ECOLOGICAL CHEMISTRY AND ENGINEERING A

Vol. 18, No. 7 2011

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WATER CONTENT MEASUREMENT OF BUILDING MATERIALS USING SURFACE TDR PROBE

POMIARY WILGOTNOŚCI MATERIAŁÓW BUDOWLANYCH Z ZASTOSOWANIEM POWIERZCHNIOWEJ SONDY TDR

Abstract: Water present in external walls is one of the basic factors curtailing the function of buildings. Its negative influence should be evaluated both in the constructional and hygienic aspects. It is caused by the fact that water is not only the cause of successive destruction of buildings' construction, but also composes the base for the growth of microorganisms and moulds. Such a problem is typical for the buildings without moisture check or monitoring and causes the respiratory system illnesses, infections, allergies, eyes and skin sensitizations. The buildings affected by the problem of moisture in most cases are stricken with the Sick Building Syndrome, which is caused by the use of not human-friendly materials, defective ventilation or high moisture previously mentioned. Presence of water in building envelopes in moderate climate is a normal and practically inevitable phenomenon. The problem of external barriers moisture becomes important in case of high moisture content. It is especially caused by the improper horizontal damp insulation and mainly observed in many historical buildings or sometimes, even new ones. Other causes of high water content in building barriers are floods, heavy rains or sanitary systems faults. Water contained in building barriers in high content is especially dangerous during winter seasons when numerous freezing and thawing causes building material disintegration. Presence of water in external walls significantly diminishes their thermal isolation, what induces the increased heat loss in cold season, reduction of perceptible temperature and thermal comfort of occupants. All the previously mentioned negative aspects of water influence on the buildings cause the need to find the precise, user-friendly method of water content evaluation in the walls. One of them is TDR (*Time Domain Reflectometry*). This technique bases on the measurement of the electromagnetic pulse propagation velocity in examined medium. The dielectric constant of the material (determined with the TDR device) is the base for its moisture content estimation. The TDR method has got a lot of advantages like high monitoring potential, insensitivity to the salinity, relatively simple service, and has been used in moisture measurements of porous materials, especially of the soils, for many years. By now, this technique has not found the common implementation in the building industry which is caused by its invasive character – it requires the installation of the steel rods in the examined medium, which sets many problems in case of building materials and

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envelopes. The aim of this paper is to propose the alternative idea of the TDR probe – surface probe, which enables the moisture measurements of hard building materials and envelopes. For these materials, the use of classical probe is difficult to realize, because of problems with the introduction of the steel rods in the examined medium. This, modified, TDR method enables the effective moisture measurements without the need to destroy the building barriers structure.

Keywords: building materials, building barriers, building envelopes, moisture, reflectometric moisture measurement methods, dielectric methods, TDR, *Time Domain Reflectometry*, surface TDR probe

The TDR method was first applied for electric cables discontinuities detection [1, 2]. It was realized by measurement of the electromagnetic signal propagation velocity and the period between sending the signal and its return indicated the discontinuity position. Development of electronics in 1970s allowed application of that idea in a reverse mode and formulization of the base for moisture measurement with this method in geotechnical sciences, agriculture and environmental engineering [3]. With the known transmission line length (rods of the probe), measurement of the signal propagation velocity enabled determination of the dielectric permittivity value of the surrounding porous material and thus its moisture.

Most of geomaterials, soils and building materials are the porous media which means that they are formed by at least three phases: solid matrix, air and water. This assumption strongly influences the idea of moisture TDR measurements. Dielectric permittivity, often called the dielectric constant is an electric parameter of materials, which in case of porous media, strongly depends on water content [2, 3]. This is mainly caused by the asymmetric distribution of electric charge in water molecules which form the electric dipoles with the dipole moment equal $6.216 \cdot 10^{-30}$ C · m [4]. External, alternating electromagnetic field, in this case generated by the TDR device, forces the water dipoles to order their directions. Because of that water permittivity is much higher than that of most liquids and solids. It is assumed that the dielectric permittivity for the solid phase varies between 1 and 4 depending on chemical composition or structure. Dielectric constant of the air is equal to 1 and for water is about 80 [5]. This significant difference of dielectric parameters between water and the other phases is the base for moisture determinations of porous hygric materials.

