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In-situ Measurements of Moisture Using Surface TDR Probes

Zbigniew Suchorab
Lublin University of Technology

1. Introduction

Problem of building barriers moisture is a well known phenomenon for almost all users of the buildings. Its presence is inevitable in moderate climate and its balanced states are acceptable. On the other hand, extended values of moisture are disadvantageous and may be caused by many factors like water vapor condensation inside the barriers, capillary rise of ground water, rainwater, inundations or sanitary systems failures. This phenomenon is also a factor which limits the object functionality both from the construction and sanitary-hygienic reasons.

Extended moisture content problem is particularly visible in the historical buildings which were set up without the suitable horizontal water-proof isolations. In this cases, ground water has the unlimited access to the groundwork and then, due to the capillary forces to the internal parts of the walls. Increased amounts of water lead to the material structure destruction by melting and thawing processes during winter season, wood decay, and accelerated corrosion of steel reinforcement elements and crystallization of dissolved salts in transported water. Also it should be mentioned here, that indirectly, water negatively influences the indoor environment providing good conditions for harmful microorganisms and mould development [3] which may consequently run to the respiratory system diseases, infections, allergies, eyes and skin irritations. All above presented negative consequences of water presence inside the building envelopes are the reason for constant development moisture detection techniques.

In this article, it will be presented a possibility of TDR (Time Domain Reflectometry) technique for *in-situ* moisture measurement of building barriers. The TDR technique has been applied for moisture measurement in soils for many years and since several years there have been made the attempts to measure moisture of building materials and barriers. But the invasive character of the method was the reason of many technical problems. Surface TDR probe presented in this article enables non-invasive moisture determination of building barriers and thus has a big potential for *in-situ* measurements.

2. TDR method description

The TDR method has been used for about 30 years for moisture measurement of the soils. It is continuously being developed by the constant improvement of the hardware, electronics, software and also sensors calibration methods. For the calibration there are used both theoretical, physical models [1, 2, 17, 19] but also the empirical calibration formulas obtained by experimental examinations [5, 6, 11, 18]. Probes presented in Fig. 1 enable accurate moisture determination without salinity and temperature significant influence in soft porous materials like soils.

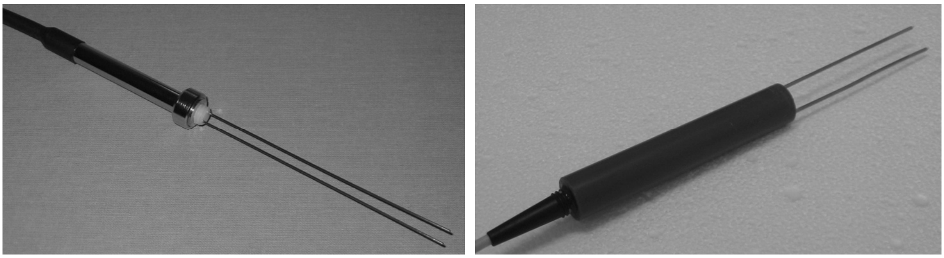

Fig. 1. TDR probe applied for invasive moisture determinations (Easy Test / Lublin / Poland). On the left LP/ms – laboratory probe, on the right FP/mts – field probe

Rys. 1. Sonda TDR używana do inwazyjnenych pomiarów wilgotności (Easy Test / Lublin). Po lewej LP/ms – sonda laboratoryjna, po prawej FP/MS – sonda polowa

Unfortunately, the above presented probes are not useful for moisture determination of hard porous media like rocks, stones and most of the building materials. Some moisture determination experiments made on building materials using typical TDR probes are presented in the following papers [4, 7, 8, 11, 16] and are mostly sacrificed to the light building materials like aerated concrete and show mainly the laboratory experiments. Also, it should be noticed here, that required techniques of samples preparation from the harder materials (drilling) may change their structure and thus their water properties in the area of the sensor sensitivity. All above mentioned inconveniences of the TDR technique regarding to the building materials made it necessary to design and manufacture the surface sensors which make it possible to do moisture measurements also in *in-situ* conditions.

