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Introduction of flat ribbon cable (FRC) sensor for density measurement of road materials using time domain reflectometry (TDR)

Mesure de la densité de matériaux routiers. Utilisation de la reflectométrie temporelle avec une ligne de transmission plate.

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ABSTRACT: Moisture content and density of unbound granular pavement materials are important properties for compaction control providing a great influence on pavement performance. Time domain reflectometry (TDR) usually uses rod probe sensors, which can provide pointwise readings of density. However, pointwise readings might not be representative enough for a complete road section. This paper introduces the application of flat ribbon cable (FRC) sensor, which can be extended up to 6 meter to measure moisture and density of road materials. Soil specific calibration is done in the laboratory considering the variation of moisture and density of materials where sensors of three different lengths are considered to enable the development of length normalized calibration. The electric parameter used to derive soil density is the voltage drop, which occurs after the passage of an electromagnetic wave along the sensor embedded in the soil. Soil moisture is related to the permittivity of the soil sample, which is obtained from the travel time of the TDR signal. Laboratory results indicate that calibration functions are independent of moisture and density. These soil specific calibration functions are useful in measuring long term pavement performance and managing rutting of roads.

RÉSUMÉ : La teneur en eau et la densité des matériaux de revêtement granulaires non liés sont des paramètres importants pour le contrôle de la compaction qui a une influence importante sur la performance de la chaussée . La reflectométrie temporelle (TDR) utilise généralement des sondes multi-tiges qui peuvent fournir des lectures ponctuelles de densité. Cependant, les lectures ponctuelles pourraient ne pas être suffisamment représentatives pour une section de route complète, Cet article introduit l'application d'un une ligne de transmission plate (FRC) qui peut être étendue jusqu'à 6 mètres pour mesurer la teneur en eau et la densité des matériaux routiers. L'étalonnage spécifique des capteurs, trois capteurs de longueurs différentes sont considérés, est effectué en laboratoire en tenant compte de la variation de teneur en eau et de la densité des matériaux cibles. Le paramètre électrique utilisé pour calculer la densité du sol est la chute de tension qui se produit après le passage d'une onde électromagnétique le long du capteur installé dans le sol. La teneur en eau du sol est liée à la permittivité electrique de l'échantillon de sol qui est obtenue à partir du temps de vol du signal TDR. Les résultats obtenus en laboratoire indiquent que les fonctions d'étalonnage sont indépendantes de l'humidité et de la densité Ces fonctions d'étalonnage propres au sol sont utiles pour mesurer les performances à long terme des chaussées et pour gérer les ornières des routes.

KEYWORDS: Density, road material, flat ribbon cable sensor, time domain reflectometry.

1 INTRODUCTION.

Material properties contributing to pavement performance are significantly influenced by moisture content and density. Particularly in post construction period, when the moisture content changes, changes in density might be accelerated under cyclic loading resulting in permanent deformation (rutting). Although, plenty of studies focus on determination of in-situ moisture content using TDR method (Topp et al. 1980, Baran E. 1994, Ekblad and Isacsson 2007), very few researchers put their attention in density measurement (Siddiqui and Drnevich 1995, Drnevich et al. 2003, Yu and Drnevich 2004, Jung et al. 2013, Bhuyan et al. 2017) providing an additional information at the place of observation. However, this local measurement might not be representative for a complete road section, and several sensors would be needed to be able to provide an overall picture. Furthermore, one needs to keep in mind, that the interconnection between changes in density of unbound road materials due to cyclic loading in flexible pavements and the role of moisture has not been studied yet.

In this study, laboratory investigations with FRC sensors are presented aiming at the development of calibration functions for measuring both, moisture and density. An important aspect in this connection is the independence of these functions from the length of the used sensor.

