TDR-BasedMeasurements of Water Content in Construction Materials for In-the-field Use and Calibration

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Abstract—In this work, a time domain reflectometry (TDR)-based system for measuring water content of raw construction materials is presented. The proposed system relies on the fact that the presence of water leads to an increase of the dielectric permittivity of materials; therefore, from TDR-based permittivity measurements, it is possible to infer the water content value.

In practical applications, the proposed system could be used for assessing the intrinsic water content of construction materials before they are poured into the concrete mixture. Knowing the intrinsic water content of the raw materials, in fact, would allow to evaluate the optimal amount of water that should be added to the mixture in order to achieve the desired water-to-cement ratio. This, in turn, would permit to fine-tune and control the mechanical properties of the final concrete structures.

For assessing the feasibility of using the proposed system for the intended purpose, water content measurements were carried out on three construction materials, namely, sand, grey cement, and white portland cement. For each of these materials, a calibration curve relating water content to the apparent dielectric permittivity was derived; additionally, through repeated measurements, also a confidence interval was associated to the calibration curves.

Index Terms—cement, dielectric permittivity, reflection coefficient, time domain reflectometry, water content.

I. INTRODUCTION

Much research effort is constantly dedicated to monitor building structures during their service life for early detection of defects, crack, corrosion, etc. [1]–[4]. However, it is as much important also to make sure that the materials used for construction are compliant with the requirements imposed by safety and quality regulations. To this end, one of the key strategies is to measure water content of dry bulk materials, such as cements [5]; in fact, an excessive presence of water may cause severe deterioration of the performance of materials [6].

Nevertheless, it is not sufficient to measure water content of the finished product; on the contrary, to guarantee the desired performance of the material, it is necessary to know the water content that is present from the delivery of raw materials and during the various stages of the production process. In particular, it is important to develop robust and low-maintenance water content measurement systems that could

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allow to retrieve in real time the moisture content of materials in containers, tanks, on conveyor belts or in pipes. Also, it is important to employ water content monitoring systems that could be used in-line (i.e., without interrupting the manufacturing process) and whose measurement output could be made readily available to the process control systems. In this way, direct process interventions could be handled remotely, through tele-control systems.

Monitoring water content of raw construction materials is also important for evaluating the exact amount of water that needs to be added to mixture in order to achieve the optimal water-to-cement ratio (w/c). It is well known that the w/c value strongly influences the hydration process and the final mechanical properties of the final concrete structure (e.g., compressive strength, ductility, durability, and abrasion resistance) [7].

During storage, cements absorb environmental moisture, and their intrinsic water content percentage may easily reach 10%. Neglecting the water content of the raw materials may lead to a higher w/c with respect to the desired one, with possible consequences on the properties of the final concrete structure. This aspect becomes particularly significant with large amount of concrete mixture (such as for dams, bridges, roof slabs, etc.). In such cases, when preparing the concrete mixtures, assessing the intrinsic water content of the raw materials would be useful to compensate it with the suitable amount of water to achieve the desired w/c value.

In industrial applications, for example, the water content could be measured right before the materials are poured into the concrete in-transit mixers (which transport the concrete mixture up to the construction site) to evaluate their water content and take it into account when adding the water necessary to obtain the desired w/c ratio.

One of the candidate technologies for achieving the aforementioned goals is time domain reflectometry (TDR), as it provides advantages that often are not simultaneously available in other technologies. In fact, at the state of the art, there are several technologies available for monitoring water content of granular materials (especially soils); however, their use is often hindered by practical limitations and high implementation costs.

For example, infrared sensors send infrared beams into the material and measure water content based on the ratio of absorbed and reflected wavelengths. However, this contactless method detects only the surface moisture content of the material sample.

Instead, neutron ray and gamma ray sensors measure the water

content of the material by sending small doses of neutron or radioactive gamma beams into the material under test. These sensors have the advantage of not requiring calibration to the specific material being analyzed; however, they are very expensive (the cost of a neutron probe is in the order of USD 10000 [8]) and the presence of radioactive materials requires special handling and caution [5].