Dielectric permittivity of the porous material from the physical point of view is a complex number and can be split into the real and the imaginary part. Real part ε' represents the amount of the stored energy in an alternating electrical field and is the major parameter considered in moisture measurement of porous materials. The imaginary part ε'' represents energy loss caused by the electrical conductivity depending on salinity. Such a dielectric permittivity in saline medium can be described by the following complex formula [2, 4]:

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

where: ε'_{ω} – real part of dielectric permittivity of medium at relevant frequency ω [-],

ε''_{ω} – imaginary part of the dielectric permittivity of medium at relevant

frequency ω [-],
i – imaginary unit,
σ_0 – electrical conductivity [S],
ε_0 – dielectric permittivity of vacuum ($\varepsilon_0 = 8.85 \cdot 10^{-12}$ [F m^{-1}]),
ω – angular frequency [Hz] of the external electric field.

Taking into consideration that the frequency range applied in the TDR moisture technique is around 1000 MHz it is assumed that the energy loss connected with ionic electrical conductivity have no influence on the TDR readouts, and only the real part of the electrical permittivity is meaningful and can be calculated from the following formula [2]:

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

where: c – velocity of light in a vacuum [$3 \cdot 10^8$ m s^{-1}],
V – electromagnetic pulse velocity [m s^{-1}] along the rods of the TDR probes.

Pulse propagation velocity can be determined with the TDR equipment measuring the signal transmission and the echo received, using the following formula:

$$V = \frac{2L}{t_p} \tag{3}$$

where: t_p – time of signal propagation [s] between transmitting and receiving the echo,
L – length of the waveguide [m] installed in a material (2 in numerator means that the signal travels along rods twice – forward and backward).

The idea of the TDR performance is based on transmitting the short needle pulse along the waiveguide inserted into the material and observing the returning echo in form of the reflectogram (Fig. 1). Interpretation (usually automated) of the reflectogram enables determination of the velocity of pulse propagation and the dielectric permittivity. This dielectric permittivity can be then recalculated into moisture using one of

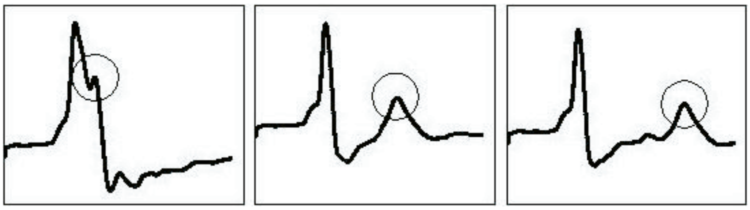

Fig. 1. Reflectograms from TDR probes. Left curve indicates dry material, middle – intermediate states and finally right – water (with the highest value of dielectric constant)

mixing models which can be divided into empirical and theoretical ones. The empirical approach seems to be more popular in the TDR method application but it requires individual material calibration or using the popular empirical formulas by Topp [3]:

$$\theta = \frac{-530 + 292\varepsilon - 5.5\varepsilon^2 + 0.043\varepsilon^3}{10000} \tag{4}$$

or Malicki [6] for example:

$$\theta = \frac{(\varepsilon^{0.5} - 0.819 - 0.168\rho - 0.159\rho^2)}{7.17 + 1.18\rho} \tag{5}$$

where: ε – real part of the dielectric permittivity measured with the TDR equipment,
ρ – bulk density of the material [g dm^{-3}],
θ – volumetric water content [vol. %].

Theoretical approach assumes the porous material as a three phase mixture. The most popular are the α models [4] and de Loor [7] model.

For more than 20 years the TDR method has been successfully applied for moisture determination of soils [1, 3] and has been continuously developed by introducing better calibration methods [6, 8] or technologies. Soils are characterized by loose structure and the invasive measurements with typical TDR probes construction have not been problematic. Figure 2 presents typical constructions of invasive TDR probes built of concentric cable, head and steel rods.

