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Evaluation of a Comprehensive Approach for the Development of the Field E* Master Curve Using NDT Data

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Abstract: Non-destructive testing (NDT) systems are essential tools and are widely used for assessing the condition and structural integrity of pavement structures without causing any damage. They are cost-effective, provide comprehensive data, and are time efficient. The bearing capacity and structural condition of a flexible pavement depends on several interrelated factors, with asphalt layers stiffness being dominant. Since asphalt mix is a viscoelastic material, its performance can be fully captured by the dynamic modulus master curve. However, in terms of evaluating an in-service pavement, although a dynamic load is applied and the time history of deflections is recorded during testing of FWD, only the peak deflection is considered in the analysis. Therefore, the modulus of stiffness estimated by backcalculation is the modulus of elasticity. While several methods have been introduced for the determination of the field dynamic modulus master curve, the MEPDG approach provides significant advantages in terms of transparency and robustness. This study focuses on evaluating the methodology's accuracy through an experimental study. The data analysis and validation process showed that routine measurements with the FWD and GPR, within the framework of a pavement monitoring system, can provide valuable input parameters for the evaluation of in-service pavements.

Keywords: dynamic modulus; FWD; GPR; MEPDG; field master curve; algorithm

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1. Introduction

In order to preserve pavements, road authorities are now concentrating on maintaining or extending the pavements' original intended lifespan through various maintenance or rehabilitation measures, thus maximising the economic efficiency of their investments. The timing of when these actions are taken is important, as factors such as pavement condition and maintenance costs must be considered. Delayed action will result in reduced pavement bearing capacity, leading to extensive intervention and higher costs.

Preventive maintenance slows pavement deterioration and delays the need for pavement rehabilitation by several years. The delay in the need for rehabilitation, combined with the relatively low cost of preventive maintenance, can result in dramatic cost savings in pavement preservation. As such, pavement treatments should be directed early in the deterioration process and restricted to the asphalt layers. This strategy will consistently extend the pavement's lifespan, achieving the goal of virtually perpetual functionality (long-life pavements) within the transportation network. Therefore, assessing the pavement's structural condition is crucial to allow road authorities and highway agencies to plan and implement proactive policies.

The structural condition of a flexible pavement depends on several interrelated factors. These factors cooperatively influence the pavement's ability to bear loads, resist distress, and maintain its functional and structural integrity over time. They can be summarised, amongst others, as follows: pavement materials; layer thickness, construction quality; and environmental factors. Asphalt layers are the dominant element in terms of pavement bearing capacity. The asphalt base layer is responsible for transferring the stresses induced by traffic, significantly reducing and distributing them in a larger area to the lower layers, especially the subgrade [1]. Therefore, mechanical properties, namely asphalt mix stiffness, is an important factor in determining to a significant extent the performance of both asphalt layers and pavements [2].

Asphalt mix experiences a viscoelastic behaviour due the presence of asphalt and the aggregates. This behaviour can be fully described through the fundamental property of dynamic modulus (E*) and its master curve [3]. To construct the dynamic modulus master curve, the principle of time–temperature superposition is utilised, so that data at various testing conditions (temperature and frequencies) are shifted to model a smooth and continuous curve at reduced frequencies [2,4].

The master curve of E* can be determined based on data obtained by laboratory tests with special equipment or by prediction algorithms. For in-service pavements, non-destructive testing (NDT) methods are becoming increasingly popular for the efficient evaluation and estimation of mechanical properties, such as stiffness. FWD (falling weight deflectometer) and GPR (ground penetrating radar) data are used as inputs for estimating asphalt layers (as well as unbound layers) through a backcalculation process [5]. Although a dynamic load is applied and the time history of deflections is recorded during FWD testing, only the peak deflection is considered in the analysis. Therefore, the modulus of stiffness estimated by backcalculation is the modulus of elasticity.

