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Error Analysis of Nonconventional Electrical Moisture-meter under Simplified Conditions

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Abstract**—**An electrical apparatus for measuring moisture content was developed by our laboratory and uses dependence of electrical properties on water content in studied material. Error analysis of the apparatus was run by measuring different volumes of water in a simplified specimen, i.e. hollow plexiglass block, in order to avoid as many side-effects as possible. Obtained data were processed using both basic and advanced statistics and results were compared with each other. The influence of water content on accuracy of measured data was studied as well as the influence of variation of apparatus' proper arrangement or factual methodics of its usage. The overall coefficient of variation was 4%. There was no trend found in results of error dependence on water content. Comparison with current surveys led to a conclusion, that the studied apparatus can be used for indirect measurement of water content in porous materials, with expectable error and under known conditions. Factual experiments with porous materials are not involved, but are currently under investigation.

Keywords**—**device, capacitance method, error analysis, moisture meter

I. INTRODUCTION

MEASUREMENTS of various transport properties of building materials are widely spread among present-day studies, including characteristics connected with water storage and water transport. This study tends to embrace the very ground of such experiments, for it deals with uncertainty estimation of the capacitance method using a nonconventional apparatus.

The capacitance method is one of the lesser used electrical methods of detecting water, mostly used in geo-engineering (see [1], [2]), food industry (see [3]) and building materials researches (see [4], [5]). Its advantages lie in providing immediate results and a variety of arrangements (with advantage of non-destructive measurements). Questions arise, whether gained data is distorted too much to be processed in complex computations (for example determining moisture diffusivity ratio using integral methods [6], [7]).

Our apparatus was designed wireless, mobile and portable. Its circuit works on the basis of detecting permittivity so that calibration for different materials is needed.

The experiment was conducted within strictly simplified conditions, i.e. specimen was made of plexiglass and its cavity was filled (partially or fully) with water. Obtained data were processed using basic descriptive statistics. Besides measurements in different states of water content, the influence of apparatus´ handling is evaluated.

Similar studies were found in literature, for example [8] showed the accuracy of TDR equipment used with granular material of 5-10%, authors of [9] showed relative uncertainty of 2% in measurements of liquids. In regard of capacitance sensors, the influence of temperature and electrical conductivity [10] or factual investigation of uncertainty of calibration curves [2] is more likely to be found.

Results are considered acceptable when the overall coefficient of variation does not exceed 10 %. In such cases, consequent experiments of this sort will be held with porous material. Stated methodology can serve as a baseline for similar reviews on electrical methods of detecting water content.

II. METHODS AND MATERIALS

A. Used apparatus

The device used is a nonconventional electrical moisture-meter (permittivity-meter respectively). It detects water content on the basis of dissimilarity of dielectric properties of water and other materials and works as a simple capacitance sensor. Gained quantity cannot be generally called relative permittivity, because it is influenced by properties of close surroundings, specifics of arrangement and non-infinity of the specimen inside. Therefore we use the denotation “permittivity ε^d” to mark its strong »dependence« on the specific arrangement and electrical field of device itself. Two electrodes (3.8 cm × 2 cm) are connected with internal electronics, which consists of the power supply, display unit, LED detector, switch and an integrated circuit. Its working frequency is between 250–300 kHz. The device is approximately 27 cm long, 8 cm wide and 5 cm thick. Configuration of the apparatus is suitable for measuring samples about 2 – 3 cm thick with flat, clean, collinear and dry surfaces. One-hand service is available.

The measurement with this device is not continual – the manipulator has to switch it on once it is placed on every single part of a sample in order to read the number. The switch button is designed to return to off-state automatically. In the off-state, the circuit is interrupted or in “relax mode”. When the button is pushed, i.e. the circuit is closed, it was observed that the given number was always slightly changing.

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B. Materials and specimens

In order to run an error analysis of the permittivity-sensitive moisture-meter, we searched for a material with very low relative permittivity to make a hollow sample. We used 2 mm thick clear plexiglass (density $\rho = 1190\ \mathrm{kg/m^3}$). Such material is expected to have only little (yet considerable) influence on total summary permittivity of a sample made of plexiglass ($\varepsilon_r = 3.4$), water ($\varepsilon_r = 81$) and air ($\varepsilon_r = 1$). Dielectric properties of possible other materials (epoxide glue) were not considered due to their insignificant contribution to total permittivity.

