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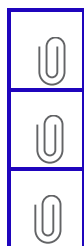
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DEFINITION OF IN SITU PAVEMENT INSTRUMENTATION FOR DATA COLLECTION TO DEVELOP A PAVEMENT PERFORMANCE MODEL

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ABSTRACT

After the implementation of the AASHTO Road Test many researches have been carried out regarding material and pavement performance, both in laboratory and in situ. Many methods for pavement evaluation and design were obtained based on empirical or empirical-mechanistic approaches. Nowadays, these methods are used in pavement analysis and design supported by a set of shift factors that consider the variables which were not included in their definitions.

At the present time, the development of economical electronic sensors has made possible a successful full-scale instrumentation of pavements that include a set of variables which were not considered in the past.

This paper focuses on reporting the instrumentation selected for a full scale research in Portugal led by the University of Minho, and some basic and limited considerations to collect relevant data for pavement modelling. The instrumentation includes monitoring environmental conditions (rainfall, air temperature, solar and UV radiations, and wind), pavement characteristics (temperature, moisture and groundwater level), pavement response (displacement, tensile and compression strains, deformations and pressures) and vehicle characteristics (type, axle configuration, tire type and pressure, speed, weight by axle at high speed and the transversal wandering).

The definition of the instrumentation for pavement response was based on conventional pavement analysis using numerical modelling in which the sensors position may ensure reliable measurements. External parameters evaluation, such as tire pressure and tire pattern, is included by sample-collection.

INTRODUCTION

Due to the mechanistic complexity of the pavement structure and the behaviour of the materials used in asphalt pavement layers, pavement design is traditionally based on simplified empirical and/or empirical-mechanistic methods.

The AASHTO experimental section (HRB 1962), made and evaluated in the 1950's, was the basis and one of the first steps to evaluate pavements in an organized and rational way, originating two of the most widely used methods for pavement design: the USACE method (Turnbull *et al* 1962) and the AASHTO method (AASHTO 1986). The approach is widely empirical, but still in use.

Many European countries tried a more advanced approach that included laboratory tests to evaluate some parameters believed as important to the pavement service life, such as stiffness modulus and fatigue life, among others. It is known as empirical-mechanistic because it is a step forward in relation to pure-empirical methods, however it does not consider all relevant variables for pavement service life (Rilett and Hutchinson 1988).

This approach reflected the technical and economical realities for that time, but important changes occurred since then due to the increase of costs for pavement construction and maintenance and a total change in the traffic profile, as vehicles have become heavier. The lack of a strictly scientific approach is one of the most important causes for incorrect pavement evaluation and design entailing a big impact on the service life (University of Minnesota, 1999).

Nowadays, thanks to the improvement of the processing speed of computers, softwares for numerical analysis and the reduction of costs of the electronic sensors, there are conditions for a strictly scientific approach on studies related to asphalt pavements under which it is possible to study every variable and aspect related to pavement service life. This new scenario has made research possible from a holistic approach, such as projects by the Virginia Smart Road and the Mn/Road.

The Virginia Smart Road test is a facility where it is possible to test pavements at full scale and with a holistic point-of-view. The facility was constructed to evaluate asphalt mixtures, calibrate responses from FWD testing, evaluate ground-penetrating radar (GPR) images and to study the performance prediction for pavements. As reported by Al-Qadi *et al* (2001) the facility includes twelve instrumented pavement sections with more than five hundred embedded instruments to measure the response of pavement systems to vehicular loadings and to environmental conditions.

Measured data include stresses and strain along the depth of the pavement, horizontal and longitudinal strains in the hot-mix asphalt and climatic factors including temperature, moisture in the base and sub-base layers and frost depth. These may be read at many depths and different axle loadings, tire inflation pressures and speeds are tested. Likewise according to Al-Qadi *et al* (2004), the generated signals clearly proved the visco-elastic behaviour of HMA (including time retardation, relaxation with time and asymmetry of response) and thus, it was possible to model some properties of the pavement behaviour using finite elements. Changes in the theoretical

model varying materials properties, bond between layers, considering the anisotropic nature of the materials and dynamic loads among others, are recommended as a way to calibrate models following the response obtained by tests in field.