Another widespread water content measurement system relies on frequency-domain probes, namely capacitive sensors whose resonant frequency changes as a function of water content of the material located between the sensor's capacitor electrodes [8]. After a material-specific calibration, these sensors can achieve an uncertainty of 1%; nevertheless, the cost of each sensor is approximately USD 280 (plus the access tube installation kit, whose cost is in the order of USD 2600). Additionally, these capacitive sensors exhibit larger sensitivity to temperature, to bulk density, and to air gaps with respect to TDR.

Based on these considerations, it is apparent that most of the technologies described above do not provide simultaneously low cost (suitable for large-scale implementation), real-time measurements, adequate accuracy and customization possibility. Conversely, TDR-based systems possess simultaneously all of these features.

A typical TDR instrument used for water content measurements on granular materials costs approximately USD 3000 (as the one used in this work); however, lower-cost TDR instruments are available with adequate specifications and with cost in the order of USD 900. Also, the probes are simple to be fabricated and the cost of a probe can be as low as USD 10. All these characteristics have contributed to making TDR an appealing solution for monitoring water content of granular materials.

Over the years, TDR has been used extensively to determine water content of granular materials [9], [10], and in particular of soils [11]–[16]. TDR has also been used for monitoring moisture content profile in concrete structures and the rising damp phenomenon in building structures [17]–[22]; for monitoring the hydration of cement-based structures [23]; for inferring the w/c ratio to determine the amount of water that has been incorporated into the hydrate; and for monitoring the formation of the developing structures [24], [25]. However, the literature regarding water content measurements of raw cements is limited; in fact, in the literature, TDR moisture content measurements on construction materials typically refer to the finished product.

Starting from these considerations and from the preliminary results reported in [6], the focus of this work is to employ TDR for evaluating the water content of particle construction materials, with the final practical aim to use the proposed system to fine-tune the water-to-cement ratio of concrete mixtures. It should be mentioned that, compared to other particle materials whose moisture content has been studied through TDR (soil in particular), construction materials, such as cements, pose a considerable challenge with regard to achieving homogeneous moistening conditions; in fact, as water content increases, the texture of the moistened material becomes such that even achieving a homogeneity is difficult.

To assess the feasibility of the proposed methods for the intended purpose, TDR-based water content measurements were performed on three types of construction materials: sand, grey cement, and white portland cement. Measurements were performed using a two-rod probe inserted into the considered materials, which were moistened at progressively higher water content values. For each considered material, TDR measurements were used to derive an empirical relationship (i.e. a calibration curve) relating the apparent dielectric permittivity ($\varepsilon_{\mathrm{app}}$) to the water content value, θ. Also, repeated measurements were carried out to associate a confidence interval to the calibration curves.

In the following, after the description of the theoretical background in Section II, the materials and methods are described in detail. Successively, in Section IV, the performed experiments are presented and considerations on the practical implementation of the proposed TDR-based monitoring system are reported. Finally, in Section V conclusions are drawn.

II. THEORETICAL BACKGROUND

The typical instrumental setup for TDR-based in situ water content measurements on granular materials includes *i*) a portable reflectometer; *ii*) a multi-rod probe; and *iii*) a laptop for data processing.

TDR measurements rely on the analysis of the signal that is reflected when an appropriate electromagnetic test signal (typically, a voltage step signal with very fast rise-time or a pulse-signal) is propagated along a probe inserted into the material under test. When the TDR test signal propagates along the probe, any impedance variation causes the partial reflection of the propagating test signal. The reflected signal carries information on the dielectric characteristics of the material in which the probe is inserted. Therefore, through a suitable data-processing, it is possible to retrieve other intrinsic (qualitative and quantitative) characteristics of the material under test [26].

The direct output of a TDR measurement is a reflectogram, which displays the reflection coefficient (ρ) as a function of the apparent distance, d^{app}. The quantity d^{app} is related to the 'actual' physical length traveled by the test signal, d, through the following equation:

$$d^{\mathrm{app}} = \sqrt{\varepsilon_{\mathrm{app}}} \cdot d, \qquad (1)$$

where $\varepsilon_{\mathrm{app}}$ is the apparent relative dielectric permittivity of the material/system in which the probe is inserted [27], [28].