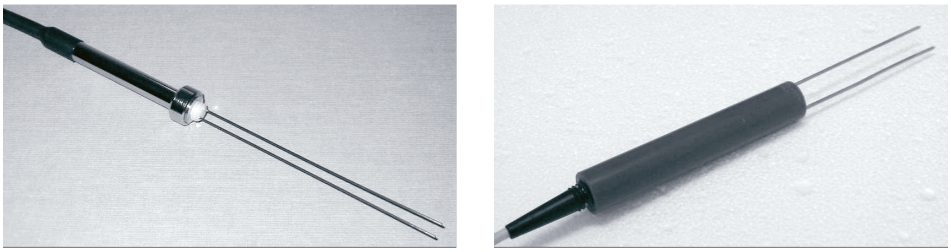

Fig. 2. Typical TDR probes for invasive moisture determinations

The typical TDR probe is an extension of a concentric cable where the core separates from screening and they both transform into the steel rods which are the previously mentioned waive-guides. Part of these rods can be closed in a small resin or plastic cover. The beginning of the probe and also its termination are the specific cable discontinuities which TDR device uses to establish the beginning and the end of the electromagnetic pulse propagation. The TDR device receives the echo of the electromagnetic signal returning from the probe in the form of reflectogram (Fig. 1), and the discontinuities are represented by peaks. The distances between two main peaks vary because of the different dielectric permittivities (due to water content change).

Modifications

As it was mentioned before, the application of classic TDR probes is nearly impossible for rocks or most of building materials which is mainly caused by problems of the steel rods installation. Some experiments have been made on light building materials like aerated concrete [9, 10] but they were mainly conducted in laboratory conditions without any perspectives for field monitoring.

The idea of surface moisture determination is not new – more than 10 year ago Persson and Berndtsson [11] proposed a surface measurement experiment using classic TDR probes covered with suitable dielectric block (Fig. 3) and after suitable readout of effective dielectric permittivity – moisture of the below medium was possible to be estimated.

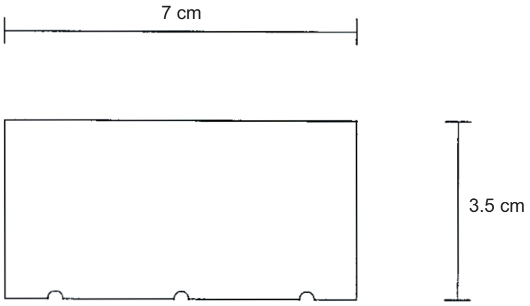

Fig. 3. The surface block for TDR moisture estimation proposed by Persson and Berndtsson in [11]

More advance idea than proposed in [11] is the application of the TDR surface probes, which can be used in moisture determination of building materials or barriers without internal rods installation. The surface probe construction for non-invasive moisture determination was previously proposed in [12] and [13] and some prototype models are presented in Fig. 4.

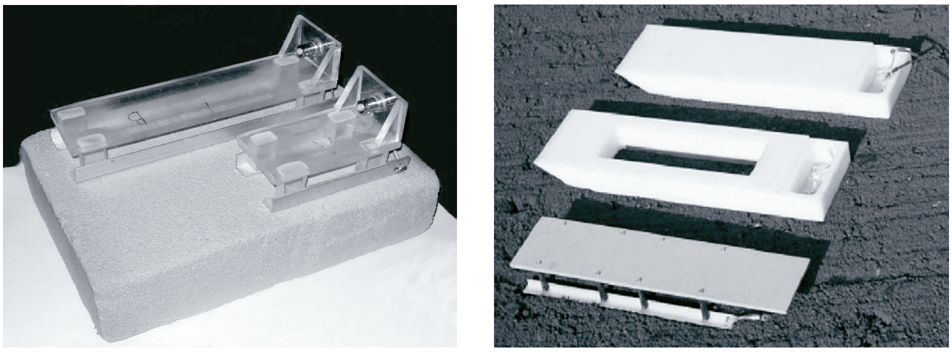

Fig. 4. TDR surface probes: left – for building materials moisture measurement [12], right – TDR surface probes for soil moisture measurement [13]

The probes described in this article are build according to [12] and made of plexi (Fig. 4 left) with aluminum angle bars as the measuring elements. Two presented prototypes where of the same construction but differed in dimensions of the measuring bars. Short probe had the bars 10 cm long and the longer sensor bars were 20 cm long.