The first ideas of the surface TDR sensor (Fig. 2) appeared about 10 ago in the world's literature [9] and were based on the traditional probes construction with measuring rods covered with especially prepared dielectric materials with the suitable thickness and dielectric parameters. This simply enabled to determine the electric and thus moisture parameters by simple and non invasive method.

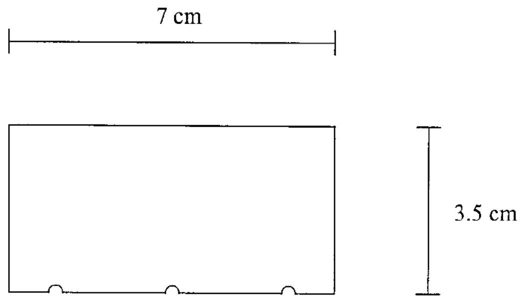

Fig. 2. The surface block for TDR moisture estimation proposed by Persson and Berndtsson in [9]

Rys. 2. Blok powierzchniowy do oceny wilgotności metodą TDR zaproponowany przez Perssona i Berndtssona w [9]

The idea of the surface TDR probe of hard building materials was presented in the following patent [10] and a similar in construction probe (Fig. 3) was presented in the following paper [20].

At Lublin University of Technology the prototypes of surface TDR probes have been built [12–15] which differ in construction – measuring rods length and distribution, number of the measuring rods (two and three-rod sensors), the shape of the measuring element (angle bar, flat bar) and finally the applied material (Plexiglas, polyamide, erthacetal). According to the preliminary experiments it has been established that the most effective solution is a two-rod surface probe with flat bar elements made of erthacetal. Connection between the concentric cable and the measuring elements is provided by the printed circuit board with the simple electronics. Fig. 4 presents the examples of the surface probes manufactured and Lublin University of Technology.

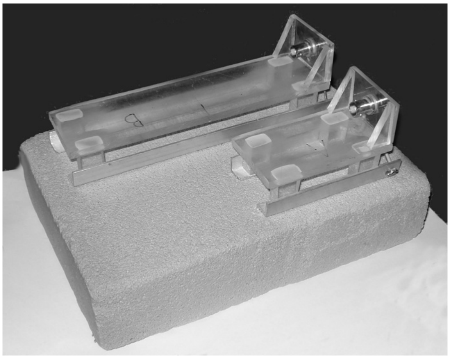

Fig. 3. Surface TDR probes for moisture measurements of hard, mainly building materials [10]
Rys. 3. Sondy powierzchniowe TDR do pomiarów wilgotności materiałów twardych, głównie budowlanych [10]

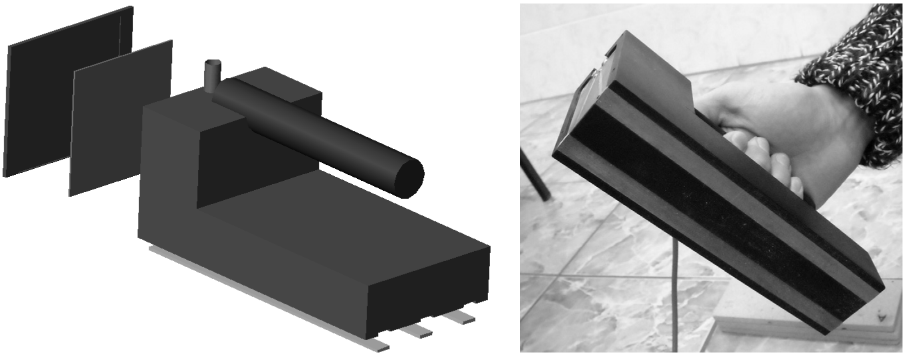

Fig. 4. Surface TDR probe. Left – three-rod sensor. Right – prototype of the surface TDR two-rod probe, applied in the described in-situ measurements
Rys. 4. Powierzchniowe sondy TDR. Po lewej – trój-prętowy czujnik, po prawej – prototyp sondy powierzchniowej TDR dwu-prętowej, stosowany w opisanych pomiarach in-situ

