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Numerical modeling using gprMax to identify a subsurface tack coat for SVM classification

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Introduction

Pavement construction results from the stacking of several layers of building materials. A poor adhesion between those layers can lead to premature deterioration of the pavement : rutting, shearing, potholes, surface cracks... In order to ensure the longevity and integrity of the structures, when they face increasing traffic volumes, it is essential to resort to a tack coat, where the wearing course and the binder course connect, so that they work as a monolithic block. To this day, the techniques used in France to estimate the condition of tack coats are destructive, as they require coring and laboratory characterization, for example with gammadensimetry. The core samples are then only representative of a small fraction of the structure, and can't be reused, never mind the costly and cumbersome equipment needed. By using the electromagnetics microwaves (EM) propagation properties to survey the pavement, Ground-Penetrating Radar (GPR) offers the advantage of a non-destructive, high efficiency technique, contact-less in most cases, which is sensitive to variations in dielectric permittivity, to thickness of layers, to moisture content, to porosity... And moreover, it doesn't use radioactive sources (Daniels, 2005; Balayssac et al., 2009; Villain et al., 2009).

Previous studies have shown that high-resolution measurement of physical and geometric parameters can be done at a shallow depth or near-surface (Fauchard et al., 2003; Ihamouten et al., 2011; Sun et al., 2015; Klotzsche et al., 2019; Todkar et al., 2019). Nowadays, only the detection of layers thickness, noteworthy cracks or debonding in weakly dispersive propagation medium (2 to 3 cm) and with an ultra wide frequency band radar is possible. It has been shown (Le Bastard et al., 2014 et Sun et al., 2020) that high-resolution signal processing used on signals coming from a conventional GPR (radar pulse) could detect and measure the dielectric permittivity of thin pavement layers (around 2 cm). In spite of these methods' strong capacity, they remain limited and not always robust to detect weaker variations in dielectric characteristics in dispersive mediums a few centimeters deep. Also, there have been attempts at using machine learning methodology to locate debonding zone (Todkar et al., 2019). The aim is therefore to use an approach based on pairing radar techniques with supervised machine learning methods, to identify tack coat defects.

Proposed Method

With the help of the gprMax software (Giannopoulos, 2005), a model of a bilayer with dielectric homogeneity, and geometric and dielectric properties that can vary, has been realized. One thin layer has been inserted, thus adding to the model the presence of a tack coat also with variable properties. As soon as time signals will be generated (A-scan), machine learning methods will enable the characterization of the tack coat. Among existing methods, the *Support Vector Machine* (SVM) is an algorithm built on the idea of maximizing decision boundary by choosing a margin that will represent distance between the variables and the best line. This will then help classifying the results (Schölkopf et al., 1999). To this end, an approaching resolution through *Two-Class Support Vector Machine* (TCSVM) was envisaged. This method allows to split the data in two distinct classes. One data set is described as the "adhered" class, and another as the "non adhered" class. To conduct this study, two approaches are possible: local or global. A resolution by the local approach is an extraction of features of the raw GPR A-scan. Conversely, a resolution by global approach would consist to use the raw data set, without any pre-processing. Each point on the signal is as important as any other. This method appeals to intuition and can be implemented quickly. This approach was chosen in this study.

Description of the modeling procedure

To be able to classify the results, an important database has been generated using the gprMax software. It allows to simulate EM waves propagation by solving Maxwell equations using the *Finite Difference Time Domain* method (FDTD). The starting point was the hypothesis that the modelled structure (figure 1) is an ideal stratified medium: homogeneous, isotropic, and non dispersive for the used frequencies. The goal is to identify a thin millimetric subsurface layer and to differentiate the signals according to the modifications of the parameters.