Another interesting holistic research is the Mn/Road Project, a full-scale pavement test facility located near Minneapolis (USA) that uses very heavily instrumented sections with more than 4500 sensors. Splitted into two, this research has a close circuit for studying low-traffic pavements and another circuit together with the Interstate Highway to study heavy-traffic, having a total of 40 sections. As mentioned in NCHRP Synthesis 325 (2004), this facility was constructed for full-scale tests in which the complex interaction between traffic, climate and material could be studied to improve the methods for pavement design and performance evaluation. A range of vehicle loads, axle configurations and vehicle speeds are being applied to instrumented pavement sections. The results were successfully used as basis for developing a mechanistic–empirical design system and provided the basis for guidelines to restrict truck loads during the thaw period of the year.

In Europe there is no facility such as Mn/Road or Smart Road Projects according to Hildebrand and Nunn (2004). Almost all the existing full-scale studies around the world use non-real traffic instead of truck simulation. This is a paradox because the climate and the monitoring of the pavement behaviour are fully evaluated, but traffic is adjusted to fit the ESAL paradigm. Studying the pavement behaviour and response at full scale implies to consider traffic with all its anisotropies.

OBJECTIVE OF TRUE FULL-SCALE INSTRUMENTATION

The purpose of this research at the University of Minho is to study the pavement behaviour at a true full scale and under a holistic approach, working with every relevant variable for the asphalt pavement life in an open highway and with live real traffic.

The final objective of monitoring all variables which influence the pavement service life is to create mathematical models (equations) for the evaluation of existing pavements and to design new ones under a strictly scientific approach with emphasis on aspects which are not possible to be studied in accelerated section tests or in laboratory, i.e. vehicle oscillations, miscellaneous of truck axle configurations, different types of tires (single extra-width, dual, etc.), tire insufflation pressure and changes due to heating when moving among others.

Models will be adjusted with the aid of the internal mechanical behaviour of the pavement measured with instrumentation of a highway segment with real traffic (full scale), under loads (vehicles) and taking environmental and climatic conditions into consideration.

With all monitored data in an organized database it will be possible to understand how so many variables interact to determine the pavement service life and its degradation. For that, the main tools will be the well-known finite element modelling, for structural simulation, and artificial intelligence for studying the variable interaction. Artificial intelligence is an efficient tool to study very complex series of data as the ones that will be generated in this research.

When validated, the models will allow a better performance of asphalt pavements, what will improve the efficiency of the financial resources used in highways.

In this planning phase of the project the main challenge to achieve the proposed objective is designing a suitable sensor network and a suitable data acquisition system by specifying the sensors for each variable and by integrating all data in a synchronized database, all at a very cost-effective way.

VARIABLES AND INSTRUMENTATION

The study of the pavement behaviour in a true full-scale is not a simple task due to the very limited know-how and the complexity of a research at this level. The selection of the variables can be made considering the existing bibliography about specific or limited pavement studies, non-full scale and accelerated pavement testing.

The variables can be grouped into three main classes: i) environmental data, ii) loading data and iii) pavement response.

Environmental data

Environmental data are very relevant because of the behaviour of the asphalt concrete layers changes according to the climatic conditions. Rains have strong influence as they alter the moisture in the sub-grade and granular layers; air temperature, solar radiation and wind speed have influence on the pavement temperature. They change the pavement characteristics, such as modulus and fatigue life; solar radiation and UV radiation have influence on the asphalt binder aging. Figure 1 shows the chart of the selected environmental variables for this research and how they will be taken into account in the data acquisition system.
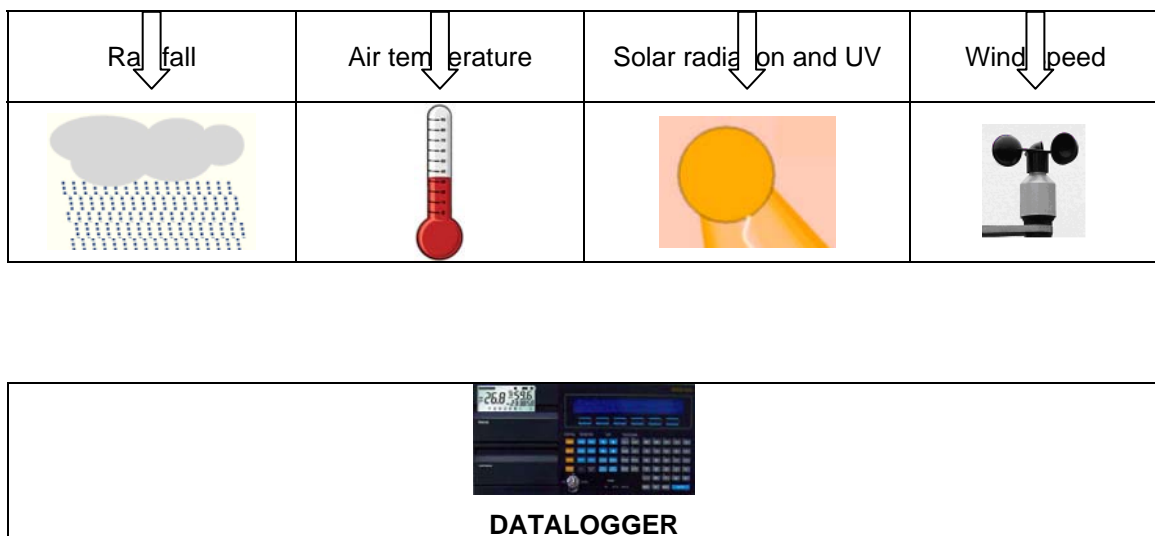

