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An experimental-based model for the assessment of the mechanical properties of road pavements using ground-penetrating radar

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HIGHLIGHTS

- Non-destructive assessment of a road flexible pavement.
- Development of an experimental-based model for road pavement stiffness assessment.
- Integration and modelling of data from GPR (2 GHz horn antenna) and LFWD equipment.
- Development of a time-efficient methodology (quantitative and qualitative modelling).

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ABSTRACT

This work proposes an experimental-based model for the assessment of the stiffness of a road flexible pavement using ground-penetrating radar (GPR – 2 GHz horn antenna) and light falling weight deflectometer (LFWD) non-destructive testing (NDT) methods. It is known that the identification of early decay and loss of bearing capacity is a major challenge for effective maintenance of roads and the implementation of pavement management systems (PMSs). To this effect, a time-efficient methodology based on quantitative and qualitative modelling of road stiffness is developed. The viability of using a GPR system in combination with LFWD equipment is also proven.

1. Introduction

Reducing the number of accidents is a priority and challenging target to pursue for road administrators. Accidents are generally related to geometric issues [1] and unfavourable serviceability conditions [2]. Firstly, improper design of road geometric elements affects drivers' perception of the road trajectory. Secondly, low road serviceability levels may lead, above all, to lack of friction between the vehicles and the road surface. In regard to the latter issue, the intercorrelation between pavement decay and frequency of accidents is well known [3]. To this effect, an extensive and time-efficient assessment of roads at the network level is crucial for road administrators and agencies to define priorities of intervention and decrease the likelihood of envisaged accidents.

Most of the damages in flexible pavements occur where stiffness of the asphalt and load-bearing layers is low. Therefore, an effective assessment of the strength and deformation properties of these layers can lead to identifying causes and locating the depth of damages. In addition, a prompt detection of early decay and loss of bearing capacity represents the real challenge to tackle for road administrators.

It is known that the bearing capacity of subgrade soils can be assessed by on-site [4,5] and laboratory [6] tests. These methods mainly measure the deformation of the pavement when a constant stress is applied. Due to the high operational time and costs, these tests are usually carried out on a few road sections and provide only partial information on the stiffness of the layers. Furthermore,

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these tests are intrusive and require to close the highway entirely or partially, with implications for the driving safety of roads.

In view of the above limitations, non-destructive testing (NDT) methods have become popular for the assessment of the mechanical properties of pavements. Falling weight deflectometer (FWD) [7] and light falling weight deflectometer (LFWD) [8,9] are widely used for the investigation of integrated flexible pavement structures and for construction quality control of unbound materials, respectively. Nevertheless, LFWD has found also effective application in the assessment of the stiffness of bound layers [10,11]. The FWD method relies on the measurement of deflections produced by a known falling mass loading the pavement surface. The main limitation of this method is that data can be collected only at discrete points, thereby affecting time and cost of the operations. To fill this gap, fully equipped non-destructive testing lorries for estimation of pavement strength and deformation properties at traffic speed started being used. In this regard, the curviameter [12] uses geophones to measure the velocity of vertical displacements of the pavement under the passage of the rear axle of the truck. Collection speed is 18 km/h. The deflection bowl is obtained by integration of the measurements from the geophones, which are placed in a chain system. The main limitation of this equipment relates with the integration process. In this regard, an accurate calibration of the geophones is required. Furthermore, the need to respect a constant speed and the impossibility to perform measurements in curves with radii lower than 40 m are worthy of mention. A traffic speed deflectometer (TSD) [13] is another moving deflectometer equipment. It operates at speeds up to 90 km/h and it is equipped with a long and rigid beam placed inside a semi-truck. A dedicated dead weight of 100 kN is located in the proximity of the rear axle. High-rate sensors, including Doppler sensors, accelerometers and laser distance sensors, ensure that vertical pavement deflection velocities are recorded. Deflection velocities divided by the instantaneous vehicle speed produce the deflection slopes at discrete points along the TSD route. Several internal and external factors may affect the accuracy and precision of TSD measurements. These include calibration and quality assurance procedures, wind and temperature during the measurement, pavement roughness and tire-pavement interaction [14]. Although all the aforementioned methods are reliable and time-efficient, estimation of the strength and deformation properties of pavement layers requires a multi-stage collection of complementary information from different equipment (e.g., ground-penetrating radar (GPR)). In addition, the integration of these pieces of information requires a repeat of the data collection stage for each equipment along the whole stretch of the investigated roadway.