Dependence of material properties on temperature were not considered; all measurements were carried out at an ambient laboratory temperature of T = 21°C.

We prepared two types of specimens. The first one was meant to simulate infinite hollow board (2.4 cm × 20 cm × 25 cm; denomination S1) and the second one was meant to be similar to samples used in our other experiments ([6], [7]; 2.4 cm × 4.4 cm × 25 cm; denomination S2). Both samples were board on surface of one side to allow filling up with water.

C. General method of measurement

The main objective was to evaluate the uncertainty of the device, which was expected to vary among different states of water content between electrodes. First appraisal was given by measuring with simulation of infinite hollow board (homogenous wet or dry environment) – sample S1. Secondly, sample S2 was filled with different volumes of water and gauged.

In the first approach, the device was placed in the middle of approximate infinite hollow board (*S1*) and without moving it, different wetness states were gauged. This arrangement was expected to eliminate influence of the edges or surrounding environment on measured permittivity ε^d.

In the second approach, hollow prism (*S2*) was left empty, then filled partially with water and finally completely filled with water. Permittivity ε^d of such system was gauged. Gained results were compared with the previous experiment.

Thus, data of measurements on prism specimens consisted of plenty of series in order to eliminate the influence of edges and the influence of repetition in a short time period. That is why we chose to move the device during measurements this way: from the left side of the specimen to the right in a first row, from the right side to the left in a second row, we let the circuit relax for five minutes and repeated two described rows again. That gave us one set of data for one state of water content (we call it "raw data file").

We also ran a special experiment focused on different handling of the tested device. *Variant 1* meant that the circuit was interrupted between subsequent gauges on a different place of the specimen. *Variant 2* meant that the circuit was permanently connected within one series of measurements and the device was moving to another place without relaxation. Again, the effect was evaluated statistically. The variant with less error was used during the rest of the experiment.

With changing volume of water in the specimen, total permittivity ε^d of simple four layer system (plexiglass, air, water, plexiglass) was changing, affecting the reading of the used device. All data sets are given in Table I to illustrate the procedure of our experiment. Each data set corresponds to part of the experiment, within which several measurements were done, therefore data files I.A, I.B, …, I.X are gained for moisture content 0%, 10%, …, X% for example. Some experiments needed several measurements for the whole range of water content, in some cases extreme values (0% and 100%) were considered sufficient.

TABLE I
DATA SETS USED IN EXPERIMENT AND ITS DESCRIPTIONS

Data sets	Description	Specimen	Water Content [%]	Number of series
I.A … I.E	No specimen	(none)	0 / 100	5
II.A … II.I	Plexiglass board	S1	0 – 100	9
III.A … III.J	Plexiglass block	S2	0 –100	10
IV.A, IV. B	Plexiglass block	S2	0 / 100	2
V.A … V.L	Plexiglass block	S2	0 – 100	12
VI.A … VI.D	Plexiglass block, Var. I, II	S2	0 / 100	4
VII.A … VII.D	Plexiglass block, Var. I, II	S2	0 / 100	4
VIII.A … VIII.H	Plexiglass block	S2	0 / 100	8

During all measurements, we focused on preserving parallelism of the device´s electrodes, the specimen´s surface and water level, constant temperature and no electromagnetic field in surroundings of the specimen. We used water with no salts. Irregularities in shape of the specimen were neglected.

D. Method of data analysis

Each data series was processed in order to evaluate accuracy, error or monitored influence. For that purpose, general statistics were used, including mean value, error of mean value, median, modus, standard deviation, sampling variance, kurtosis of data distribution, skewness of data distribution, minimum, maximum and coefficient of variation (see [11], [12][1]). Distribution of gathered data was expected to be normal, so that outliers and extremes could be found by Grubbs tests [13]. After eliminating deviating values, each series of data set was statistically described again.