Generally, TDR-based measurements of water content rely on (1), as the water content value (θ) is inferred from measurements of $\varepsilon_{\mathrm{app}}$. In fact, the relative dielectric permittivity of water (approximately 78.3 at 25°C [29]) is considerably higher than the typical relative permittivity of many granular materials of interest (e.g., cement, sand, etc.); therefore, the presence of water leads to a considerable increase of the overall dielectric permittivity of the material under test. In practice, by measuring the apparent length of the probe (L_{app}^{P}) when it is inserted into the material, it is possible to retrieve the $\varepsilon_{\mathrm{app}}$ and, hence, the θ value.

For deriving the functional relationship between θ and $\varepsilon_{\mathrm{app}}$ from TDR measurements, a simple approach relies on the use

of empirical, material-specific calibration curves. These curves are determined through preliminary measurements on samples moistened at pre-fixed, known water content levels (θ_{ref}), and evaluating the corresponding ε_{app} from measurement of the apparent length of the probe. The points ($\theta_{\text{ref}}, \varepsilon_{\text{app}}$) are then fitted through a third-order polynomial which has been found to be generally suitable for the considered types of granular materials [30]:

$$\theta = B_0 + B_1 \varepsilon_{\text{app}} + B_2 \varepsilon_{\text{app}}^2 + B_3 \varepsilon_{\text{app}}^3 \tag{2}$$

where B_0, B_1, B_2 and B_3 are the regression coefficients. Equation (2), with the proper coefficients, represents the calibration curve: in successive water content measurements on the same type of material, it is enough to measure ε_{app}, and the corresponding (unknown) water content level is simply retrieved from the calibration curve.

III. MATERIALS AND METHODS

A. Materials

Three construction materials were considered: sand, grey pozzolan cement, and white portland cement. As well known, sand is used to fill the large voids that are present in coarse aggregate.

Pozzolan cement is the general name for a group of cements that contain not less than 20% active mineral additives. It differs from ordinary portland cement for its higher resistance to corrosion (especially in soft or sulfate waters), reduced rate of hardening, and lower frost resistance. Pozzolan cement is used mainly to produce concretes used in underwater and underground structures [31].

Finally, white portland cement is similar to ordinary, grey Portland cement in all aspects except for its high degree of whiteness. Obtaining this color requires substantial modification to the method of manufacture, and because of this, it is somewhat more expensive than the gray product. White Portland cement is used in combination with white aggregates to produce white concrete for prestige construction projects and decorative work.

TDR measurements were performed through a portable TDR instrument, namely the Campbell Scientific TDR100 [32]. The generated TDR test signal is a step-like voltage signal with rise time of approximately 200 ps and amplitude of 250 mV. One of the advantages of this TDR instrument is that it supports multiplexers, thus allowing the simultaneous connection of several probes to a single TDR unit. This feature is particularly useful for practical purposes (e.g., for monitoring along the production lines), as it can lower the implementation costs.

With regard to the probe, two-, three- or multi-rod probes are typically used for TDR measurements on granular materials, thanks to the easiness of insertion [33]. In this work, a 10.5 cm-long two-rod probe fabricated in-house was used (shown in Fig. 1). As a general rule, if the probe length is excessively short, then the evaluation of L_{app}^P from the reflectogram becomes less accurate; on the other hand, if the probes are too long, the signal attenuation increases and it becomes more difficult to identify the probe-end in the reflectogram
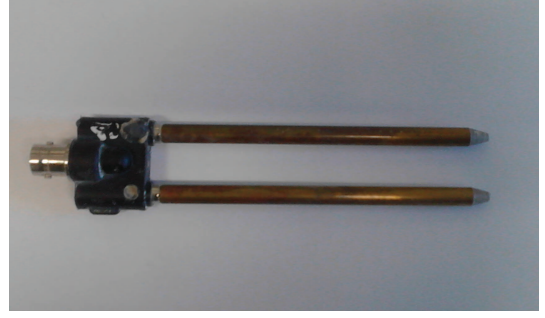

Fig. 1. Picture of the two-rod probe used for the TDR measurements.