Researchers have recognised this drawback as well as the importance of the main E* curve in the evaluation of pavements. Therefore, they have focused their research on further using the deflection data time history from FWD measurements and recording to obtain the E* mater curve of asphalt pavements. In this direction, Kutay et al. [6] established a process to obtain the E* mater curve by backcalculation based on the time deflections. The process uses a stratified viscoelastic forward algorithm in an iterative backcalculation procedure for estimating the linear viscoelastic properties of flexible pavements. Using the deflection time histories from a single FWD measurement, the backcalculation of the relaxation modulus curve and the complex modulus curve was made possible. Varma et al. [7] developed a viscoelastic backcalculation algorithm to estimate the time–temperature displacement factor of asphalt mixes based on a genetic optimisation method and a stratified viscoelastic forward solution. A series of FWD measurements at various temperatures are required, and the time history of deformation is used for the backcalculation process. Zaabar et al. [8] used the DYNABACK-VE program to backcalculate pavement mechanical properties based on field obtained data. A viscoelastic dynamic solution in the time domain was used as the forward routine and a genetic algorithm was used for the backcalculation analysis.

The progress of this research resulted in the development of an algorithm that uses the FWD time histories of deflection at more than one temperature to backcalculate the dynamic modulus master curve [9]. ANNs (artificial neural networks) are a promising tool for estimating the E* master curve of in-service pavements, but further efforts are needed to address issues related to prediction accuracy [10–12]. Lee et al. [13] managed to construct an E* master curve using FWD deflection- time history data. ViscoWave was employed for forward analysis, while Microsoft Excel Solver was utilised for backward analysis. Hamin et al. [14] proposed a method by incorporating the finite element method and two types of ANN, with promising results as to the capability of producing accurate results.

Du Tertre et al. [15] proposed an alternative to evaluate the elastic properties of asphalt by ultrasonic-based testing. Their primary objective was to investigate two NDT methods: ultrasonic surface wave (USW) testing; and lightweight deflection (LWD testing). The aim was to achieve a satisfactory estimate of the E* over a range of frequencies, eliminating the need for laboratory testing, which is a destructive method for in-service pavements. Based on the comparison of the elastic moduli of laboratory prepared samples (control samples) and in-service pavements, they concluded that testing from USW is a convenient and reliable method for the assessment of in-service flexible pavements.

The above methods are promising but time-consuming. Therefore, their applicability is not practical. The MEPDG (Mechanistic-Empirical Pavement Design Guide) represents a significant milestone in the field of pavement engineering [16]. It is a rigorous, multi-parametric method and presents various aspects such as material characterisation, new pavement design, rehabilitation design, and characterisation of existing pavement layers characteristics. For the latter, the MEPDG introduces a method that involves creating a damaged E* master curve tailored to field conditions, utilising in situ NDT data from the FWD, along with an algorithm to estimate E* (Figure 1). Unlike the traditional modulus master curve, which assumes a pristine, undamaged state, the damaged modulus curve accounts for the degradation of the material over time due to repeated traffic loads and environmental stresses. Step 3 can be realised either through extensive laboratory testing on field cores (Level 1) or through limited laboratory testing and/or historical data (Levels 2 and 3). However, research on the applicability and accuracy of the proposed damaged E* master curve method is limited. Loulizi et al. [17] concluded that the proposed methodology can provide accurate results, but also pointed out some drawbacks. Solatifar et al. [18] made some adjustments to the method to accurately estimate the E* master curve.