Experiment

The experimental setup (Fig. 5) consisted of the following elements:
- TDR device – FOM/mts (*Field Operated Multimeter* – Easy Test/Lublin),
- PC computer as a control station (connected with FOM via RS-232c interface),
- TDR surface probes described above, connected with FOM via concentric cable,
- aerated concrete samples.

Application of the new TDR probes required modification of the TDR device handling – standard operation of FOM TDR device requires only pressing of the buttons and reading out the moisture, or eventually dielectric constant – easily recalculated into moisture with calibration formulas.

For the surface TDR probes a PC computer was used which provided widespread control over the measuring device, and allowed the collection of full reflectograms (not only the simple moisture readouts).

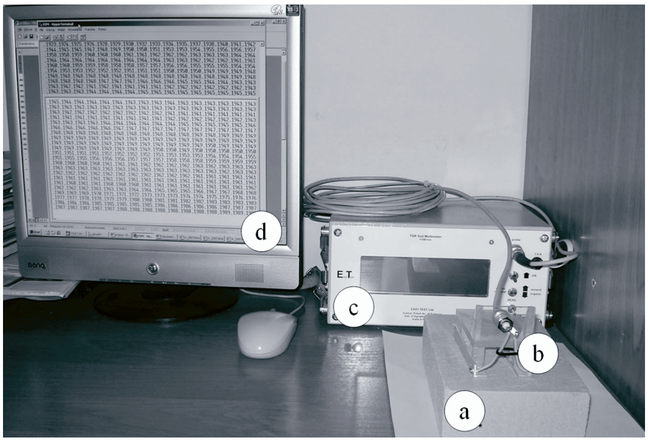

Fig. 5. Measurement setup: a) AAC sample, b) surface TDR probe, c) FOM (TDR device), d) PC display

Three samples of AAC (*aerated autoclaved concrete*) were prepared for examination. They were dried out in the temperature of 105 ^{o}C. Surfaces of the samples were polished to provide the maximal probe-material contact and minimize the eventual measurement errors. First sequence of measurements was made on dry samples. Together with the TDR, a sequence of gravimetric measurement was done (to compare the reflectometric readouts with the gravimetric ones). Then the samples were moistened and another sequence of measurements was done. Each cycle was repeated several times until the samples of AAC were saturated.

Results and discussion

For each water content of the sample a reflectometric measurement was done. Diagrams below (Fig. 6) represent the TDR readouts from the surface probe with different water contents. It is clearly visible that first positive peak is located at the same place of each reflectogram and it indicates the beginning of the probe. The second one is shifted to right on each reflectogram which means that the signal needed more time to return from the end of the probe. The velocity of the signal changed (slowed down) because of the rise of the dielectric permittivity. It was caused by increasing water content in the examined AAC samples.

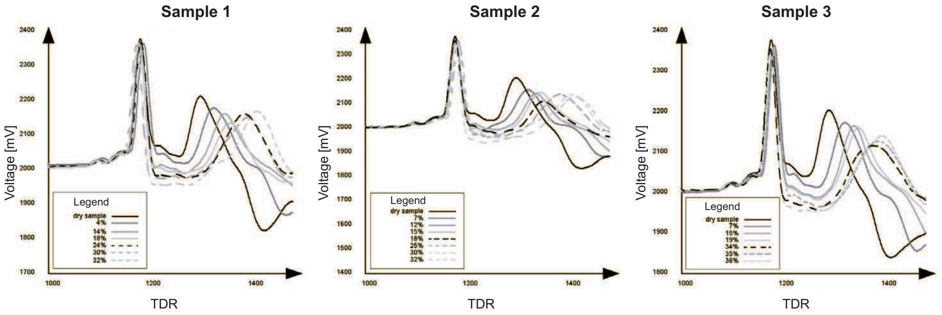

Fig. 6. TDR curves collected from surface probes on three different samples

A special program was prepared to analyze the reflectograms externally out of the device. The aim of the program was to find the voltage extremes determining the beginning and the end of the probe. Distances between the first and the second peak were expressed in time unit (nanoseconds or picoseconds) and allowed determination of the dielectric permittivity using the following formula [2]:

$$\varepsilon = \frac{c \cdot t_p}{2 \cdot L} \tag{6}$$

where: ε – effective dielectric permittivity read by the surface TDR probe [-],
c – light velocity in vacuum [m s^{-1}],
t_p – electromagnetic pulse propagation time [s],
L – length of measuring bars of the surface probe [m].