This analysis necessarily needs criterions to state which error is acceptable. Generally, our limit of acceptable results for coefficient of variation was 10% in data files and 5% on average for all parts of complex experiment. Influencing factors are detected in mean of coefficient of variation or error of mean value.

III. RESULTS

All together our experiment consists of 71 data files of 19-92 measurements (67 on average). To obtain such files, outliers and extremes were found with Grubbs tests (for confidence level 95%, [13]) and eliminated.

It was observed, that the device was giving slightly descending numbers converting to average value, when

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[1] we suppose those indicators to be well known, so that extension of this paper by quoting each and every equation is not necessary

readings follow each other immediately. We eliminated this difficulty by gauging each state in four rows (four times whole specimen one centimeter after another). Unfortunately, data files grew bigger with this need.

It was presumed, that the measured data would show normal distribution. This was proved both visually (histogram of values) and numerically (kurtosis coefficient is -0.02 on average and skewness coefficient is 0.39 on average. At least one of these coefficients had values expected for normally distributed data, i.e. 0, in 56 data files; both coefficient were approximately 0 in 14 data files).

Since there is not enough space to show all results in this paper, we show some statistical indicators for coupled groups of data files. Each data set corresponds to one type of experiment and may consist of several data files (see Table I). Overall statistics is shown in Table II below.

TABLE II
STATISTICS INDICATORS FOR GROUPS OF DATA FILES

Data set	Water Content [%]	Average for data set			
		Number of values per file (files)	Standard deviation [-]	Sampling variance [-]	Coefficient of variation [%]
I	0 / 100	29 (5)	0.468	0.391	0.9
II	0 – 100	24 (9)	0.252	0.080	5.5
III	0 –100	84 (10)	0.197	0.048	4.0
IV	0 / 100	84 (2)	0.593	0.400	6.9
V	0 – 100	80 (12)	0.264	0.082	3.5
VI	0 / 100	77 (4)	0.316	0.131	3.0
VII	0 / 100	70 (4)	0.409	0.251	3.9
VIII	0 / 100	71 (7)	0.264	0.108	4.1

The coefficient of variation for the worst data file was 9.7 %. Threshold of 5 % was exceeded in 12 cases, but overall average coefficient of variation was only 4.0 %.

The evaluation of accuracy in measurements for different water contents is shown in the following figures. Fig. 1 gives mean values detected for varying water content (average for all “good” measurements for current water content) and Fig. 2 gives coefficient of variation for varying water content (same data source). These results were obtained by gauging on specimen *S1* (data files V.A, V.B, …, V.L – see Table I).

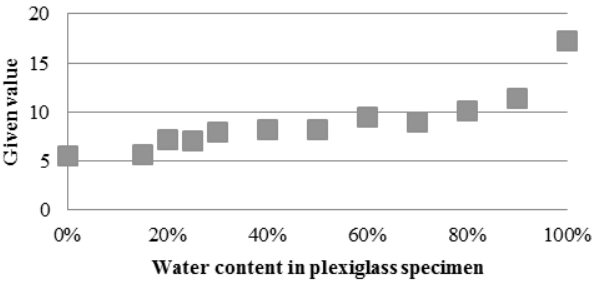

Fig. 1 Mean values for varying water content

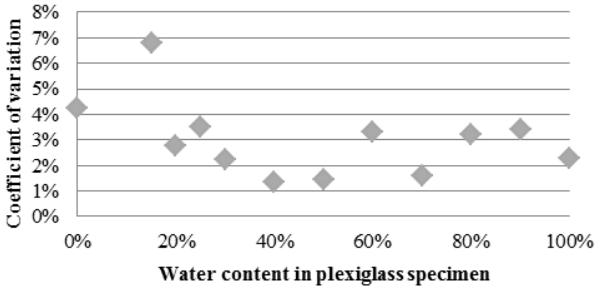

Fig. 2 Coefficient of variation for varying water content

Next, two types of experiments were conducted in regard to apparatus´ handling. We concluded that Variant 1 (interrupted gauging) gives less error than Variant 2 (non-relaxed circuit).