2 MATERIALS AND METHODS

Unbound granular (UBG) road base material is normally used as a base or sub-base material in road construction. In this study, UBG material is used as testing material to investigate the suitability of FRC sensors for measuring moisture and density. The material was manufactured at a quarry in South-East Queensland to the C grading classification according to MRTS05 (UBG, DTMR, 2015). The sample was manufactured using a fine-grained contact metamorphic source rock of hornfels origin. Primary mineralogy of the rock consists of 32 to 58% feldspar, 6 to 13% quartz, 4 to 19% microcrystalline feldspar, 3 to 6% epidote and 1 to 4% calcite. Moreover, the sample has roughly a volume of 26% soft, deleterious minerals including 15 to 21% biotite mica, 3 to 6% sericite, 1 to 4% limonite, 1 to 4% chlorite and trace amounts of pyrite.

The optimum moisture content (OMC)-maximum dry density (MDD) relationship and Atterberg limits were determined in accordance with the DTMR Material Testing Manual 2014. The OMC of the material was determined as 8.3% with the MDD value of 2160 kg/m^3. The fine fraction of the sample had a liquid limit of 22.6%, plasticity index of 5.0% and linear shrinkage of 5.0%.

2.1 Preparation of Calibration Box and FRC sensors

The laboratory calibration box was constructed of 14 mm thick polyvinyl chloride (PVC) with internal dimensions of 557 x 155 x 159 mm (length x width x height). The box was placed within a steel frame during sample compaction and removed from the frame prior to testing to avoid the influence of the imposed electromagnetic wave pulse. The UBG material was compacted within the calibration box in three horizontal layers. The electromagnetic field does not exceed 30 mm and thus is not influenced by the walls of the calibration box (Suwansawat, S., and Benson 1999) as the distance between sensor and box was 55 mm for all experiments. Moreover, the sensors were placed horizontally in between layers with thicknesses of the top and bottom UBG layers of approximately 50 mm.

In order to take into account the influence of the length of the sensor on the propagation of an electromagnetic wave, FRC sensors of three different lengths (12 cm, 24 cm, and 40 cm) were prepared as shown in figure 1. Details of the sensor preparation and working methodology of the FRC sensor can be found in Scheuermann et al. (2009).

Figure 1. FRC sensors of three different lengths 12 cm, 24 cm, and 40 cm with black boxes to secure transition from coaxial cable to FRC

2.2 Soil compaction in calibration box

The soil sample is compacted in the box in three horizontal layers. Initially, a 50 mm horizontal layer of soil is compacted and two sensors (12 cm and 24 cm) are placed upon the soil layer as shown in Figure 2(a). Afterwards, another 50 mm horizontal layer of soil is compacted and the third sensor (40 cm) is placed upon the soil layer as given in Figure 2(b). Finally, the last horizontal layer with a thickness of 50 mm of soil is placed and compacted upon the sensors and the system becomes ready for TDR measurements.

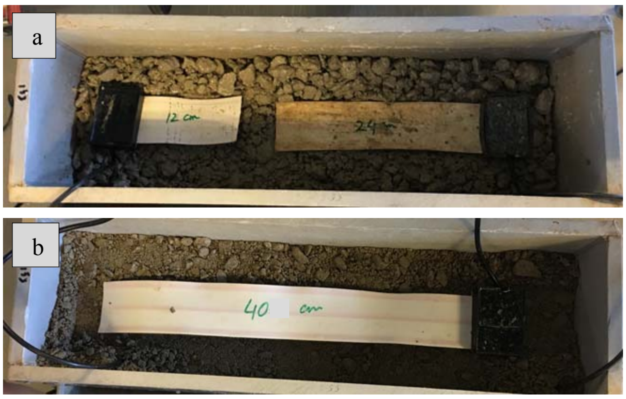

Figure 2. Placement of (a) 12 cm and 24 cm sensors after first layer compaction and (b) 40 cm sensor after compaction of second layer

2.3 Observation of TDR measurements

Based on the compaction curve defining the optimum moisture content and maximum dry density of the material, different moisture and density variations have been considered in the experiment. In one set of measurements, the moisture varied from 4% to 10%, while keeping the density fairly constant. In another set, the density ranged from 8% to 100% of maximum dry density while keeping the gravimetric moisture content as constant as possible. In both cases, volumetric moisture content increases with increasing gravimetric moisture content as well as dry density of the material. Results of TDR measurements are presented in figure 3(a) and 3(b) for the 40cm long FRC sensor.