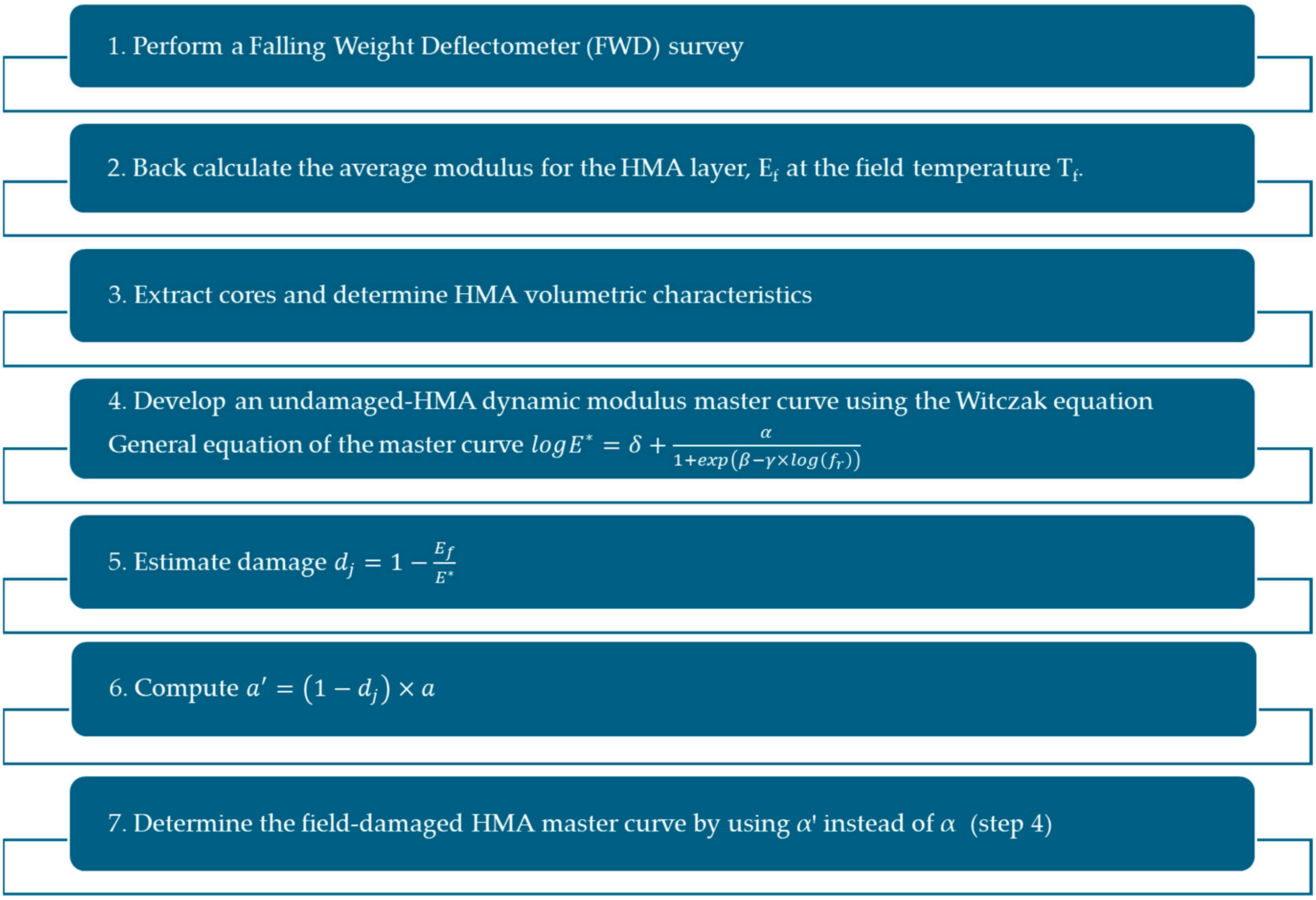

Figure 1. MEPDG methodology for E* field-damaged master curve.

In contrast with the approaches described previously, the proposed damaged E* master curve method provides a mechanistic method for the determination of the damaged E* master curve that can be implemented as part of a routine pavement monitoring system procedures. It requires a single measurement with the FWD and the backcalculation procedure can be completed with traditional back analysis tools. This results in reduced time for both gathering the input data and analysing them, thus reducing the related cost.

To this end, this study focuses on exploring the implementation of this methodology, and thus the capability of using NDT systems, to determine the E* field master curve. The objectives are to assess each step of the process, identify potential weaknesses, suggest improvements, and evaluate the methodology's accuracy in predicting performance characteristics such as percent of fatigue cracking (FC) and rut depth (RD) in the asphalt layer. The experimental study was conducted in order to: (1) collect FWD and GPR data and perform coring; and (2) conduct laboratory tests on the extracted cores. The validation was achieved through the fatigue cracking (FC) and rutting performance (RD) indices.

2. Materials and Methods

2.1. Field and Laboratory Testing

A highway in-service pavement section was selected for the conduction of in situ testing. The pavement cross-section consists of the subgrade, the base/subbase layer of unbound material, and the asphalt layers. The asphalt layers consist of the asphalt base layer (dense grades asphalt mix) and the antiskid asphalt layer (open graded asphalt mix). The binder of the asphalt base is classified based on the penetration index to 50/70 PEN, while for the antiskid wearing course a modified 50/70 PEN binder with 4% SBS was used.