[34]. On the basis of these considerations, the chosen probe length ensured an optimal trade-off of the aforementioned requirements; also, it was short enough to easily guarantee the parallelism between the two rods. Each probe rod was made of brass and its diameter was 5 mm, while the mutual distance between the rods was 2 cm. These dimensions allowed to obtain a good impedance mismatch with respect to the 50 Ω impedance, and also allowed to use standard adapters to fabricate the probe.

B. Methods

To verify the practical feasibility of the proposed system, the construction materials were moistened at progressively higher reference gravimetric water content levels, θ_{ref}. To achieve the pre-established θ_{ref} values, first, each material sample was dried in an oven. Then, water was weighed through an electronic balance (with an uncertainty of 0.1 g), and added to the material under test. Material and water were then mixed, so as to ensure a homogeneous water content level. The percentage gravimetric water content of the moistened sample was calculated as

$$\theta_{\text{ref}} = \frac{W_{\text{wat}}}{W_{\text{tot}}} \cdot 100 \tag{3}$$

where W_{wat} is the weight of the added water, and W_{tot} is the total weight of the mixture.

For each value of θ_{ref} and for each material, TDR measurements were repeated ten times. As detailed in the following section, this strategy allowed to evaluate the confidence level for the calibration curves.

IV. EXPERIMENTAL RESULTS

Before proceeding with the water content measurements, the first step was to carry out the probe-length calibration [35], as the actual length of the probe (L_{act}^P) may be slightly different from the length measured with a tape. This is mostly due to the presence of the probe-head, which is used to assemble the probe and provide mechanical stability; in fact, a small portion of the rods is contained inside the probe-head and, if not properly compensated for, this could lead to the presence of an offset error. Hence, the need to carry out the probe-length calibration and compensate for this offset error. This procedure is performed only once for the probe.

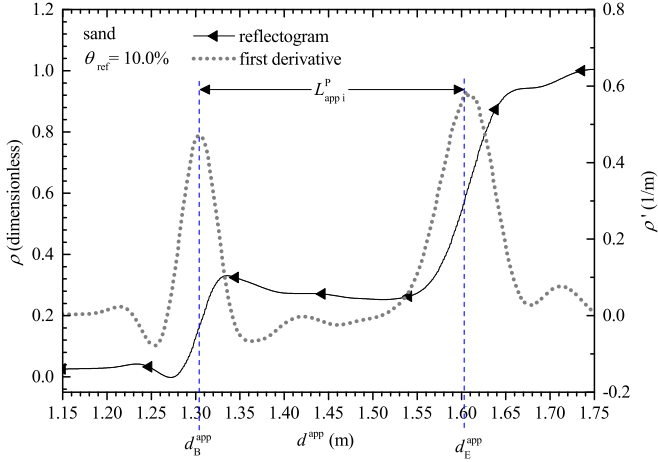As reported in [36], the probe-length calibration consisted

Fig. 2. TDR reflectogram and first derivative, for sand, for $\theta_{\rm ref}$ = 10.0%. The abscissae corresponding to the beginning and to the end of the probe are also indicated.

Fig. 3. TDR reflectograms acquired for sand, for increasing values of $\theta_{\rm ref}$.

in carrying out ten repeated measurements with the probe inserted into materials with well-known dielectric permittivity (namely, air and deionized water). The actual value of the probe length was $L_{\rm act}^{P}$ = 10.59 cm ± 0.25 cm.

After the probe-length calibration, TDR measurements were carried out on the construction materials as described in Section III.

For each considered value of $\theta_{\rm ref}$, ten repeated TDR measurements were peformed. For each acquired reflectogram, the value of the corresponding apparent length of probe, $L_{\rm app,i}^{P}$, was evaluated through the so-called derivative method [36]; in fact, the derivative of the TDR reflectogram typically exhibits prominent peaks in correspondence of the probe-beginning and probe-end sections. In particular, the value of $L_{\rm app,i}^{P}$ was evaluated by identifying the peaks of the derivative corresponding to the beginning (B) and to the end (E) of the probe:

$$L_{\rm app,i}^{P} = d_{E}^{app} - d_{B}^{app} \qquad (4)$$

For the sake of example, Fig. 2 shows one of the 10 reflectograms acquired for sand, for $\theta_{\rm ref}$ = 10.0%; the apparent length of the probe, $L_{\rm app,i}^{P}$, is also indicated.