The idea of moisture measurement using the surface sensor is corresponding to the classical, invasive method physical bases. The TDR multimeter generates the electromagnetic impulse to the probe which due to the different electrical parameters of the medium (mainly moisture) propagates with the different velocity. Basing on this velocity changes it is possible to determine the dielectric permittivity and establish material moisture. The difference between the traditional and the surface technique is mainly connected with suitable returning signal echo interpretation. In case of the invasive TDR probes, the returning pulse indicates the real dielectric parameters of the measured medium and in case of the surface measurement, the situation is more complicated – because the electromagnetic pulse propagates along the waveguide with combined dielectric parameters of the environment. Partially it is covered with the dielectric material (ertacetal with the permittivity equal 3.8) and partially with the measured medium with the dielectric permittivity depending on moisture. To estimate the real material moisture it is necessary to separate the all above mentioned values influencing the effective dielectric permittivity of the medium. The most simple, but also the most accurate is the empirical calibration presented in the following literature positions [5, 11, 18].

2. Materials and Methods

The measurements were conducted in summer 2009 with 7 day intervals between 7th and 21st August 2009. The measured barrier was the historical object set at the Ku Farze Street, Lublin Old Town. The examined wall is made of red brick, covered with thin layer of cement and sand plaster. Fig. 5 presents the photograph of the barrier with marked measured area. The measurements were repeated three times to show moisture changes of the wall in time. For the determinations it was chosen the part of the wall with the increased water content. The whole measuring surface was 5.6 m^2 (width – 2.8 m, height 2.0 m). A measuring mesh presented on Fig. 6 was separated from the whole wall to present water states in a form of a moisture map. The mesh was consisting of 7 rows and four columns. The column width was constant – 70 cm and the height depended on the initially determined moisture and were varying between 10 cm in the lowest parts of the mesh, and 50 cm in the highest parts of the wall, where moisture was almost constant.

Fig. 5. Measured barrier with marked measured area
Rys. 5. Badana przegroda z zaznaczonym obszarem pomiaru

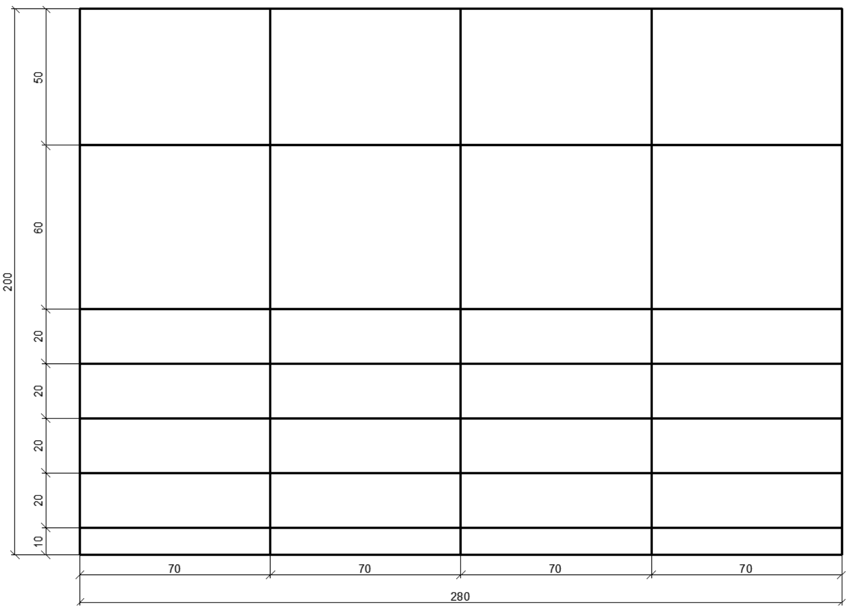

Fig. 6. Measuring mesh
Rys. 6. Siatka pomiarowa

For the experiment the following hardware was applied:

- Mobile Time Domain Reflectometry Multimeter – FOM (Field Operated Multimeter – Easy Test/ Lublin, Poland, Fig. 7) with time rise of the needle pulse 200 [ps],
- PC mobile computer as a control station (communicating with FOM device via RS-232c interface and processing the read information),
- Concentric cable with 50 Ω impedance connecting the probe with the Multimeter.
- TDR surface probe presented on Fig. 4 (two-rod sensor).