Non-destructive testing was performed along the pavement section with FWD (Figure 2) and GPR (Figure 3) systems. The FWD load was 50 kN applied on 300 mm diameter loading plate; thus, the produced stress was 700 kPa [18]. Holes drilled in the pavement enabled the recording of temperature at the mid-depth of the asphalt layers. Figure 4 illustrates the distance of the geophones from the centre of the loading plate. Data recorded from air-coupled GPR system with an antenna operating at 1000 MHz were utilised for the estimation of the layers thicknesses, in order to be used as input parameters, along with the deflections, for the backcalculation procedure. The backcalculation procedure was performed based on genetic algorithms (GAs) [19–26]. The methodology does not provide any guidance on how to treat multilayered asphalt layers. In this study, for the backcalculation procedure, the pavement was modelled through a cross-section consisting of a single asphalt layer, a base/subbase layer, and the subgrade. Asphalt layers were not considered as separate layers and therefore, the backcalculated modulus corresponds to the composite modulus of the asphalt layers, which is a function of each asphalt layer modulus and its thickness.

Figure 2. FWD measurements.

Figure 3. GPR measurements.

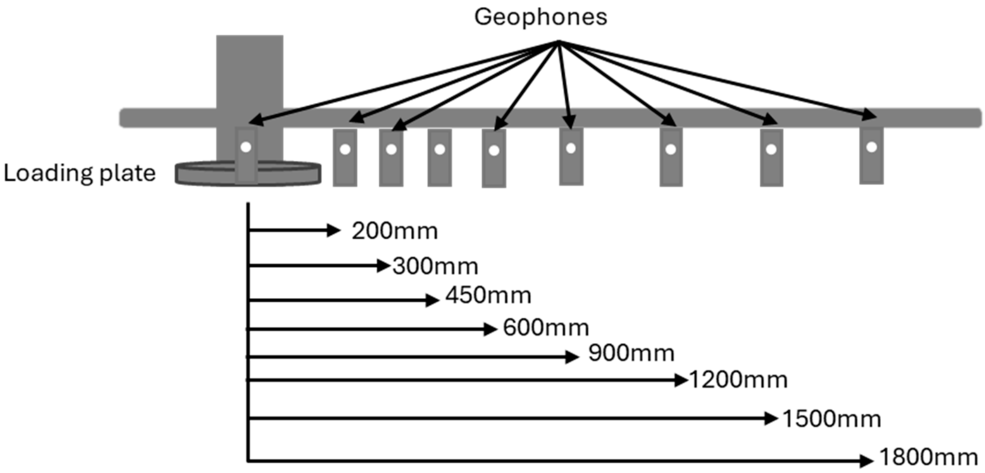

Figure 4. FWD deflection sensors set up.

Upon completion of the NDT measurements, five cores were extracted at selected locations where the FWD measurements were taken. Core extraction served several purposes. First, to determine the volumetric characteristics of the cores that will serve as input parameters for the algorithm estimation of E*. Second, for the calibration of the asphalt layer thickness estimated through GPR data analysis. Last, for determining the E* in the lab according to AASHTO T 342-11. The determination of the E* on the cores was enabled due to the fact that the asphalt layers' total thickness was equal to or greater than 15 cm, which is the required specimen height for conducting the E* laboratory test. Moreover, there were no signs of deterioration (cracking). The E* determined refers to the composite modulus, in the sense that specimens consisted of two asphalt mixes: the asphalt base; and the antiskid layer.

2.2. Materials

Figure 5 presents the aggregate gradation of the asphalt layers. Figure 6 shows the volumetric composition of mixes, namely air voids content (Va), asphalt content (Vb), and effective asphalt content (Vbeff).