GPR has been extensively used in highway engineering as a result of the high reliability in the assessment of the geometric properties and physical properties of the pavement layers. GPR systems equipped with air-coupled antennas and connected to vehicles are mostly used for data collection at traffic speed. The GPR working principles rely on the emission of electromagnetic (EM) waves towards the ground. The emitted waves are then reflected back from the targets (typically represented by the interfaces of the layers) and are received by a receiving antenna. The collected signal is therefore displayed and stored for data processing and interpretation purposes. To date, GPR is successfully utilised in several disciplines including civil engineering [11], demining [15], archaeology [16], geology [17], glaciology [18] and much more.

As a common practice in highway engineering, the GPR and FWD methods are used separately for the assessment of the geometric (i.e., evaluation of the layer thicknesses) and the strength and deformation properties (i.e., evaluation of the deflection bowl) of road flexible pavements, respectively. The integration of the above information allows to evaluate reliable values of stiffness modulus of the pavement layers.

In view of the aforementioned limitations and state-of-the-art practices in the assessment of the mechanical properties of flexible pavements, the development of a non-destructive testing methodology for real-time identification of early decay and loss of bearing capacity of roads at traffic speed would stand as a step forward compared with the traditional methods. Value added would be to provide an estimation of the pavement stiffness based on geometric, physical and mechanical attributes of the subsurface integrated into a unique model. This would emphasise strengths and narrow weaknesses of the above NDTs.

A first modelling approach was developed by Tosti et al. [19]. A ground-coupled GPR antenna system and LFWD equipment were used to collect a dense dataset on a flexible pavement structure. The model was based on the peak amplitudes of the GPR signals reflected at the interfaces of the road layers and the stiffness moduli estimated using LFWD. The concept proposed by Tosti et al. [19] is here taken as a reference and it is further developed using an air-coupled GPR antenna system.

It is important to emphasise the importance of the proposed methodology in assessing early decay and loss of bearing capacity of the load bearing layers more efficiently than the state-of-the-art NDT methods. This information would be crucial for road administrators in order to create comprehensive databases of the road pavement conditions at the network level for implementation in pavement management systems (PMSs). This would allow for prioritisation of road maintenance operations, reduction of costs and a decrease in the likelihood of envisaged accidents.

The paper is outlined as follows: in Section 2, the aim and objectives are presented. The theoretical framework is discussed in Section 3. Section 4 presents the methodology, whereas the experimental design (test site and equipment) is detailed in Section 5. The ground-truth information and the preliminary data analysis are discussed in Section 6. The modelling is presented in Section 7, whereas results and discussion are reported in Section 8. Finally, the conclusion and future prospects are discussed in Section 9.

2. Aim and objectives

The primary aim of this project is to address a major challenge in the identification of early decay and loss of bearing capacity in road flexible pavements using GPR and LFWD. To achieve this aim, the following objectives are set:

- to develop a time-efficient methodology for estimating the stiffness of the pavement structure;
- to demonstrate the viability of using an air-coupled GPR antenna system in combination with LFWD equipment.

3. Theoretical framework

The GPR method is based on the theory of the EM fields. When an EM wave is emitted by a source, propagation is ruled by the dielectric properties of the medium that is passed through (case of non-magnetic targets). In more detail, propagation speed and attenuation of the wave are related to the relative dielectric permittivity ε_r [−] and the electrical conductivity σ [Sm^{-1}], respectively. When a dielectric discontinuity is encountered, the radiated energy is partly reflected back to the receiving antenna and partly transmitted in depth. From the analysis of the collected signal, it is therefore possible to reconstruct the geometric features of the discontinuities.