For each $\theta_{\rm ref}$, the ten measured values of $L_{\rm app,i}^{P}$ were averaged, and the corresponding $\varepsilon_{\rm app}$ was evaluated by applying (1):

$$\varepsilon_{\rm app} = \left(\frac{\frac{1}{10} \sum_{i}^{10} L_{\rm app,i}^{P}}{L_{\rm act}^{P}} \right)^{2} \qquad (5)$$

Fig. 3 shows the reflectograms acquired for sand, moistened at progressively higher level of $\theta_{\rm ref}$. It should be mentioned that the abscissa corresponding to the end of the probe, d_{E}^{app}, coincides with the second inflection point on the reflectogram. This point shifts towards higher abscissae values as $\theta_{\rm ref}$ increases. This leads to a progressive increase of $L_{\rm app}^{P}$, which corresponds to the increase of the distance between the two flex points on the reflectogram.

Fig. 4(a) shows the dispersion of the $\theta_{\rm ref}$-$\varepsilon_{\rm app}$ measurement points as evaluated, for sand, from the TDR measurements. As expected, as water content increases, also the value of the
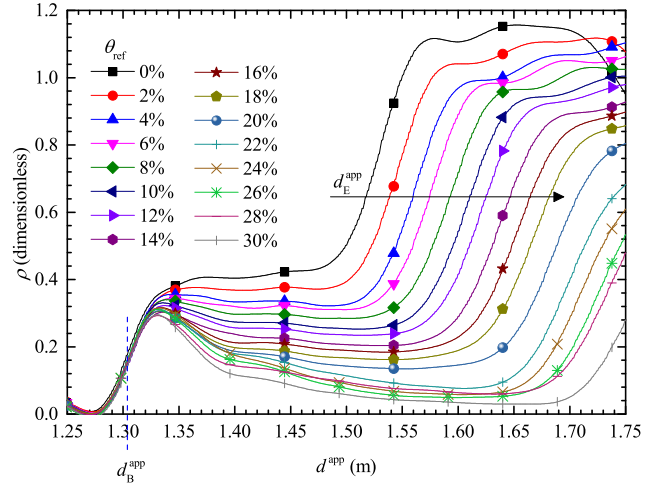
apparent dielectric permittivity generally increases.

The $\varepsilon_{\rm app}$-$\theta_{\rm ref}$ measurement points were then fitted through a third-order polynomial equation as reported in Section III [37]. However, when fitting the measurement points through the third-order polynomial described by (2), the resulting values of the coefficients B_2 and B_3 were more than two orders of magnitude lower than the coefficients B_0 and B_1. This suggested that, for sand, the empirical relationship followed a linear-like trend; therefore, the measurement points were fitted through a linear equation. Fig. 4(a) shows the obtained calibration line: the linear trend of the calibration curve for sand is attributable to the fact that the fine grains allowed an easier diffusion of the added water.

In practical applications, once the calibration curve is obtained, it suffices to evaluate the $\varepsilon_{\rm app}$ value and to infer the corresponding value of θ from the calibration curve.

The same procedure described so far for sand was carried out also for the other two construction materials. Fig. 4(b) and Fig. 4(c) show the dispersion of the measurement points and the calibration curve, for grey cement and white cement, respectively. It can be seen that, for both these types of cement, a third-order polynomial suitably fits the measurement points. For the sake of direct comparison, the three calibration curves are reported in Fig. 4(d).

Table I summarizes the calibration equations for the three types of materials.