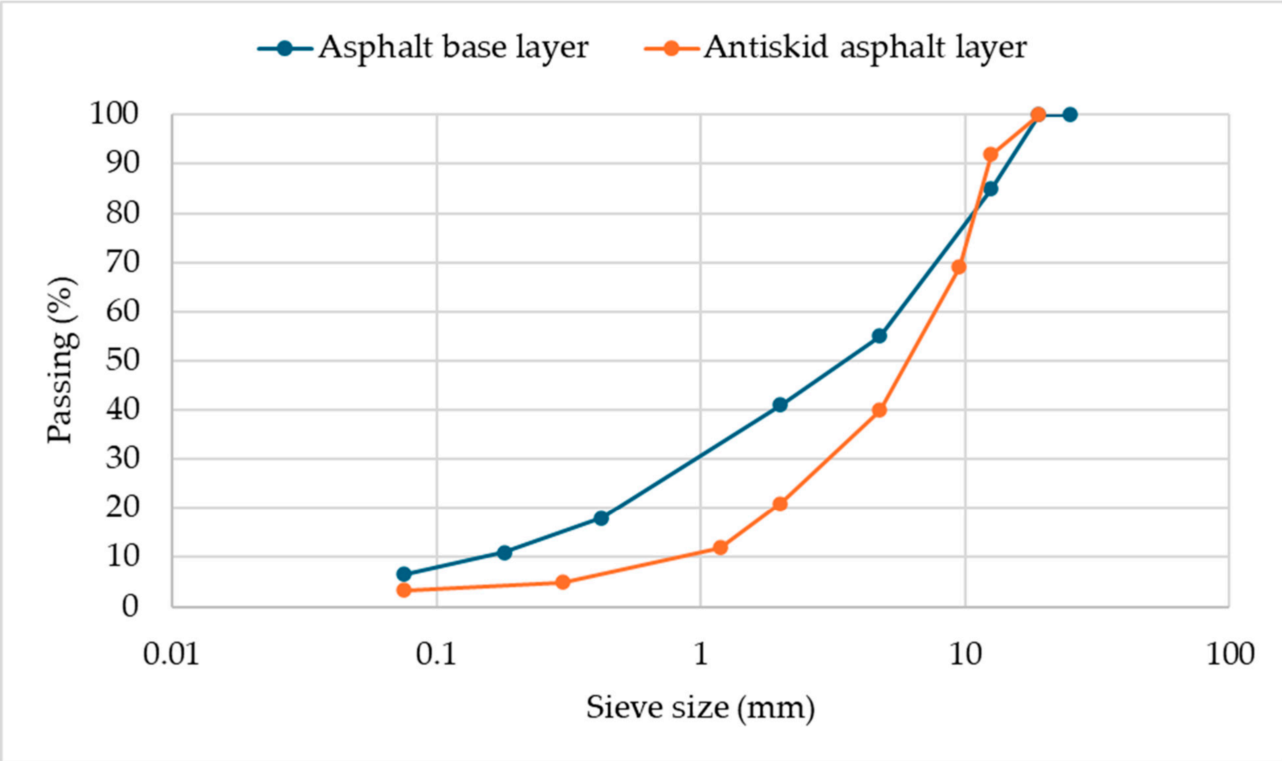

Figure 5. Aggregate gradation of the asphalt layers.