The TDR wave pulse – also called TDR trace – represents normalised voltage reflections and is measured in time. It is comprised of multiple reflections, dielectric dispersion as well as attenuation from the conductive loss of the surrounding material and cable resistance (Chen et al. 2009). The TDR trace significantly changes at two locations measured at different times. The first change occurs at the transition of the coaxial cable to the FRC sensor marking the starting point of the sensor (point A in figure 3(a)) where the reflection increases due to impedance mismatch. The second change happens at the end of the FRC sensor marked as point B showing the overall loss of voltage along the length of the sensor where the TDR trace reaches the lowest reflection. The peak value of the reflection at the starting point of the 40 cm sensor for 8.5% moisture and 100% density is termed V1 whereas the overall voltage loss from point A to point B of the sensor is termed as V2 (see figure 3b). The combination of V1 and V2 represents the dimensionless reflection coefficient representative for the complete sensor. V1 and V2 can easily be identified in the TDR trace. As can be seen in figures 3(a) and 3(b), the overall voltage loss V2 increases significantly with increasing dry densities as well as moisture contents.

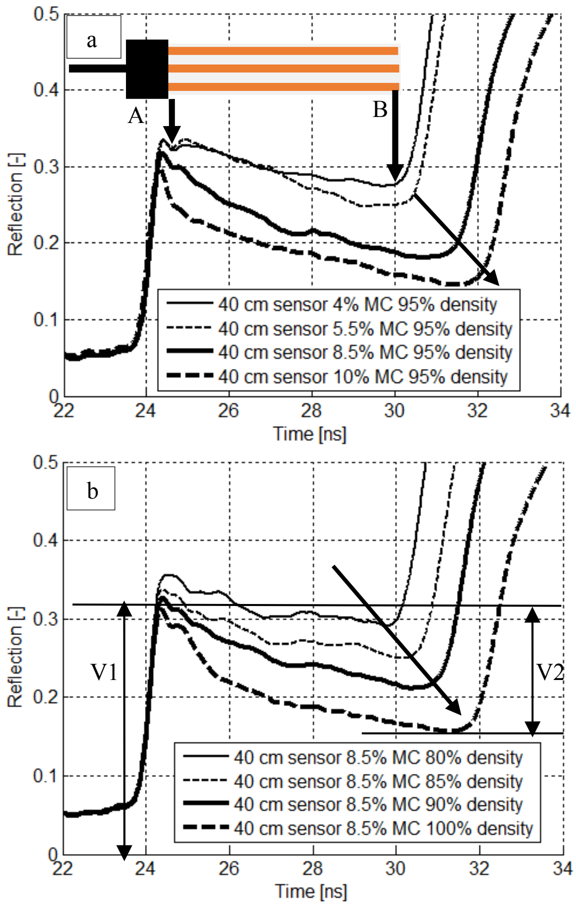

Figure 3. Variation of TDR traces for (a) varying moisture content while density is kept constant and (b) varying density while moisture content is kept constant

3 DATA ANALYSIS AND RESULTS

3.1 Effect of sensor length on TDR measurements

Figure 4 shows the variations in TDR traces with constant moisture content and density where longer sensors show a higher voltage loss compared to shorter sensors. This observation shows that the sensor length has a significant effect on the overall voltage loss. As changes in parameter V2 with changing material properties are considerably larger compared to V1 (see figures 3a and 3b), V2 basically determines the normalized voltage ratio, (V2/V1). Figure 5 shows the voltage ratio over the sensor length for different moistures and constant density. It is found that the ratio V2/V1 shows a linear relationship with the length of the sensor. From this perspective, it can be stated that the overall voltage drop changes significantly not only for changing material properties but also sensor length. As a consequence, the sensor length needs to be considered together with the material properties in the development of a calibration function for calculating density.