Fig. 7. Mobile TDR Multimeter (FOM – Field Operated Multimeter) applied in the presented *in-situ* experiments
Rys. 7. Przenośny multimetr TDR (FOM – Field Operated Multimeter) stosowane w prezentowanych badaniach in-situ

To control the device and read the obtained data the special software was developed (Fig. 8) which enabled *in-situ* reflectometic measurements using the surface TDR probes. Name of the program was TDR Reflectometer v.1.0 and its interface allowed device control, data readouts and transformation. Also it enabled reflectometric echo interpretation to avoid measurements errors caused by unexpected external factors.

To conduct the measurements, the probe was set at the particular points of the measuring mesh (Fig. 6), precisely with the uniform pressure at the whole surface, trying to avoid any gaps between the measuring elements and the barrier. As a result of the particular measuring step the controlling software was reading the reflectometric curves (Fig. 8) and recalculating it into the dielectric permittivity and thus moisture at the area of TDR probe influence.

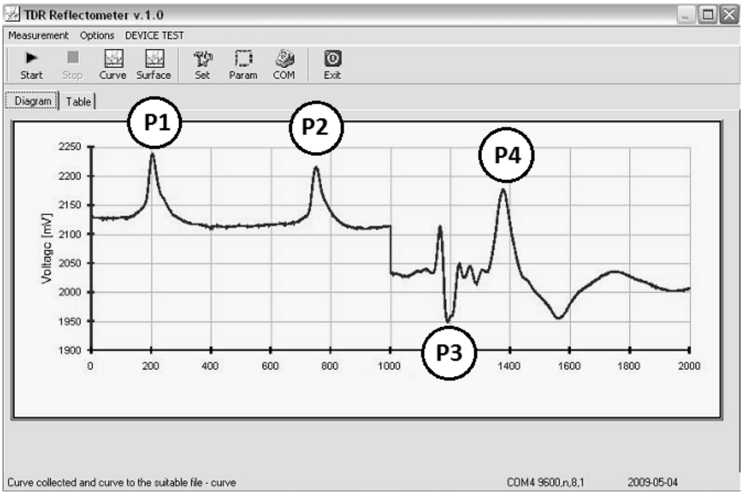

Fig. 8. Main window of program for surface TDR probe measurements with the visible reflectogram (also added the peeks valid for reflectometric measurements)
Rys. 8. Główne okno programu do pomiarów sondą powierzchniową TDR z widocznym reflektogramem (również dodano piki ważne dla pomiarów reflektometrycznych)

The algorithm which is implemented to the control software covers several stages, which are automated in the program. The first stage is to determine the time of signal propagation [ps] along each particular share of the reflectogram. Depending on the individual features of each device, but also the measurement conditions (for example the temperature), time of the particular share may differ for about several picoseconds. Length of each share, expressed in [ps], the TDR Reflectometer v.1.0 application calculates with the following formula:

$$t_1 = \frac{t_{pattern}}{p_2 - p_1} \tag{1}$$

where:

t_1 – time of the particular share, ps,

$t_{pattern}$ – time of pulse propagation along the pattern, constant for each Multimeter specimen, ps,

p_1, p_2 – position of the control peaks determining the beginning and the termination of the pattern.

Peaks marked on Fig. 8 as p_3 and p_4 are significant for the moisture measurement. They are the consequence of the surface TDR probe construction. First, negative peak is the consequence of the current resistor presence, which is applied intentionally to set the constant point of signal interpretation. It should be mentioned here, that there are also TDR surface probes manufactured without this resistor. They are prone to p_3 peak position movement, which may be the reason of significant measurement errors. Application of the resistor reduces the risk of that type of errors. Second peak, determined as p_4 is the base for dielectric permittivity determination of the examined material. Its position along the reflectogram depends on the electromagnetic pulse velocity – dielectric properties of the medium. Time of electromagnetic pulse propagation along the whole probe is determined using the following formula:

$$t_p = (p_4 - p_3) \cdot t_1 \tag{2}$$

where:

t_p – time of pulse propagation along the surface TDR probe, ps,

p_3, p_4 – positions of measuring peaks during pulse propagation.

