Time Domain Reflectometry Measurements of Road Basecourse Moisture Content

Experimental Results

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Abstract—**This paper describes an empirical transform between the propagation time (tp) data obtained from a non invasive Time Domain Reflectometry (TDR) sensor to the percentage moisture content θ_v within two different road making basecourse aggregate material. Results show that a simple quadratic fit between t_p and θ_v can be given leading to a maximum error in the estimate of 0.55%. It is also shown that the dielectric model underlying each of the basecourses is different enough to warrant the use of a unique quadratic function (i.e. different quadratic coefficients) for each.**

Keywords-component; TDR; road; basecourse; dielectric; moisture content;

I. Introduction

The most important factor in determining the integrity of road structure is the amount of water within its basecourse . The moisture content within the basecourse has considerable influence on its mechanical properties both during and after its construction. For example, before the top seal is laid the basecourse material is compacted to maximize its dry matter density. For a particular aggregate type this maximum dry matter density will only occur at a specific value of material moisture content (e.g. for one of the aggregates tested here "Belmont aggregate" the optimal level of moisture content is 5.1% by volume). Deviations from this value degrade the overall performance of the road structure so it is important to determine its value (to within 0.1 – 0.2%) and adjust if necessary. Once the road is complete there is a continual risk of structural failure due to the ingress of water from external sources (e.g. flooding, creeks, cracked pipes, cracks and defects in the surfacing etc) weakening the cohesion. Detection of excess water in the basecourse before major damage occurs – leading to surface collapse – is clearly useful and a large amount of effort is expended upon this by road authorities worldwide. By far the most common method of inspection is to dig a section of the road up and have a look, an expensive, spatially limited and often inaccurate method. Some more accurate methods for moisture measurement and the closely related compaction, such as nuclear densitometers (e.g.) also exist, but again these have limitations on deployment.

We have developed a non-invasive method for determining the moisture content of a roads basecourse during all phases of its construction and operational life by using Time Domain Reflectometry (TDR) . The TDR sensor has the ability to image variation in the volumetric moisture content, θ_v and determine its value over large areas by using a pair of portable transmission lines on the road surface (Fig. 1). Measurements are made by exploiting the changes in amplitude, A_p and propagation time, t_p, of a pulse travelling down the lines caused by its interaction with the polarization charge of the water molecules . The material relative permittivity, ε_r is obtained from t_p via an inverse optimization procedure with an empirical model used to convert this ε_r to the required θ_v. The process is illustrated in equation (1) where *f* is the theoretically derived transmission line function and thus has the same form for every sample material and *g* is the dielectric model that is usually derived empirically and thus may vary for each material.

$$\boldsymbol{t_p} \xrightarrow{f^{-1}} \boldsymbol{\epsilon_r} \xrightarrow{g} \boldsymbol{\theta_v} \qquad (1)$$

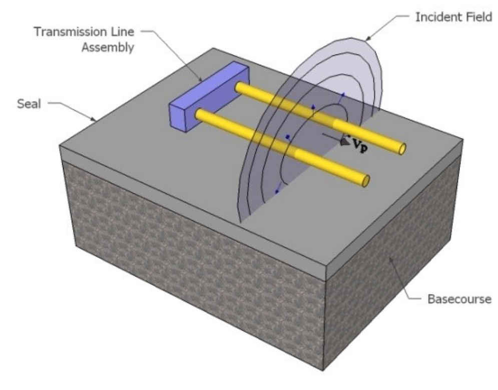

Figure 1 TDR sensor above road surface - the incident field generated by the pulse interacts with water below the surface which decreases both the amplitude and propagation time of the pulse.

While it is known that different materials (e.g. soil mixtures) will often require different empirical models the extent of the variation, if any, between aggregate varieties commonly used for basecourse construction is unknown.

This paper presents the results of recent tests[1] performed using the TDR system to; a) determine if the non-invasive TDR system can be used to measure the volumetric water content of the road basecourse, b) empirically determine a composite function of the form:

$$\boldsymbol{\phi} = \boldsymbol{f}^{-1} \circ \boldsymbol{g} \qquad (2)$$

that can be used to transform the measured propagation time t_p directly to the volumetric moisture content θ_v (i.e. $t_p \rightarrow \theta_v$) and c) how much the form of this composite function varies for different basecourses and finally d) an assessment of the error involved in the process.