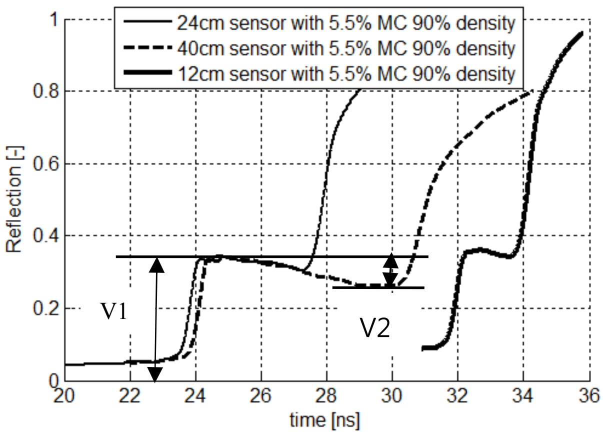

Figure 4. Variation of TDR pulses for varying sensor length while density and moisture are kept constant

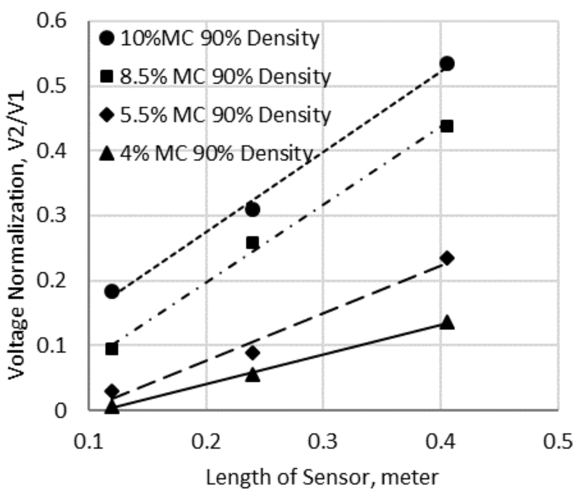

Figure 5. Voltage ratio V2/V1 over the length of the sensor

3.2 Permittivity Calculation

The TDR trace can easily be analyzed to obtain the travel time of an electromagnetic wave along the sensor. TDR traces become wider with increasing moisture as well as density (figure3a and 3b). It basically means that the electromagnetic wave requires more time to travel along the sensor. Starting and ending point of the sensor can be located within the TDR trace with tangents drawn as shown in figure 6. The time between the intersection points of the tangents constructed at the starting and ending point of the TDR trace is termed travel time. Detailed information about the tangent method can be found in Bhuyanet al. (2017). The travel time is then used to determine the so-called capacitance, which can be recalculated into the permittivity with suitable capacitance models representing the electric characteristics of the sensor (Scheuermann et al. 2009).

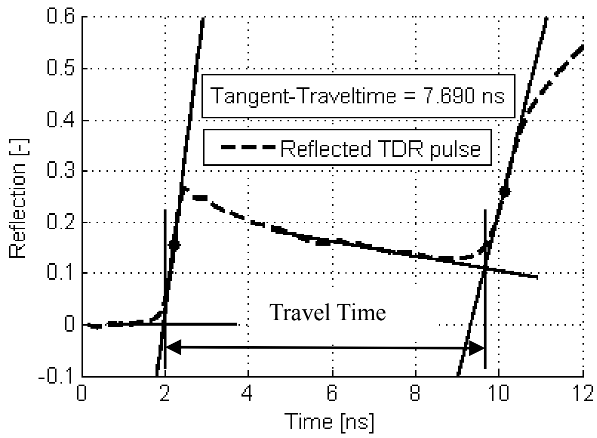

Figure 6. Travel time calculation using tangent method

3.3 Development of Calibration function

Four parameters or parameter combinations are considered in empirically developing the calibration function. Voltage drop, densities of water and soil, permittivity and length of sensor. Since the voltage drop is influenced by the bulk density of the soil, it seems to be obvious to relate the voltage ratio with the bulk density and the density of water to create the dimensionless number (V2/V1)*(ρw/ρb) named as voltage and density normalization. The permittivity is dominated by the water content and independent of the sensor length. The overall voltage loss, however, is strongly dependent of the sensor length. Therefore, as a first step (V2/V1)*(ρw/ρb) is plotted against the permittivity multiplied by the length of sensor. The plot shows a linear relationship with a good regression coefficient forming the basis for the calibration function (figure7).