Time of pulse propagation (t_p) along the surface TDR probe is not actually the time of propagation along the measuring elements. In real, it is the sum of propagation along the sensor rods and along the printed circuit board. This is constant and specific for any surface probe construction. It can be only determined experimentally for each type of the device. In case of the probe applied in the described experiment the time of signal propagation along the board was 650 [ps], that's why the real time of the TDR pulse propagation along the measuring elements (t_{TDR}) can be calculated from the following difference:

$$t_{TDR} = t_p - 650 \tag{3}$$

Presented above electromagnetic pulse propagation along the surface probe rods (t_{TDR}) is the base for determination of the dielectric parameters of the whole medium (effective dielectric permittivity) and thus moisture.

To establish the material moisture using the TDR technique, it is necessary to find the dependence between measured dielectric permittivity and moisture. They mainly depend on the measured medium properties but also on the individual properties of the sensor. They may be determined using physical or empirical models [1, 2, 5, 11, 17, 18, 19]. In case of the probe used for the presented measurements it was applied a formula elaborated in the previous calibration experiment:

$$\theta = -6.6 \cdot 10^{-9} \cdot t_{TDR}^{\ 3} + 6.1 \cdot 10^{-5} \cdot t_{TDR}^{\ 2} - 0.16 \cdot t_{TDR}^{\ 3} + 130 \tag{4}$$

where:

θ – volumetric moisture of the examined material, $\%_{vol}$.

4. Results Discussion

The reflectometric measurements were made on presented on Fig. 5 barrier. Reflectograms analysis was conducted automatically by the TDR Reflectometer v.1.0 (Fig. 8) program with the algorithm presented in the previous chapter. The readouts can be presented in the form of the tables or diagrams. Table 1 presents the example readouts of times of pulse propagation along the rods of the surface sensor in the first measuring period – the 7th August.

Table 1. Times of electromagnetic pulse propagation in surface sensor rods read in particular points of the measured brickwork on 7th August

Tabela 1. Czasy propagacji impulsu elektromagnetycznego w prętach czujników powierzchniowych odczytane w poszczególnych punktach badanego muru 7 sierpnia

	Time of signal propagation [ps]			
Height [cm]	Width [cm]			
	0	70	140	210
200	3311	3257	3147	3032
150	3541	3512	3210	3024
90	3582	3570	3497	3134
70	3654	3582	3511	3457
50	3648	3657	3602	3519
30	3644	3662	3611	3604
10	3687	3667	3679	3601

Obtained results are recalculated into the volumetric moisture and presented graphically on Fig. 9 in the form of moisture maps for three measurement steps (7^{th}, 14^{th} and 21^{st} August 2009). The diagrams are presented with the resolution of $2\%_{vol}$. Generally, the resolution of the obtained results depends on the surface probe construction (length of the measuring rods). In case of the applied probe it is about $0.3\%_{vol}$, but due to the large results dispersion it was better to present the moisture maps with the step of $2\%_{vol}$.