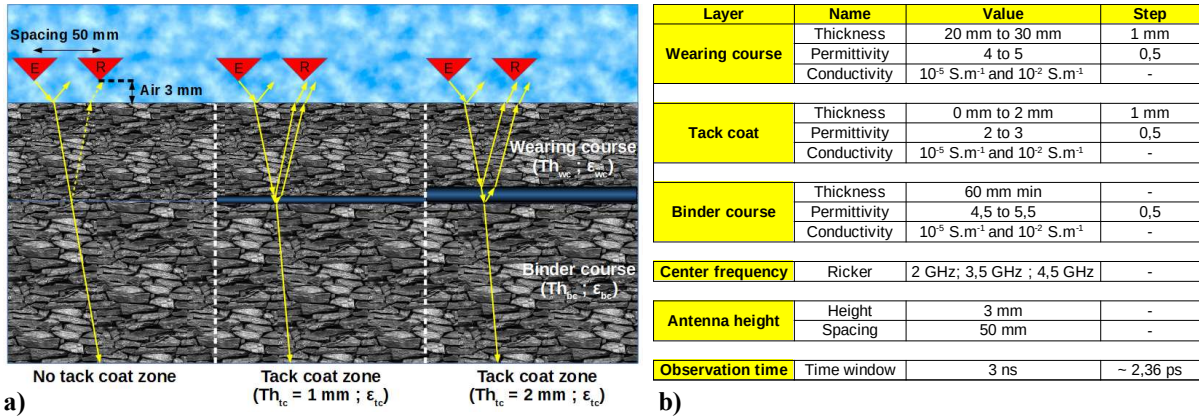


Figure 1 a) Model of an homogenous and isotropic stratified medium of the form Wearing course / Tack coat / Binder course, **b)** Parameters used to generate the database

Parameters such as thickness, dielectric permittivity ϵ , conductivity σ and permeability μ are essential in characterizing the bilayer. In this area, a relative permeability μ_r was defined as equal to 1, like in most geological materials (Jol, 2009) and no magnetic loss was taken into account, as it was negligible. Besides, as conductivity is also almost negligible for this type of material, the values of $\sigma = 10^{-2} \text{ S.m}^{-1}$ and 10^{-5} S.m^{-1} was selected. Depending on the kind of cover aggregate, the size of the granulates and the compactness of the layer, the permittivity value of the layer is bound to vary. A permittivity varying around $\epsilon_{wc} \approx 4,5$ (Adous et al., 2006 ; Araujo et al., 2016) was chosen for the surface coat, and around $\epsilon_{bc} \approx 5$ for the binder coat, in order to study the cases when the formulation is identical between both layers, and the changes in permittivity. The tack coat was considered as a thin layer without rugosity. The frequency range of the radar measured the relative permittivity of pure bitumen, giving a result of $\epsilon_{tc} \approx 2,41$. A significant variation of permittivity around $\epsilon_{tc} \approx 2,5$ was then applied while modelling the tack coat.

More than 5000 A-scans was modelled with diverse geometric and dielectric characteristics for each center frequency. This set of simulated data will be supplemented in the future with experimental laboratory data, and with field data observed on new roads or on works around a suspicion of defect.

In figure 2, on a frequency of 4,5 GHz, a model of a bitumen monolithic block has been extracted from the database. It comprises the following parameters: thickness of the wearing course = 25 mm ; $\epsilon_{wc} = \epsilon_{bc} = 4,5$; $\sigma = 10^{-5} \text{ S.m}^{-1}$. A tack coat with a permittivity $\epsilon_{tc} = 2,5$; $\sigma = 10^{-5} \text{ S.m}^{-1}$ and a variable layer thickness has been inserted. In this model, the wave emitted by the antenna has been removed (Air wave filtering).

A_{wc} is the amplitude of the material level echo, A_{tc} is the amplitude of the echo located on the area to be monitored.

A clear variation can be shown in the amplitude level, given the presence or absence of the tack coat: a change in dielectric contrast appears, as well as a modification of thickness.

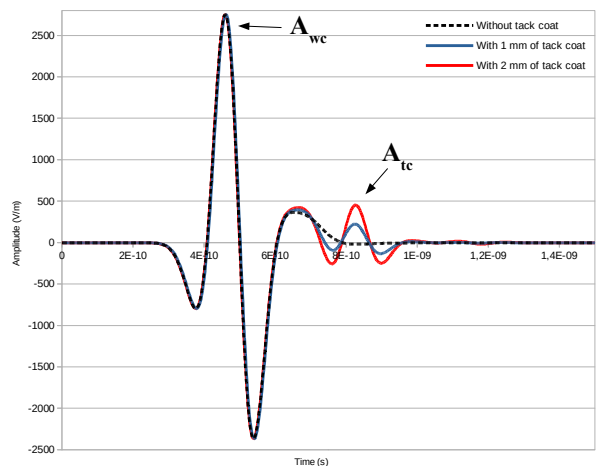


Figure 2 Time signals (A-scans) showing differences in thickness of tack coat.