A. Confidence interval evaluation

In order to characterize the extrapolated values of θ from a metrological point of view, the associated uncertainty was evaluated through the nonlinear regression theory [38]. The variance analysis for the single values expected from the calibration curve equations was carried out through the following equation:

$$var[\theta] = \sigma^2 \left(1 + \frac{1}{n} + \sum_i \left(\frac{\partial \theta}{\partial B_i} \right)^2 var[B_i] + 2 \sum_{i,j} \left(\frac{\partial \theta}{\partial B_i} \frac{\partial \theta}{\partial B_j} \right) cov[B_i \right. $$
$$(6)$$

TABLE I
CALIBRATION EQUATIONS FOR THE CONSIDERED MATERIALS

material	calibration equation	R-square
sand	$\theta(\%) = -6.116 + \varepsilon_{app} \cdot 2.504$	0.98899
grey cement	$\theta(\%) = -43.724 + 18.850 \cdot \varepsilon_{app} - 2.090 \cdot \varepsilon_{app}^2 + 0.086 \cdot \varepsilon_{app}^3$	0.97568
white cement	$\theta(\%) = -28.450 + 11.403 \cdot \varepsilon_{app} - 1.036 \cdot \varepsilon_{app}^2 + 0.034 \cdot \varepsilon_{app}^3$	0.97970

where $var[\theta]$ is the variance of the water content level; σ^2 is the variance between experimental and fitted data; n is the number of experimental points; $i, j = 0,1,2,3$ refer to the subscripts of the regression curve coefficients; and $cov[B_i, B_j]$ is the covariance between B_i and B_j parameters.

For a confidence level of 95%, the equations associated to the upper and lower confidence limits for the regression curve are given by the following equations:

$$L_{up} = (B_0 + B_1\varepsilon_{\mathrm{app}} + B_2\varepsilon_{\mathrm{app}}^2 + B_3\varepsilon_{\mathrm{app}}^3) + t_{\mathrm{n}-4,1-\frac{\alpha}{2}}\sqrt{var[\theta]}$$

$$\tag{7}$$

$$L_{low} = (B_0 + B_1\varepsilon_{\mathrm{app}} + B_2\varepsilon_{\mathrm{app}}^2 + B_3\varepsilon_{\mathrm{app}}^3) - t_{\mathrm{n}-4,1-\frac{\alpha}{2}}\sqrt{var[\theta]}$$

$$\tag{8}$$

where α is the significance level (5%).

The same procedure was applied for each of the considered materials. Fig. 5(a), Fig. 5(b) and Fig. 5(c) show the calibration curves and the 95% confidence intervals for sand, grey cement and white cement, respectively.

It should be mentioned that the differences from the results reported in [6] are due to the fact that, although the considered materials belong to the same category of cements (white and grey), their origin and composition is different (in particular, the white cement considered herein is specific for hindering rising damp phenomenon in walls); hence, the diverse behaviour in the calibration curve. These results allowed to verify the referability of the confidence interval for the different materials and confirmed that the obtained calibration curve represents a signature of the specific material.

B. Considerations on practical implementation

In practical applications, by measuring the $\varepsilon_{\mathrm{app}}$ of each material before it is poured into the concrete mixture, the corresponding θ and the associated confidence interval could be retrieved from the calibration curve. In this way, knowing the intrinsic water content of each material, the appropriate amount of water could be added to the concrete mixture, thus achieving the desired water-to-cement ratio.

Fig. 6 shows the steps for the possible industrial implementation of the system. The system would require two phases: a preliminary one (to be carried off-line once), followed by the use of the system.

More specifically, first, the calibration equations should be identified for each of the considered raw materials. The obtained calibration equations could be implemented in a management software to be used for the subsequent in-line, water content monitoring.

After this preliminary phase, the intrinsic water content of each single component could be evaluated in-line by using the calibration equations.

