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Assessing the pavement subgrade by combining different non-destructive methods

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HIGHLIGHTS

- Air-coupled antennas are more suitable for measuring layer continuity.
- Ground-coupled antennas had better signal to noise ratio and better resolution.
- LWD is more suitable for the evaluation of the surface layer.
- FWD is more appropriate for the structural evaluation of the overall pavement.
- NDT techniques combined proved to be a useful approach to access the subgrade.

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ABSTRACT

The subgrade provides support to the pavement system and assures an effective distribution of traffic loads in depth. Therefore, a failure in the subgrade will have consequences on the entire pavement behaviour.

This work presents an integrated approach for the analysis of the road subgrade condition by combining different Non-Destructive Testing (NDT) techniques. Different Ground Penetrating Radar (GPR) systems, both antennas configuration and frequencies, were tested in order to achieve the best methodology for subgrade cracking detection. Additionally, NDT load tests were performed with two deflectometers, Falling Weight Deflectometer (FWD) and Light Weight Deflectometer (LWD), aiming to determine the elastic modulus of the subgrade and consequently detect damaged areas.

The tests were conducted at a real scale test section built to simulate pavement foundation layers consisting of clay soil subgrade, frequently used in African countries. The main tests performed are presented and analysed in this paper. Troubleshooting's are referred mainly related with GPR wave propagation on clayey materials, due to high absorption. Recommendations are made regarding the use of GPR antennas as air-coupled antennas lead to a better identification of pavement layer interfaces while ground-coupled antennas were preferable to detect anomalous areas, namely cracking and debonding. The results showed good agreement between both NDT methods (GPR and load tests) in the identification of the anomalous areas and were validated with some in-situ cores extracted.

1. Introduction

The road transportation system has an important role in today's society with a direct influence in its economic development. The effect of vehicle loads is the lead cause of pavement deterioration over time, followed by the influence of the weather conditions and errors in design or construction that can intensify those effects resulting in a quicker decrease of the pavement condition [1]. With increasing demands in terms of traffic volumes and vehicle loads together with limited resources (time, money and personnel) to intervene in the road, pavement asset management has therefore become a vital activity at the network level [2].

Road inspections normally imply visual inspection, to evaluate cracks and delamination and also functional evaluation of

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pavements, by assessing the surface parameters such as roughness and skid resistance [3]. However, it is also important to look beyond the surface as deficiencies in thickness, lack of interlock between bound and unbound layers and the loss of structural support have a significant impact on the reduction of pavements lifetime [2]. Therefore, it is more and more important to perform a structural evaluation of the pavement for a complete diagnosis of its condition.

The subgrade provides support to the entire pavement system and assures an effective distribution of traffic loads in depth. Thus, proper pavement behaviour is directly related to the subgrade integrity. In the case of low-volume traffic pavements (with thinner asphalt layers), the subgrade is particularly relevant, as the stress magnitude from the traffic loads can be significant at subgrade level. In addition, the subgrade is more sensitive to environmental conditions variations.

Non-destructive testing (NDT) methods are preferable over time-consuming, unsafe and costly traditional destructive methods. Ground Penetrating Radar (GPR) is one of the most efficient NDT for subsurface monitoring [4]. GPR provides continuous monitoring along pavements with the advantage of operation at traffic speed, without causing disruption to traffic. The main applications in pavement engineering are the layer thickness measurement and detection of changes in structure [5] but also the assessment of moisture and air void content [6,7], detection of subsurface defects [8–10] and, at the experimental level, the estimation of the mechanical characteristics of the pavement layers [11]. The most common GPR systems are based on impulse frequencies which apply a single electromagnetic wave at a selected frequency [5]. The wave travels from the antenna into the pavement and is reflected when it meets an interface between two materials that present different dielectric constants [5,12]. Two different antennas setups can be used in roads inspections: ground-coupled antennas, that require contact with the pavement surface, and air-coupled horn antennas, that operate suspended, generally 40–50 cm above the pavement surface. The ground-coupled antennas can provide higher penetration depth for the same frequency, whereas air-coupled horn antennas, as they work suspended over the pavement, allow higher acquisition speeds [1].