Figure 1 – Selected environmental data

Collecting the selected environmental data is relatively simple. There are different models of compact weather stations in the market. It is important to evaluate if those are maintenance free stations, completely automatic and connectable to an electronic data acquisition system (datalogger). Some of these stations are cheap, but only connectable to a computer, not to a datalogger. The connection to a datalogger is important to easily obtain synchronization with data collected from other instruments and sensors. Anemometers need to be able to measure the horizontal wind speed; sensors for solar and UV radiations will register the instant as well as the historic short-term (hours) radiations and likewise for the thermometer; the rainfall sensor needs to have a self-emptying system.

Loading data

The relevant loads for any pavement structure behaviour and performance are vehicles, trucks mainly. Those have always constituted the most complex data to be collected due to its highly dynamic and variable nature. Nevertheless this difficulty has been somehow resolved by means of the current integrated weigh-in-motion systems at reasonable prices and accuracy.

Vehicle classification and axle configuration are important to know the traffic profile. In the future, it will be helpful to use the results of this research to design and evaluate pavements based on traffic profile, avoiding the ESAL paradigm. The axle load is probably the most important factor for pavement deterioration. The problems generated by slow traffic in pavements are well known, what means that vehicle speed is a relevant aspect that influences the asphalt concrete fatigue life and permanent deformation. The transversal traffic distribution (wandering) is the way to measure the concentration of vehicles over the most solicited pavement fibres. The tire characteristics, including pressure and type, and its interaction with the pavement (foot-print) are important because the tires are the physical means by which loads are transferred to pavements. Figure 2 shows the variables selected for the research at the University of Minho.

Sensors for vehicle counting, classification, detecting axle configuration, speed and weight checking per axle are commonly integrated in a weigh-in-motion system. For a research such as this, the system needs to be able to check accurately the weight, axle by axle, at standard highway (high) speeds, without creating interferences with the traffic in order to be reliable, with a long service life (5+ years) and not subjected to temperature interferences. The sensor for detecting the tire type needs to be able to distinguish among single, single extra-width and dual tires; these sensors are available in the market and are mainly used in highway toll stations.

It is worth to mention the problem generated by the vehicle transversal distribution due to the lack of suitable high speed sensors in the market at a reasonable price; this can be solved by placing a transversal line of pressure sensors on the pavement or reading the vehicle lateral position as marginal information from the horizontal strain gauge sensors positioned at the bottom of the asphalt concrete layer in the transversal direction to the highway axle.