II. Experiment

A. Preparation and Procedure

Two greywacke basecourse mixes commonly used in New Zealand were chosen for the test; Belmont aggregate and Pound Road aggregate named after their quarry source. To accommodate the aggregate during test six metal bins were constructed with dimensions 1195 x 530 x 400 mm, providing a minimum aggregate depth of 300 mm and sufficient room for the sensor placement, Fig. 2.

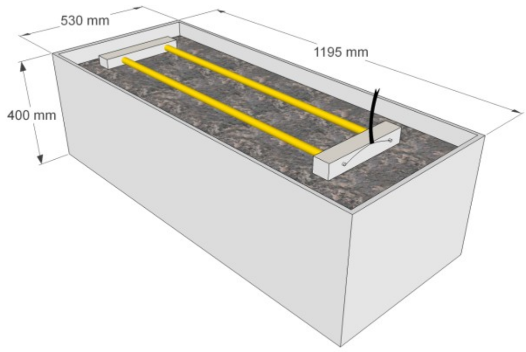

Figure 2. TDR sensor in position over packed aggregate specimen. Note that the transmission lines have length 1000 mm with spacing between them of 200 mm.

The Belmont aggregate was prepared with 6 different moisture contents and packed into each of the bins. The TDR transmission lines were then placed at a height of 5 mm over the aggregate sample in each bin and a measurement of pulse propagation time t_p taken. Reference moisture contents were made immediately after the TDR measurements by taking two samples from the top 100 mm and two samples from about 100 mm from the bottom of each specimen bin and oven drying (105°C) until constant weight was obtained (typically 48 hrs).

The same procedure was then performed on the Pound Road aggregate.

B. Results

The results of the above procedures are shown for the Belmont aggregate in TABLE 1 and for the Pound Road aggregate in TABLE 2. In both cases the oven dried moisture content (θ_v) values for the top and bottom samples are averaged with the TDR measured propagation time the average of 3 readings with identical setup.

TABLE 1. RESULTS FOR THE BELMONT AGGREGATE

Box Number	**θ_v Top** from drying	**θ_v Bottom** from drying	**TDR measured $t_{p\ ns}$**
1	3.1	3.3	1.45
2	3.1	2.8	1.41
3	2.3	1.8	1.36
4	3.6	4.5	1.51
5	5.5	5.8	1.59
6	4.9	5.9	1.52

TABLE 2. RESULTS FOR THE POUND ROAD AGGREGATE

Box Number	**θ_v Top** from drying	**θ_v Bottom** from drying	**TDR measured $t_{p\ ns}$**
1	0.4	0.4	1.36
2	3.7	4.4	1.43
3	6.2	4.5	1.55
4	5.0	5.3	1.51
5	3.5	3.4	1.51
6	4.4	6.2	1.47

For the TDR transmission line dimensions used here (i.e. length = 1000 mm, line radius r = 7.6 mm, separation between the lines of d = 200 mm) the effective penetration depth of the incident electric field over which the integrated moisture content can be determined is approximately 100 mm. Consequently only the θ_v reference measurements from the top 100 mm of each bin are used for constructing the required composite function defined by equation (2).

[1] Tests conducted through October – November 2013 at Opus Research Labs, Wellington New Zealand

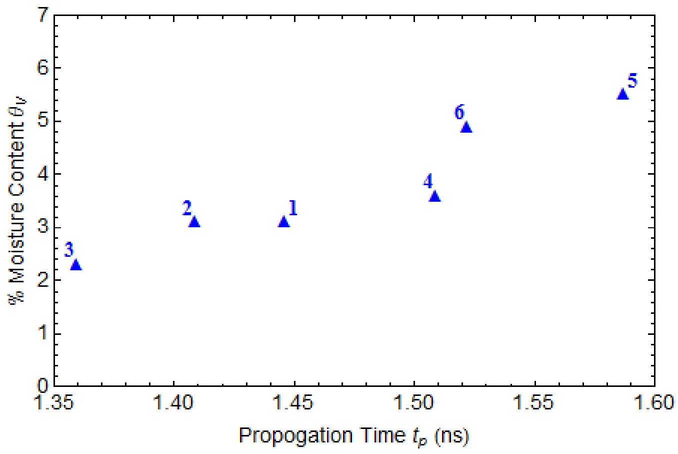

Figure 3. Plot of t_p vs θ_v for the Belmont aggregate. The number of the box corresponding to each point is annotated in the plot.