This enabled finding the dependence between the dielectric constant read by the surface TDR probe and the samples moisture. The results are presented in Fig. 7.

Effective dielectric permittivity determined in above described way shares the fractions of dielectric permittivities of water inside the concrete pores, air inside the pores, solid phase and the ambient air covering the sensors of the probe along the surfaces not touching the examined material. It should be underlined that ambient air share is always constant, independently on examined material moisture, that is why

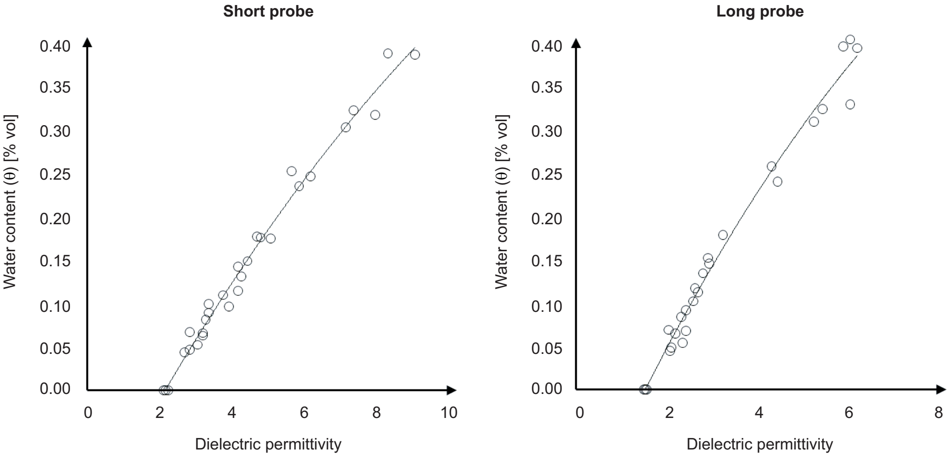

Fig. 7. Dependences between water content and dielectric constant determined with Time Domain Reflectometry for short surface probe (left diagram) and the long surface probe (right diagram)

it can be covered in suitable calibration formulas of particular surface probe construction.

Basing on the research run and the formula (6) the following calibration dependences were established for the described surface probes. For the short probe:

$$\theta_{TDR} = \frac{-19.4\varepsilon^2 + 791.4\varepsilon - 16000}{10000} \tag{7}$$

where: θ_{TDR} – volumetric water content measured with TDR [vol. %],
ε – effective dielectric permittivity determined with particular TDR probe construction [-].

Correlation factor for above presented formula was r = 0.993.
For the longer version of the sensor:

$$\theta_{TDR} = \frac{-446\varepsilon^2 + 1167.9\varepsilon - 1665.4}{10000} \tag{8}$$

with the correlation factor r equal 0.991.

Calibration dependences presented in formulas (7) and (8) and the curves in Fig. 7 differ in particular details. These differences are the results of the shares of ambient air on the measuring bar exposition. For the longer version of the sensor, the ambient air (with the dielectric permittivity equal 1) influence is greater than shorter version. This explains the differences in effective dielectric permittivity readouts of completely dry aerated autoclaved concrete (for short probe more than 2, for long about 1.5).

Conclusions

TDR technology is a good option for moisture measurement of the porous media. The major advantages of the method are high monitoring potential and good accuracy.

Presented probes constructions enable non-invasive reflectometric measurements of building materials. The advantage of the longer probe is better resolution which is the result of the TDR device properties and the sensors dimensions. For the applied TDR device – LOM and the long probe the resolution is 0.3 %vol and for the short one is almost twice worse and equals 0.6 %.

It seems that introduction of the surface TDR probes has a high potential in moisture measurements of the building barriers and materials. It enables to avoid the problems of probes installation. This article presents the possibility of application of the surface TDR probes, which can be used externally and not invasively on building materials or barriers.