The obtained water content results could be used to evaluate the water amount that needs to be added in order to achieve the desired w/c ratio. Finally, the concrete mixture could be prepared and sent to the construction sites.
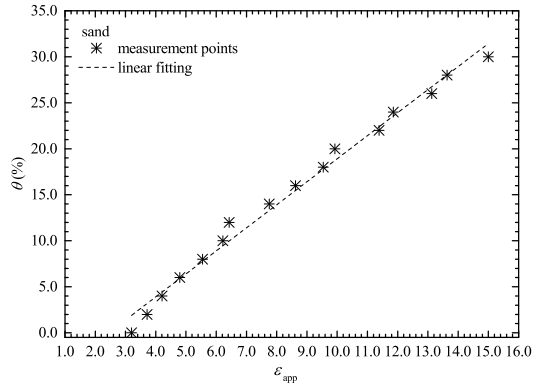
It should be mentioned that some TDR instruments allow the use of multiplexers (for instance, the TDR100 allows multiplexing up to 512 probes); therefore, a single measurement instrument could be used to control simultaneously several probes inserted for example either in one big container or even in different containers, with a substantial reduction of implementation costs.
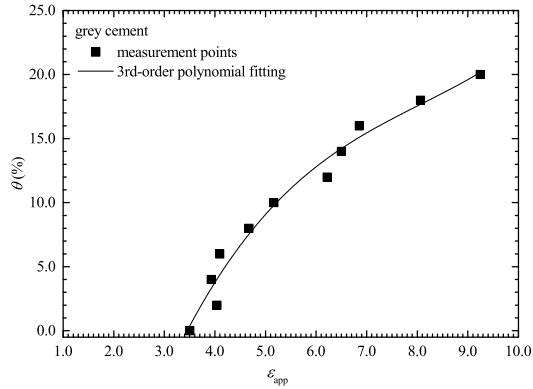
V. CONCLUSION

In this work, a TDR-based system for monitoring water content in construction materials was presented. The proposed system resorts to the evaluation of the moisture content from TDR measurements of the apparent dielectric permittivity of the material under test.

To assess the adequacy of the system for construction materials, measurements were carried out on three types of construction materials, and the corresponding calibration curves were derived. The proposed system is flexible and adaptable to the operating conditions also along the concrete production line. The calibration curves can be integrated within a management software, and used to automatically retrieve the value of moisture content directly in-line.
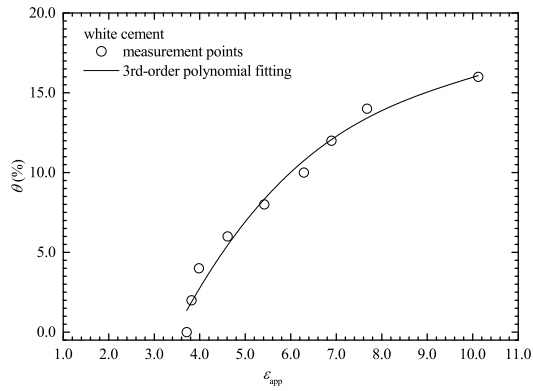
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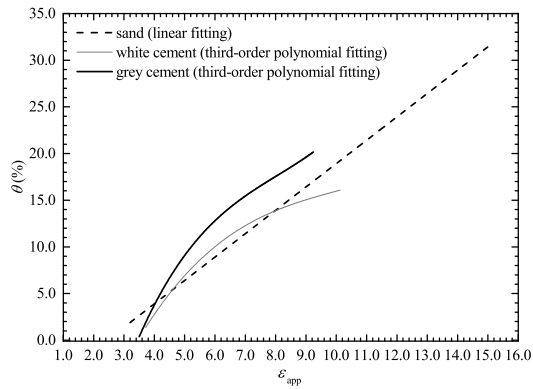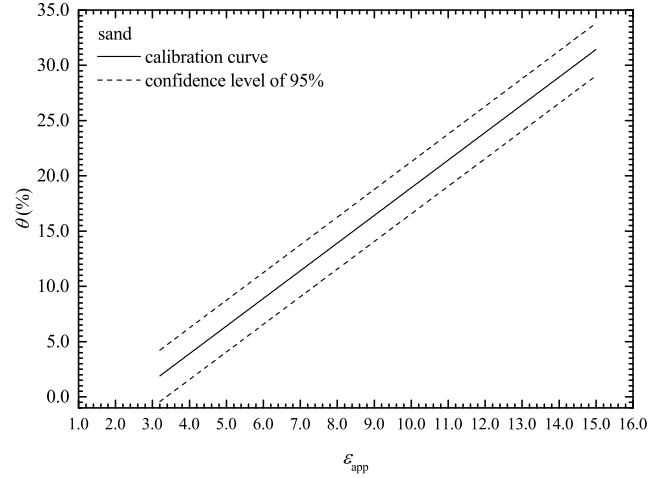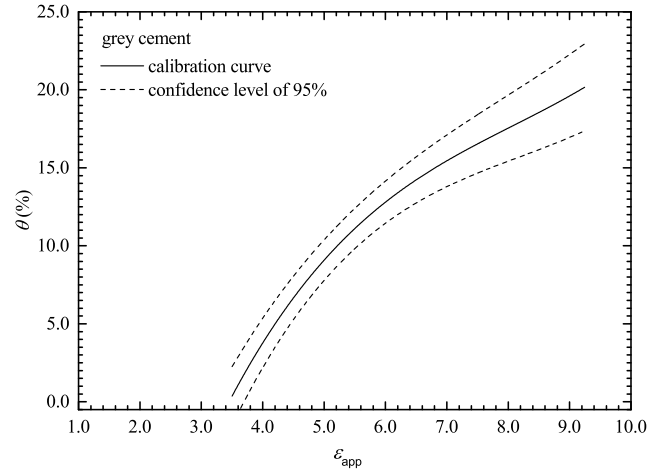
Fig. 4. Dispersion of the averaged θ_{ref}-$\varepsilon_{\mathrm{app}}$ calibration curves for sand (a), grey cement (b), and white cement (c). Direct comparison of the three calibration curves (d).
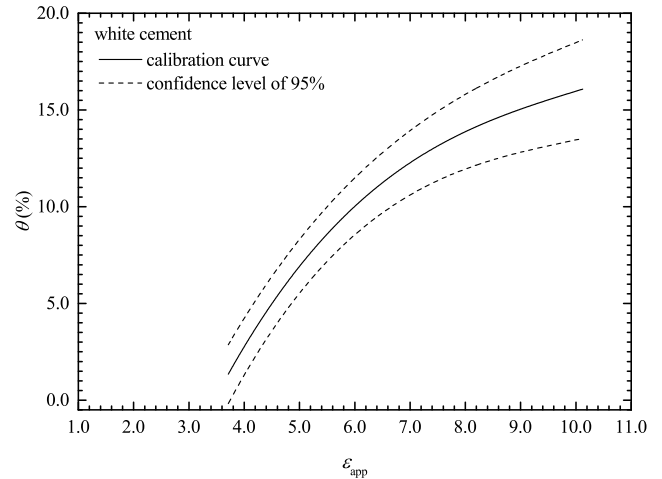

