high monitoring potential and is still being developed and applied for different materials. Application of the TDR surface probes offers new application possibilities, especially for water migration in materials and structures which were not measured before like rocky soils, rocks or building materials and constructions.

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REFERENCES

[1] CURTIS H.L., DEFANDORF F.M., *Dielectric constant and dielectric strength of elementary substances, pure inorganic compounds, and air*, International Critical Tables of Numerical Data, Physics, Chemistry and Technology, 1929, Vol. 6., 73–107.

[2] MOJID M.A., CHO H., *Response of the core and shield rod soft time-domain reflectometry probe to transverse soil-water content heterogeneity*, Journal of Hydrology, 2002, 262, 21–27.

[3] NOBORIO K., *Measurement of soil water content and electrical conductivity by time domain reflectometry: a review*, Computers and Electronics in Agriculture, 2001, 31, 213–237.

[4] O'CONNOR K.M., DOWDING C.H., *GeoMeasurements by Pulsing Cables and Probes*, CRC Press, 1999.

[5] SKIERUCHA W., MALICKI M.A., TDR Method for the Measurement of Water Content and Salinity of Porous Media, Institute of Agrophysics, Polish Academy of Sciences, Lublin, 2004.

[6] SOBCZUK H., Patent Nno. PL 198492 B1, *Sonda do pomiaru wilgotności ośrodków porowatych, zwłaszcza materiałów budowlanych*, 2008.

[7] SUCHORAB Z., JEDUT A., SOBCZUK H., *Water Content Measurement in Building Barriers and Materials Using Surface TDR Probe*, Proceedings of ECOpole, Vol. 2, No. 1, 123–127.

[8] TOPP G.C., DAVIS J.L., ANNAN A.P., *Electromagnetic determination of soil water content: Measurements in coaxial transmission lines*, Water Resources Research, 1980, 16, 574–582.