Moreover, it was observed that the device tends to give distorted values for first few readings – at least first 5 values are far-off overall mean value (during data processing, most of these values appeared to be extreme or outlying).

When comparing different specimens, measurements on board-like specimen (*S1*) naturally gave generally smaller values than those held on balk-like specimen (*S2*). For dry state, increase was 50% and for wet state, increase was 31%.

IV. DISCUSSION

The occurrence of extreme values (which were removed from raw data files) was assumed to result from the character of the device´s circuit (i.e. relaxation tendencies, heating, electrical field of its own components, loss factor due to its imperfection), influence of the edges (extremes occurred mostly close to edges) and last but not least from imperfection of the specimen´s construction.

The distribution of values in one data file was in good agreement with normal distribution, although most of histograms were more or less differing in either shape (skew and kurtosis) or symmetry.

General demand on the coefficient of variation for good experimental results (20-30%) was accomplished in every data series (both raw and net). Demands stated by us (10% in one data file and 5% on average) were also fully accomplished.

A. Sources of errors

Evaluation of systematical errors was in focus of this study and was taken in account through a statistical analysis performed on a series of repeated measurements. Complex contribution of both systematic and random errors will be considered in a following study dealing with experiments on porous material.

Sources of random errors were quoted above and are the following: fluctuations due to environmental and operating conditions, properties and imperfection of the device´s circuit (its own electrical field, heating of components, noise etc.). Of course, human factor has to be also stated herein, though both assembly of the specimen and measurements were done manually as well as the reading of varying measured values.

The following sources of systematical error were considered: shape and quality of the specimen (body of the device, edges of specimen), water content inside specimen, handling of the device, possible non-co linearity of electrodes, material properties of used water and plexiglass.

B. Dependence of error on moisture content

There was no specific trend found during our experiments considering dependence of error (*error of mean value* or *coefficient of variation*) on moisture content. Differences are too small to draw a clear conclusion to decide whether the uncertainty was dependent on moisture content or not.

C. Influence of handling and used specimen

Based on our experiment, interruption of the circuit is strongly recommended in order to gain more precise results. The non-relaxed circuit can lead to impacted results.

The difference between results gained from experiments held on different samples (S1 and S2) was believed to result from the influence of the surrounding environment and edges, i.e. side sheets of plexiglass along the length of specimen and the edges themselves.

D. Comparison with other studies

Similar analysis was run for the TDR devices [8] with resulting relative standard uncertainty lower than 10% for the portable low-cost TDR unit and lower than 5% for the more performing unit, respectively. Measurements were held on granular materials and rather bigger samples.

Uncertainty estimation using the TDR technique for measurements on liquids [9] concluded with a result of 2%.

E. Suggestions for improvements

Based on our study, we propose restrictions for the handling and usage of our capacitance moisture-meter, which can be (after appropriate consideration) applied to other electrical methods of detecting water in porous systems with similar methodology or arrangements. For samples, we recommend to flatten the surface as much as possible to avoid distortions. For handling, we recommend to run the apparatus idle several times and to interrupt the circuit between reading values during the series, because the circuit tends to give false (bigger) values during a few “start-up” readings. Further, we recommend repeating gauging several times in order to give precision to obtained results.

Repeating of an experiment of this kind with different fill of specimen (porous material, granular or solid) will also give reliability of used methodology, as well as corrections for temperature effect. The influence of an electromagnetic field or water salinity on output values was not studied, but should be taken into consideration in following experiments.

V. CONCLUSION

We investigated and evaluated the uncertainty of measurements with our non-conventional capacitance moisture meter. The overall coefficient of variation was 4%, so that we consider this device to be useable for complex experiments dealing with indirect water content measurements.

Proposed factors of influence (moisture content, handling with the device) on final error of measurements were studied and enumerated and important demands on usage of the device were drawn. Our apparatus is suitable for measuring water content in porous materials, on samples of moderate sizes under constant temperature. The best results will be obtained for low-permittivity materials with a uniform system of pores and a flat surface. This paper deals with part of a complex experiment involving experiments on real porous material and estimation of its certainty, which is currently under investigation.

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