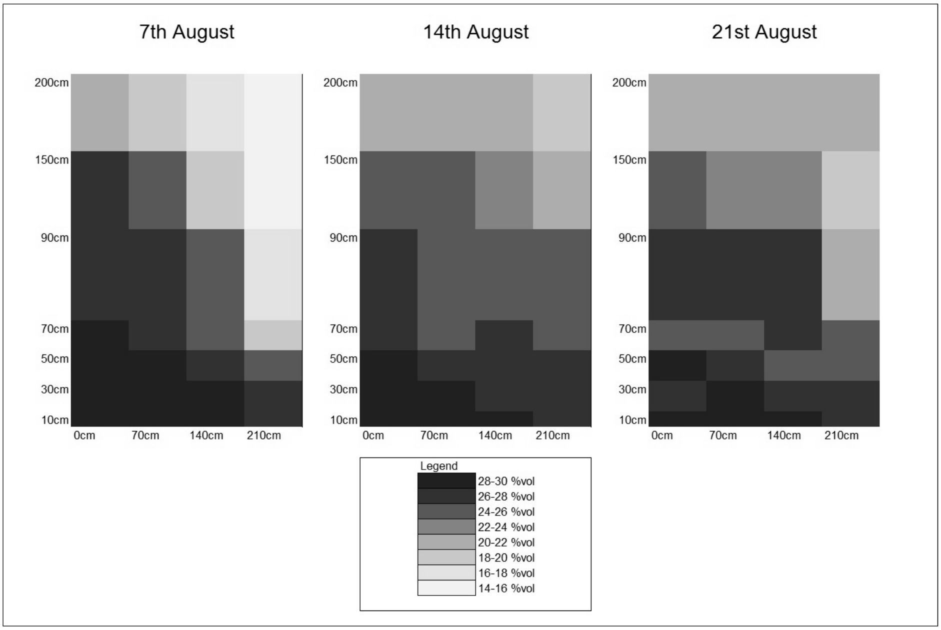

Fig. 9. Moisture maps of the examined barrier in three measuring steps
Rys. 9. Mapy wilgotności badanej przegrody w trzech krokach pomiarowych

From the obtained results it can be concluded that the examined barrier is on object with high moisture value, even in hot summer days. In the upper layers, water content is lower, especially on the right side of the barrier, which was exposed on the solar radiation. It was varying between 14 and $16\%_{vol}$. This situation is mostly visible in the first measurement, on 7^{th} August. During the periods with smaller solar radiation levels, water content in upper layers was also relatively smaller, but these differences were not so significant. In lower layers of the investigated barrier, moisture states were the greatest and were reaching about $30\%_{vol}$ without any noticeable dependence to weather conditions. Knowing that maximum water content for the red brick is about $35\%_{vol}$, it can be presumed that the whole moisture read by the surface TDR sensor is caused by the ground water and capillary rise phenomenon. It is also confirmed by the moisture distribution in the moisture maps – it consequently decreases from the bottom to the upper layers of the measured barrier in all measuring steps described in the following paper.

5. Conclusions

Application of the surface sensors for measurements using the TDR technology, significantly extends the measuring potential of the applied technique. Using the surface probes eliminates the necessity of invasive inserting the measuring rods into the structure of the examined material and enables material destruction.

TDR method enables the accurate volumetric moisture measurements. The resolution of the applied probe is $0.3\%_{vol}$, but it must be underlined here, that the suitable precision should be kept during the experiment – no movement of the sensor and no gaps between the sensor and the material are allowed.

Measurements with the surface TDR sensor confirmed high water content in old historical buildings which is mainly caused by lack of horizontal isolation layers.

Also, it should be underlined here, than non-invasive method character enables quick moisture estimation and may be applied to arrange the moisture maps of the building barriers which may be useful in renovation procedures.

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Pomiary wilgotności *in-situ* przy zastosowaniu powierzchniowych sond TDR

Streszczenie

Zjawisko zawilgocenia przegród budowlanych jest znane w zasadzie wszystkim użytkownikom obiektów budowlanych. Występowanie tego zjawiska jest praktycznie nie uniknione w warunkach klimatycznych w jakich znajduje się Polska. Jego zrównoważona obecność polegająca na ciągłym pochłanianiu wilgoci i jej odparowywaniu jest jak całkowicie akceptowalna. Szkodliwym jest natomiast zjawisko nadmiernej zawartości wilgoci, które może być wywołane wieloma czynnikami do których zaliczamy kondensację pary wodnej wewnątrz przegrody, podciąganie kapilarne wód gruntowych, wody rozbryzgowe z deszczy, wody powodziowe czy też awarie instalacji sanitarnych. Zjawisko powyższe jest niekorzystne z punktu widzenia budowli i jest czynnikiem ograniczającym funkcjonalność obiektu zarówno ze względów konstrukcyjnych, jak i higieniczno-sanitarnych.