Application of the probes of following construction requires a special calibration for each specimen separately, but it can offer a high potential for laboratory and *in situ* measurements.

Acknowledgement

This work was supported by the Ministry of Science and Higher Education of Poland, No. 4952/B/T02/2008/34.

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POMIARY WILGOTNOŚCI MATERIAŁÓW BUDOWLANYCH Z ZASTOSOWANIEM POWIERZCHNIOWEJ SONDY TDR

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Abstrakt: Woda zawarta w zewnętrznych przegrodach budowlanych należy do podstawowych czynników ograniczających funkcjonowanie budynków. Jej negatywny wpływ na obiekty należy oceniać zarówno ze względów konstrukcyjnych, jak i higieniczno-sanitarnych. Duża wilgotność przegród budowlanych jest przyczyną sukcesywnego niszczenia konstrukcji budynków (krystalizacja soli, wielokrotne procesy zamarzania i rozmarzania w okresie zimowym, rozkład drewna oraz przyspieszona korozja stalowych elementów zbrojeniowych). Woda, w sposób pośredni, wywołuje negatywny wpływ na środowisko wewnętrzne pomieszczeń, tworząc podłoże do rozwoju szkodliwych mikroorganizmów oraz grzybów pleśniowych. Jest to problem typowy dla obiektów z nieuregulowaną i niemonitorowaną wilgotnością przegród, będący przyczyną chorób dróg oddechowych, infekcji, alergii oraz podrażnień oczu i skóry. Obiekty dotknięte problemem zawilgocenia przegród zewnętrznych w większości przypadków określamy jako dotknięte zespołem chorego budynku SBS (*Sick Building Syndrome*), którego przyczyną jest zastosowanie nieprzyjaznych człowiekowi materiałów budowlanych, wadliwa wentylacja lub właśnie nadmierne zawilgocenie przegród. Woda w przegrodach budowlanych w znaczący sposób obniża ich charakterystyki cieplne, co w konsekwencji prowadzi do zwiększonych strat ciepła w sezonie grzewczym, obniżenia temperatury odczuwalnej, obniżenia komfortu cieplnego pomieszczeń. Wszystkie wyżej przedstawione negatywne aspekty wpływu wody na obiekty budowlane stwarzają potrzebę znalezienia precyzyjnej i możliwie łatwej metody oceny zawartości wody w przegrodach. Do takich metod zaliczamy reflektometryczną metodę pomiaru wilgotności TDR (*Time Domain Reflectometry*). Funkcjonowanie tej techniki oparte jest na pomiarze prędkości propagacji impulsu elektromagnetycznego w badanym materiale. Wyznaczona ze znanej zależności względna stała dielektryczna materiału jest podstawą do ustalenia jego wilgotności. Metoda ta ma wiele zalet (możliwość ciągłego monitoringu, brak wrażliwości na zasolenie, stosunkowa prostota obsługi) i od wielu lat stosowana jest do pomiaru wilgotności ośrodków porowatych, a w szczególności ośrodków gruntowych. Nie znalazła ona do tej pory szerokiego zastosowania w dziedzinie budownictwa. Przyczyną tego jest jej inwazyjny charakter – do realizacji pomiaru niezbędne jest wprowadzenie stalowych prętów w badany ośrodek, co stwarza wiele problemów w przypadku materiałów oraz przegród budowlanych. Celem pracy jest przedstawienie alternatywnej konstrukcji – powierzchniowej sondy TDR, która umożliwia pomiary wilgotności materiałów oraz przegród budowlanych charakteryzujących się znaczną twardością, dla których zastosowanie klasycznej, dwuprętowej sondy, wymagającej wprowadzenia stalowych prętów w badany ośrodek jest trudne do zrealizowania. Metoda ta umożliwia skuteczne pomiary wilgotności bez konieczności niszczenia konstrukcji przegrody.

Słowa kluczowe: materiały budowlane, wilgotność przegród budowlanych, reflektometryczne metody pomiaru wilgotności, metody dielektryczne, TDR (*Time Domain Reflectometry*), powierzchniowa sonda TDR