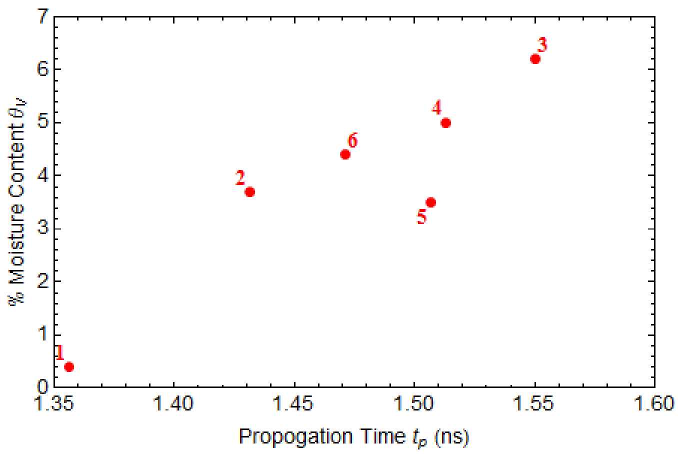

Figure 4. Plot of t_p vs. θ_v for the Pound Road aggregate. The number of the box corresponding to each point is annotated in the plot.

Fig. 3 and Fig. 4 show a plot of θ_v (top) vs. t_p of TABLE 1 and TABLE 2 respectively. There are a couple of points to note from these two figures. Firstly, in Fig. 3, there is obviously some discrepancy in either the measured value or the propagation time for boxes 1 and 2. It is likely that the measured value of θ_v is not representative here since the measurements of t_p with height are very consistent arguing against a random error in this measurement. Secondly, the box 5 value in Fig. 4 for either t_p or measured θ_v is likely to be incorrect since it is an outlier (for fitting purposes) to the reset of the data and consequently it will not be included in analysis of the data set.

III. Interpretation of Results

Fig. 5 shows a least squares quadratic function of the form

$$\phi(t_p) = A\, t_p^{\,2} + B\, t_p + C \qquad (3)$$

independently fitted to each of the data sets of Fig. 3 and Fig. 4.

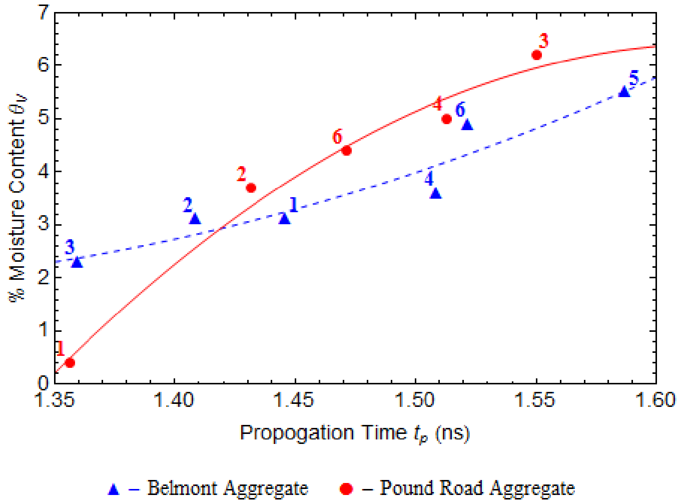

Figure 5. Best fit quadratic function for Belmont ϕ_B and Pound Road ϕ_P aggregate. Note bin 5 is not included for the Pound Road aggregate fitting.

Note that while an attempt was made to fit different polynomial forms to the data, the quadratic provided the best fit and of course the greatest stability. It is also close to the form other dielectric models for soils follow over the regions of interest for this work (i.e. θ_v between 0% - 20%).

Evident from Fig. 5 is that the t_p measurements from the TDR system are consistent with a transformation function $\theta_t = \phi(t_p)$ where ϕ is given by equation (3) and can thus be used to directly measure the basecourse moisture content.

In Fig. 5 each set of aggregate data is fitted independently resulting in a different quadratic function ϕ_B (Belmont) and ϕ_P (Pound Road) for each aggregate. To explore whether a single transform function can be used, data from both aggregates is fitted to the single transformation curve ϕ_T shown in Fig. 6.