Problem nadmiernej zawartości wody w murach jest szczególnie widoczny w budynkach historycznych wznoszonych bez zastosowania właściwych izolacji poziomych. Wówczas woda gruntowa posiada nieograniczony dostęp do fundamentów budynku, a następnie przy udziale sił kapilarnych do wnętrza murów. Nadmierna ilość wody w zewnętrznych przegrodach budowlanych prowadzi do zniszczenia struktury materiału poprzez wielokrotne procesy zamarzania i rozmarzania w okresie zimowym, rozkład drewna, przyspieszoną korozja stalowych elementów zbrojeniowych oraz krystalizacja soli rozpuszczonych w transportowanej wodzie. Istotnym problemem jest również fakt, że woda pośrednio negatywnie oddziałuje na środowisko wewnętrzne pomieszczeń, przyczyniając się tym samym do rozwoju szkodliwych mikroorganizmów oraz grzybów pleśniowych. Może w konsekwencji przyczyniać się do chorób dróg oddechowych, infekcji, alergii oraz podrażnień oczu i skóry. Przedstawione powyżej negatywne skutki obecności wody w przegrodach budowlanych są podstawą do rozwoju i ciągłego opracowywania i udoskonalania technik detekcji wilgoci w przegrodach budowlanych.

W niniejszym artykule przedstawiono możliwość przeprowadzenia badań *in-situ* przy zastosowaniu techniki pomiarowej TDR (Time Domain Reflectometry). Technika ta od wielu lat stosowana była do pomiarów wilgotności ośrodków gruntowych. Od początku XXI wieku trwały prace nad zastosowaniem techniki TDR do oceny zawilgocenia twardszych od gruntu materiałów i przegród budowlanych. Jednak inwazyjny charakter metody w większości przypadków uniemożliwiał jej praktyczne wykorzystanie lub był przyczyną wielu problemów technicznych.

W ramach części badawczej artykułu przedstawiono pomiary wilgotności muru z cegły ceramicznej pełnej pokrytej warstwą tynku wapienno-piaskowego. Badany obiekt znajduje się na Lubelskiej starówce i jest to ściana bramy przy ul. Ku Farze. Jest to przegroda dotknięta zjawiskiem podciągania kapilarnego wynikającego z braku właściwych izolacji poziomych. Badania przeprowadzono w trzech terminach pomiarowych przy pomocy opracowanych na Politechnice Lubelskiej sond powierzchniowych TDR, umożliwiających bezinwazyjne pomiary wilgotności. W celu wykonania pomiarów, badaną przegrodę podzielono na charakterystyczne fragmenty tworzące siatkę pomiarową o określonych wymiarach. W trakcie eksperymentu w charakterystycznych punktach przegrody umieszczano czujnik i odczytywano parametry dielektryczne ośrodka, automatycznie przeliczając je na wilgotność objętościową. Wyniki przeprowadzonych badań naniesiono na siatkę pomiarów różnicując je kolorami w zależności od odczytanej wilgotności. Rezultatem powyższych zabiegów było uzyskanie tzw. map wilgotności przegrody budowlanej w trzech różnych terminach pomiarowych. Przedstawione w artykule mapy wilgotności potwierdzają fakt podwyższonej wilgotności przegrody i jednocześnie pozwalają na ukazanie jego rozkładu w pionie oraz poziomie. Przeprowadzone badania wyraźnie ukazują, że badana przegroda wykazuje nadmierną wilgotność w swych dolnych partiach, natomiast wyższe partie są nieco mniej wilgotne. Świadczy to o tym, że przyczyną nadmiernego zawilgocenia są wody gruntowe podciągane kapilarnie do wewnątrz struktury materiału.

Wyniki badań przedstawione w artykule dowodzą skuteczności rozwijanych powierzchniowych sond TDR do bezinwazyjnego pomiaru wilgotności materiałów i przegród budowlanych oraz wskazują na przyczyny tego zjawiska w obiektach rzeczywistych.