Fig. 5. Calibration curves and 95%-confidence interval for sand (a), grey cement (b) and white cement (c).
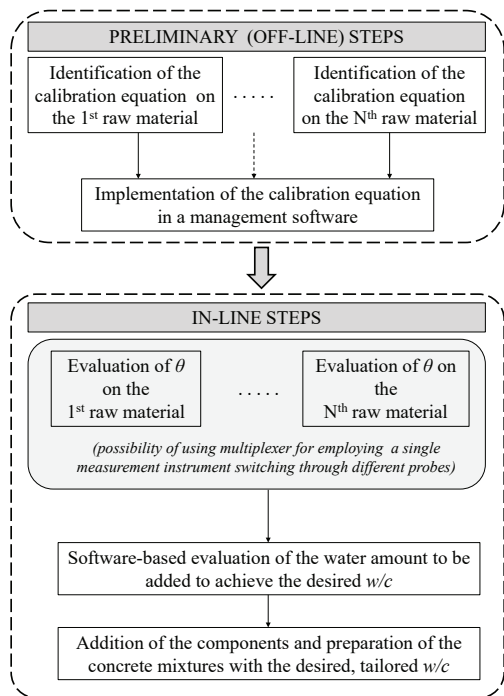
Fig. 6. Steps for the practical use of the proposed monitoring system.

In this way, measuring the intrinsic water content of materials before they are mixed would allow to compensate the intrinsic water content (absorbed, for example, from the environment) with the addition of the exact amount of water that is necessary to achieve the desired w/c ratio.

Finally, the proposed system could also be employed to monitor the water content of construction material inline, throughout the manufacturing process, thus guaranteeing that final product will exhibit the desired properties.

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