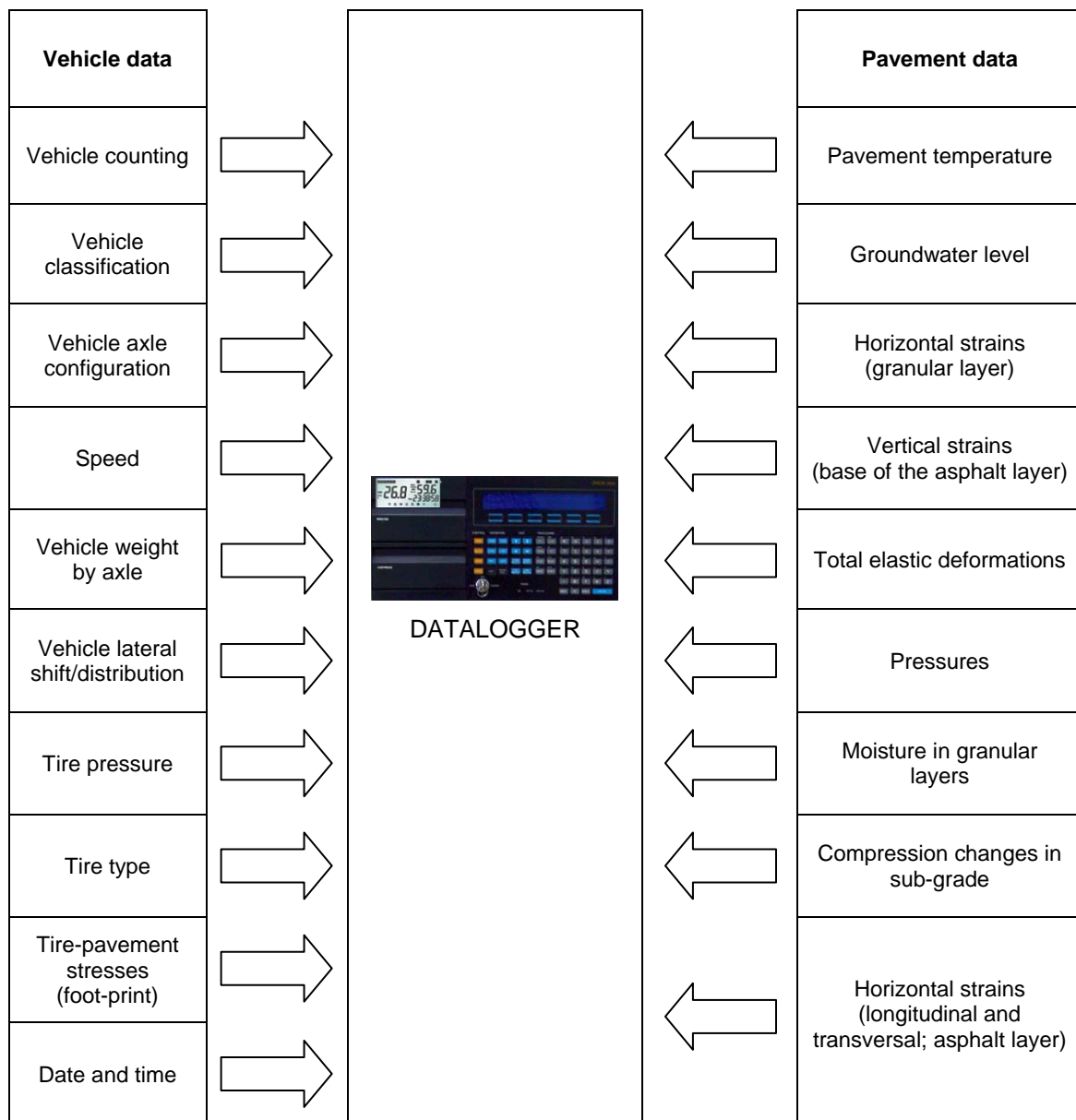| Vehicle data		DATALOGGER		Pavement data
Vehicle counting	→		←	Pavement temperature
Vehicle classification	→		←	Groundwater level
Vehicle axle configuration	→		←	Horizontal strains (granular layer)
Speed	→		←	Vertical strains (base of the asphalt layer)
Vehicle weight by axle	→		←	Total elastic deformations
Vehicle lateral shift/distribution	→		←	Pressures
Tire pressure	→		←	Moisture in granular layers
Tire type	→		←	Compression changes in sub-grade
Tire-pavement stresses (foot-print)	→		←	Horizontal strains (longitudinal and transversal; asphalt layer)
Date and time	→			

Figure 2 – Selected loads (vehicles) and pavement data

Some variables need a sample-based evaluation using manual methods. Land-based systems or sensors that identify the tire pressure at a high speed do not exist; for sampling collection of the tire pressure by hand in motionless vehicles, any device available in the market is suitable for this purpose. On the other hand, only one device (South-African) is available to check the stresses on the tire-pavement contact area with a high density mesh of readings, but it is not able to work at high speeds, as desirable.

Pavement response

The structural response of the asphalt concrete layer and the other layers constitutes the most relevant data for pavement studies. The monitoring of the pavement response will register:
i) values for the pavement temperature; ii) horizontal strains at the bottom of the asphalt concrete and of the granular layers, in the longitudinal and transversal directions, for both layers; iii) vertical strains at the bottom of the asphalt layer; iv) pressures at the bottom of the granular layer; v) total elastic vertical deformations in many depths; vi) moisture changes in the granular layer; vii) changes in the compaction in the sub-grade; viii) the groundwater level.

Strains sensors will allow identifying how important the extensions in many critical positions are in all environmental and loading configurations; strains have a well known importance for fatigue life, among other characteristics of the materials. The vertical strains on the asphalt concrete layer will help to identify the mechanism of the permanent deformation. Some precautions are necessary when choosing the strain gauge models for the asphalt concrete due to the very high temperature of the hot mix asphalt in the construction phase.