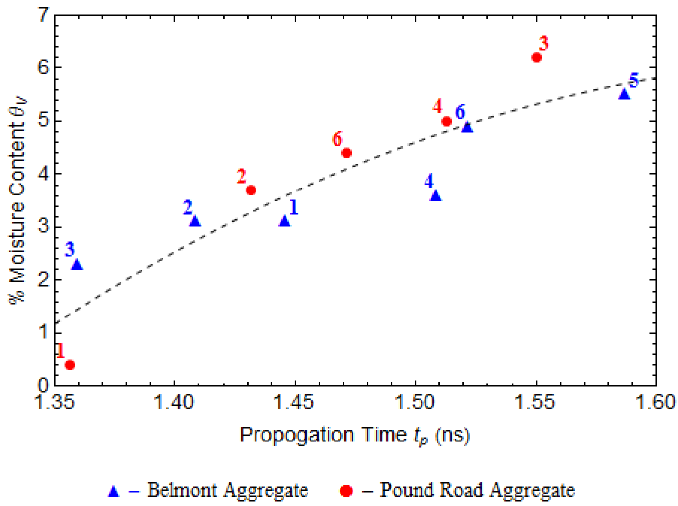

Figure 6. Best fit to all aggregate data using the quadratic composite function ϕ_T.

The errors arising from fitting each aggregate with its own function (using ϕ_B and ϕ_P) and both aggregates with the same function (using ϕ_T) are shown in Fig. 7.

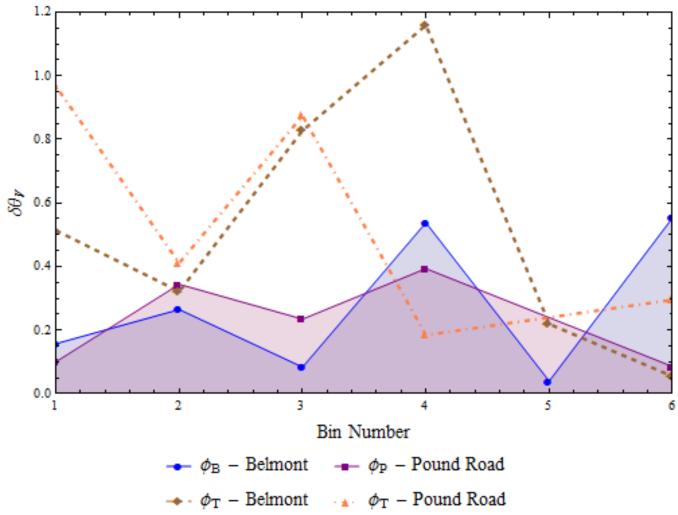

Figure 7. Errors in using a single function, ϕ_T for both aggregates as opposed to using a function for each aggregate type (ϕ_B for the Belmont grade and ϕ_P for the Pound Road grade).

It is evident from Fig. 7 that an independent fit to each aggregate provides overall less error in the final value for θ_v for the fitted quadratic and will thus require different coefficients for the form of equation (3).

TABLE 3. ERRORS IN SMOOTHLY FITTING DATA TO A QUADRATIC TRANSFORM CURVE

	using ϕ_B and ϕ_P	using ϕ_T
Max[$\delta\theta_v$]	0.55%	1.16%
Mean[$\delta\theta_v$]	0.25%	0.53%

IV. Conclusion

We have shown in this paper that a non invasive Time Domain Reflectometer (TDR) sitting above a road basecourse can accurately measure its volumetric moisture content to an accuracy of less than 0.55% for the two basecourse aggregates measured. Also shown is that there is sufficient difference in the dielectric properties (represented by the model transform g in equations 1 and 2) that a separate composite transform (ϕ_B and ϕ_P) must be used for each type. Over the region of interest, between $\theta_v = 0 - 20\%$, a quadratic function provides a good and stable fit to both data sets, so that ϕ_B and ϕ_P differ only in their quadratic coefficients; equation (3).

While the errors resulting from the expected quadratic function are reasonably small there are a couple of important points to be noted regarding the reference measurements obtained by drying the samples. Firstly, even though mixing of aggregate with moisture for each box was thorough and measurements were taken within 8 hours of preparation there was some substantial variation in moisture values of samples taken from the same layers within the box. This highlights the difficult nature of such experiments where complex moisture movement redistributes the volumetric content unevenly throughout the sample. Secondly, this variation in moisture content, measured from small samples throughout the volume (by drying), is at odds with the way in which the TDR measurements work. The TDR measures an effective propagation time resulting from the *integration* of moisture content from between 0 – 200 mm below the surface. It is therefore unlikely that non-homogeneous moisture content measurements taken from sample locations will match this integrated value exactly. The only real way to ensure this effect can be accounted for is to know in detail the moisture distribution throughout the whole sample or ensuring only test cases where variation is small are used. This should be the aim of future work.

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