These first results corroborate the preliminary work on tack coat characterization by full waveform inversion (FWFI) (Ihamouten et al., 2017). Given the weak tack coat thickness and the modelling conditions (ground coupling, center frequency, thickness of the top layer), caution should be exercised regarding echoes. That said, the presence of an A_{tc} echo will be the primary feature enabling us to classify the data especially in the case of a local approach.

Machine learning – preliminary results and discussion

In figure 3, a *Two-Class SVM* method of supervised machine learning was used with a global approach. In figure 3a, the B-scan (concatenation of A-scans) shows visually the difference between an adhered area and a non-adhered area, as well as a model of the differences in tack coat thickness. Binary classification allows to identify clearly and automatically the presence of both areas (3c). Preliminary results show excellent performance with over 99% positive detections. It can be explained by the hypothesis of no rugosity, lossless and homogeneous media at the considered central frequency, inducing no scattering noise in the data.

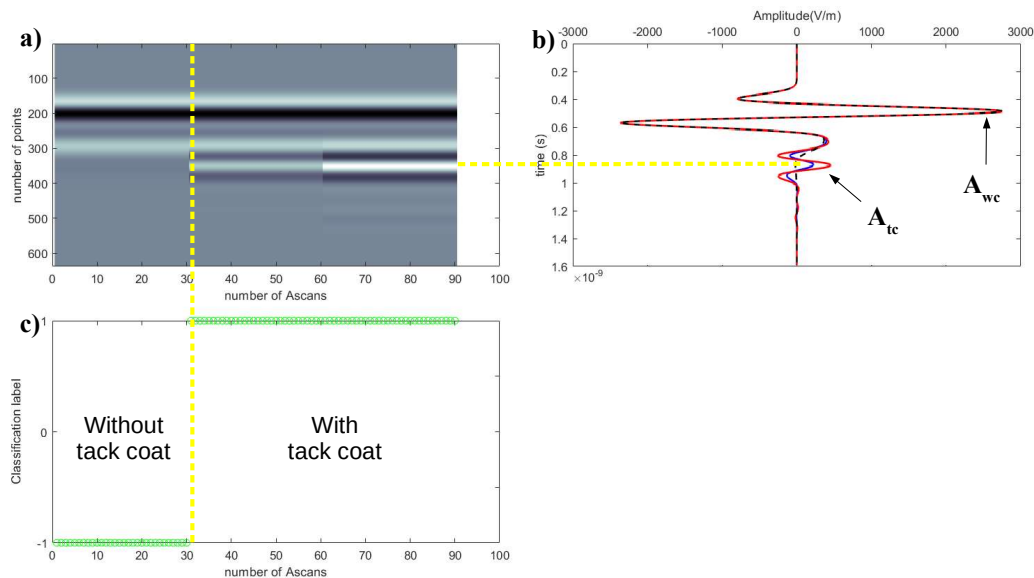


Figure 3 a) The B-scan (concatenation of A-scans, presented as examples) shows scanning of adhered and non adhered areas **b)** Time signals of the areas **c)** Classification of data using *Two-Class SVM* method, with and without tack coat

Conclusions

In conclusion, it is possible to identify a change in dielectric contrast in a millimetre-thin subsurface layer, in a simulated setting, using FDTD. This study allowed for the first attempts at a promising classification by *Two-Class SVM* machine learning. A short-term prospect will be to increase the reliability of this classification method, by optimizing the settings of the classifier, and to carry out the extraction of certain features with a local approach. The performances will be compared with those of other methods like *One-Class SVM*, the principle being to gather in one class the readings produced by an adhered area. The readings produced by a non-adhered area will be treated as data anomaly. At a later stage, a classification can be envisaged depending on the dosage (under dosed, excessively dosed, or dosed according to the standard) with methods such as *Multi-Class SVM* or *Support Vector Regression* (SVR).

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