The total elastic pavement deformation, read with multi-depth deflectometer (MDD) sensors in many depths and layers, is an interesting variable to be studied as it shows how the entire pavement, with all layers plus the subgrade, responds to loads.

Sensors on the top of the subgrade will read the pressures in the interface between the granular layer and the subgrade. This is a critical value to understand the mechanism of the permanent deformation originated by deformations on the top of the subgrade.

Registering moisture in the granular layers and the groundwater level is not only important to know their influences in the pavement mechanical behaviour and response under loads, but also to determine the importance of rainfall and the efficiency of the drainage system. The information obtained will be helpful to improve the drainage design as it will make possible to know the critical depth of the groundwater. Sensors to detect changes in the subgrade compression (compactation) will facilitate this study. Monitoring the groundwater level is important to ensure a proper pavement evaluation under a realistic and standard situation, without any major drainage failure or with the pavement fully saturated.

Analysis can start once all read values – pavement response, environmental and loading data –, are integrated and synchronized in the database. Artificial intelligence will be the tool to determine the influence of each variable in the pavement service life and its degradation, creating mathematical models. Non-linear visco-elastic finite elements will be used to test and calibrate the models in an interactive process, allowing the results to be replicated to design new highways and to evaluate the existing ones.

IMPLEMENTATION OF THE INSTRUMENTATION

The inherent nature of a full scale with live traffic research creates new challenges to start and administrate the project throughout time. Many details are site-specific and the know-how on laboratory or accelerated tests only provide a limited aid.

Good Practices for Instrumentation

A full scale section test implies that a large amount of details are planned, constructed and evaluated. Some basic good practice needs to be observed when studying the pavement at a full-scale with live and real traffic:

1. When an ultra weighted non-standard truck passes over the test section, protect the weight-in-motion sensors with metallic plates to avoid damage or destruction;

2. Locate the position of all in-pavement sensors with a mesh of coordinates and references to be able to identify sensors location in the future, after the pavement construction is concluded;

3. All materials need a proper characterization and testing in laboratory before the construction of the section test. This can be used to correlate the laboratory with the field results;

4. No pavement maintenance can be made in the section test until the end of the study, due to the changes in the pavement characteristics and behaviour;

5. Calibrate the sensors. Many sensors are delivered without any calibration;

6. Use standard equipment to construct the pavement in order to follow traditional practices;

7. Check the signals from the instruments and sensors before the construction of the following layer to early identify any failure;

8. The use of a large number of sensors can change the original mechanical behaviour of the pavement, so the sensors layout need to be studied to minimize this problem.

Selection of the Highway Section

A successful full scale with real traffic pavement study starts by selecting a suitable highway section. These are some recommendations in order to choose the most appropriate section:

1. Solar orientation: expose the pavement to solar effects. It is recommendable to avoid shadowy sections;

2. Topography: check if the area is subjected to river overflows, soil collapses or other potential interferences;

3. Geometry: choose a section where the vehicle speeds are representative, avoiding sections with slopes or curves;

4. Climate and subgrade soil: choose a place where the climate and the natural soil are average considering the highways system, so the results will be more representative and useful when transferring this know-how to standard practice;

5. Avoid areas subjected to interferences such as pollution, vibration, explosions, close to mining areas, etc., because they will affect the service-life, readings and accuracy of the sensors;

6. Communications: choose a place where there exist electrical power and communications for the equipment. That will avoid costs related to the installation of those systems;

7. Install protection against rays and other adverse atmospheric conditions to keep the devices and electronic components safe; if the in-pavement sensors get damaged, the project will be compromised.

CONCLUSIONS

The study to establish a model to evaluate pavement performance based on a completely mechanistic approach, still in progress at the University of Minho, allowed to obtain the following conclusions:

-   There are available sensors in the market which cover most important variables to study pavements at full scale at reasonable costs;
-   To better understand the causes (loads and environment) and consequences (pavement response and behaviour), all data need to be recorded in a single and synchronized database;
-   Sensors cannot be replaced after the pavement has been constructed and the research started; if the sensors fail, the research is naturally compromised. The performance, quality, rate of failure and other important aspects about the sensors throughout a period of time are unknown and it is very difficult to find organized trustworthy information. The research community needs to consider the creation of a database, based on an international research centre, with factories, sensor models and performance data as a means to help and orientate reliable research in the future.

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