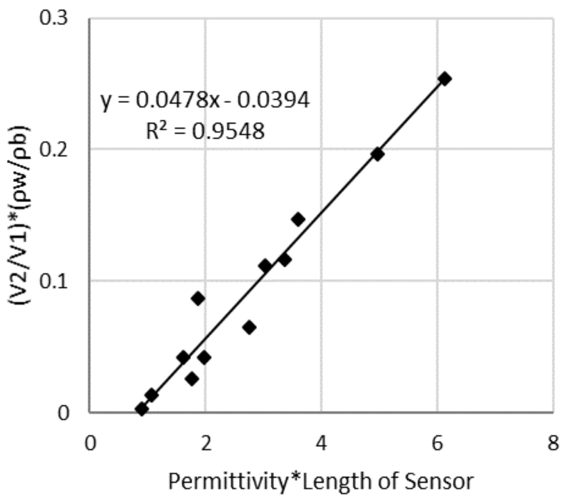

Figure 7. Development of calibration function using normalization concept

3.4 Calculation of bulk density

The calibration function to calculate bulk density can be written as follows:

$$(V2/V1)\times(\rho_w/\rho_b) = 0.0478\times\varepsilon\times L - 0.0394 \quad (1)$$

Equation (1) can be rewritten in the following form as equation (2) to obtain bulk density directly when the voltage normalization (V2/V1), density of water (ρ_w), Permittivity (ε), and length of sensor (L) are known from TDR measurements.

$$\rho_b = \frac{(V2/V1)*\rho_w}{0.0478*\varepsilon*L - 0.0394} \quad (2)$$

When density is obtained, it is easy to calculate moisture content using volumetric water content and density relationship (discussed in detail by Bhuyan et al., 2017).

3.5 Laboratory Justification

A different set of data was prepared for validating the density calibration function. In these experiments, density variation range from 80% to 100% of MDD, and three different sensors have been considered. The 1-1 line is drawn to visualize the correlation which shows that most of the points fall very close to the 1-1 line. A simple statistical analysis shows that the percent error is approximately 3.5% between calculated and measured values.

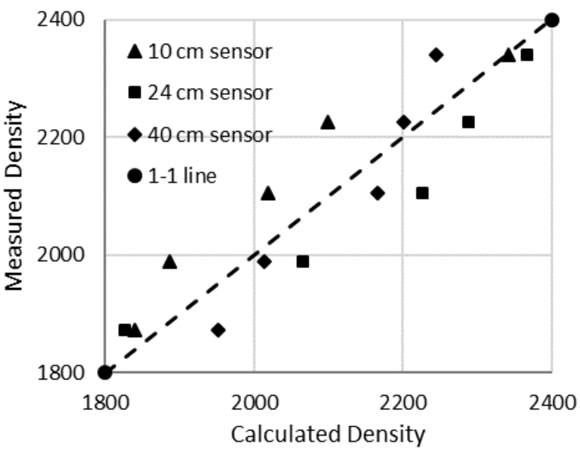

Figure 6. Comparison of laboratory measured values with calculated densities obtained from TDR measurements.

4 CONCLUSIONS

The use of FRC sensors for measuring density of road materials is new and offers multiple potential applications in geotechnical engineering. Although, rod probe sensors are capable of measuring density at single points, the use of FRC sensors has the potential to provide a more representative average value along the sensor. In the presented paper, laboratory experiments have been conducted to develop a calibration function for calculating an average value of density along the sensor.

The overall voltage drop along the sensor changes significantly not only for changing material properties as moisture and density, but also with changing length of the sensor. Because of this reason, the length of the sensor needs to be included in the calibration function. The calibration function developed within this study includes the densities of the bulk soil and water, as well as permittivity and voltage loss.

The calibration function was tested with another set of measurements showing a satisfactory agreement between calculated and measured densities. In future investigations, FRC sensors will be installed in real roads and laboratory wheel tracker experiments to investigate their performance for transiently changing density conditions. Potentially, these sensors will provide useful information to optimize the management of roads and to minimize rutting.

5 ACKNOWLEDGEMENTS

This work was funded by a Queensland Science Fellowship awarded to Alexander Scheuermann. The support through the Department of Transport and Main Roads and Australia Road Research Board is appreciated.

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