Additionally, Falling Weight Deflectometer (FWD) is considered to be the most effective NDT device for pavement deflection measurements worldwide, realistically simulating the pavement responses under traffic loading [13]and consequently, it is generally used for bearing capacity evaluation [14–16]. The FWD applies an impulse load that consists of a mass dropped onto a damped spring system mounted on a loading plate and measures the shape of the deflection bowl resulted with a series of geophones located at different distances from the load. Using the deflection values obtained in-situ, elastic modulus can be estimated for each layer throughout back-calculation when the thicknesses of the pavement layers are known. The FWD is nowadays used in combination with GPR to determine elastic modulus of pavement layers [14,15] and, more recently, in subsurface cracking detection [17]. Moreover, Light Weight Deflectometers (LWD) are portable devices traditionally used for quick quality control of unbound layers at subgrade and subbase level. LWD provides a direct estimation of the elastic modulus for such layers [18]. However, the measuring depth (normally twice the plate diameter) is lower than the FWD because it uses lower loads, so the LWD modulus characterises only the upper part of the pavement structure condition. Also, the LWD only measures the deflections on three points up to 0.60 m from the load, compared with the FWD that can measure deflections on nine points, with the farthest located at 2.10 m from the application of the load.

This work presents an integrated approach by combining different NDT techniques focused on the analysis of the road subgrade condition. Different GPR systems and Load test equipment were used in order to define the best methodology. Thus, the GPR data allowed for cracking detection, while the deflectometers provided the elastic modulus of the subgrade. Apart from other structural deficiencies such as moisture and delamination, the existence of subsurface cracking decreases the elastic modulus of the layer. The tests were performed on an experimental test section, built to simulate pavement subgrade layers consisting of clay soil materials, generally used in African countries for low-volume roads foundations. This paper covers the construction period and intents to characterize the pavement before the beginning of the service life. Nevertheless, this methodology combining NDT techniques can be used to access in service pavements over climate changes, time and traffic.

2. Materials and methods

2.1. Experimental area

An experimental test section was constructed in order to simulate a pavement subgrade and evaluate the feasibly of the use of different NDT methods to analyse its behaviour.

The physical model was built in a concrete pit section with a maximum depth of 1.97 m and a total area of 3.07 m wide and 31.5 m long. The test section was implemented in an area of approximately 36.0 m^2 limited transversally by concrete walls and below by a concrete floor (Fig. 1).

The test section structure comprises the foundation of the pavement constituted by a 0.15 m capping layer of improved subgrade with a soil with 95% compaction, a 0.90 m layer of compacted subgrade of the same soil with a compaction of 93% applied in four layers of 0.15 m and one layer of 0.30 m (Fig. 1). Above the concrete slab, a 0.48 m layer of soil was applied to install the drainage of the test section. This layer was built with the same soil and compaction values as the compacted subgrade above.

The soil used in the subgrade layers is classified by the Unified Soil Classification System (USCS) as clay of low plasticity, lean clay and by the AASHTO Soil Classification System as A-7-6, clay material with general rating as a subgrade fair to poor.

Physical properties were evaluated such as grading, Atterberg limits, linear shrinkage and optimum water content, correspondent maximum dry density, as well as mechanical properties like Californian Bearing Ratio. The properties of the soil obtained are presented in Table 1 and the grading curve is shown in Fig. 2. The grading curve was obtained using two methods: hydrometer for the finest particles and sieving for the rest.

From the properties of the soil used in the subgrade layers (Table 1), we may conclude that its behaviour is highly influenced by the water content. It should be mentioned that the swelling values obtained (about 5%) for a compaction degree of 96% and 98% can be a problem with moisture changes and the consequent increase of volume. The effective stiffness of this soil highly depends on its saturation degree.

As previously referred, the foundation of the pavement was constructed in layers. For construction quality control, different tests were performed immediately after compaction on the top of each layer (Fig. 3). Water content, dry density and the compaction degree were determined by the nuclear density test method and these results were calibrated with the measurement obtained by the sand-cone method. The surface moduli (E_{LWD}) of the subgrade layers were calculated using the Light Weight Deflectometer (LWD).

Fig. 3a shows some deviations in compaction values between layers at different positions of the whole test section. This can partially be explained by some limitations during the compaction of