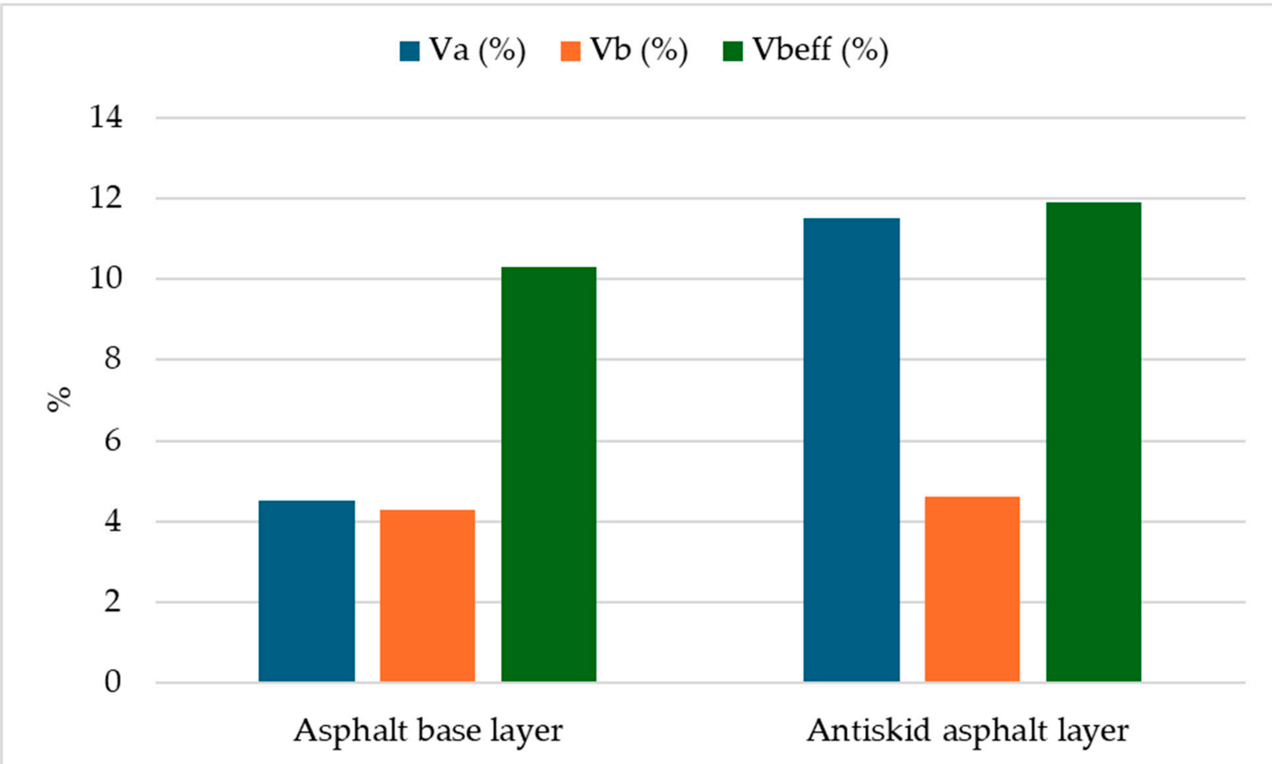

Figure 6. Volumetric composition of mixes.

Laboratory testing showed that the cores' characteristics were similar, which was expected since the pavement cross-section was uniform. Specifically, the air voids content of the five specimens was 4.21, 4.05, 4.46, 4.2, and 4.1% with an average value of 4.2%. The coefficient of variation (CV), calculated as the ratio of the standard deviation to the average value, is 3.7%, indicating that the asphalt mix of the cores is uniform regarding the air voids content. Therefore, the core specimen with air voids content of 4.2% was considered as representative of the asphalt mix. As such, further analysis and results presented below correspond to a single core.

3. Results

3.1. Development of the Undamaged E Master Curve*

According to the proposed methodology, the Witczak prediction equation [27] is used for the development of the undamaged E* master curve. However, Georgouli et al. [4] have proved that the Witczak equation seems not to produce accurate results for this type of asphalt base course mixes, although it is suitable for the prediction of the antiskid surface course mixes E*. Therefore, for the asphalt base mixes, the prediction algorithm developed by Georgouli et al. [4] was used (Equation (1)), while for the antiskid surface course mixes, the Witczak equation [27] was used.

$$\begin{aligned} &logE^* \\ &= 3.9 + 0.37437p_{200} - 0.0298(p_{200})^2 - 0.01221p_4 - 0.08686V_a \\ &-0.94215\left(\frac{V_{beff}}{V_{beff}+V_a}\right) \\ &+\frac{3.04483-0.01124p_4+0.00242p_{38}+0.00025(p_{38})^2+0.00111p_{34}}{1+exp(-1.07682-0.47006logf-0.62593log\eta)} \end{aligned} \tag{1}$$

where p_{200} is the percentage passing 0.075 mm sieve, p_4, p_{34}, p_{38} is the cumulative percentage retained on a 4.75 mm, 19 mm, and 9.5 mm sieve, respectively, η is the viscosity of binder (10^6 poise), and f is the loading frequency (Hz).

Since the asphalt layers consist of two different asphalt mixes, upon the estimation of the E* values for each mix, the E* values were combined with the thickness of each asphalt layer (Equation (2)) so that the 'composite' dynamic modulus of the total asphalt layers could be determined [28].

$$E^*_{comp} = \left(\sum\left((h_i/h_{comp}) \times E_i^{(1/3)}\right)\right)^3 \tag{2}$$

where E^*_{comp} is the E* of the total asphalt layers, h_i is the thickness of the i layer, h_{comp} is the total thickness of the asphalt layers, E_i is the E* of the i layer and i = 1 to n, where n is the number of individual asphalt layers. The total thickness of the HMA layers is 154 mm, consisting of 126 mm asphalt base and 28 mm antiskid surface course.

These E* values were used for the development of the undamaged E* master curve at the selected reference temperature of 20 °C presented in Figure 7.

The sigmoidal function describing the undamaged HMA E* master curve is provided in Equation (3).

$$logE^* = 0.521715 + \frac{2.823081}{1 + exp(-1.595648 - 0.473622logfr)} \tag{3}$$

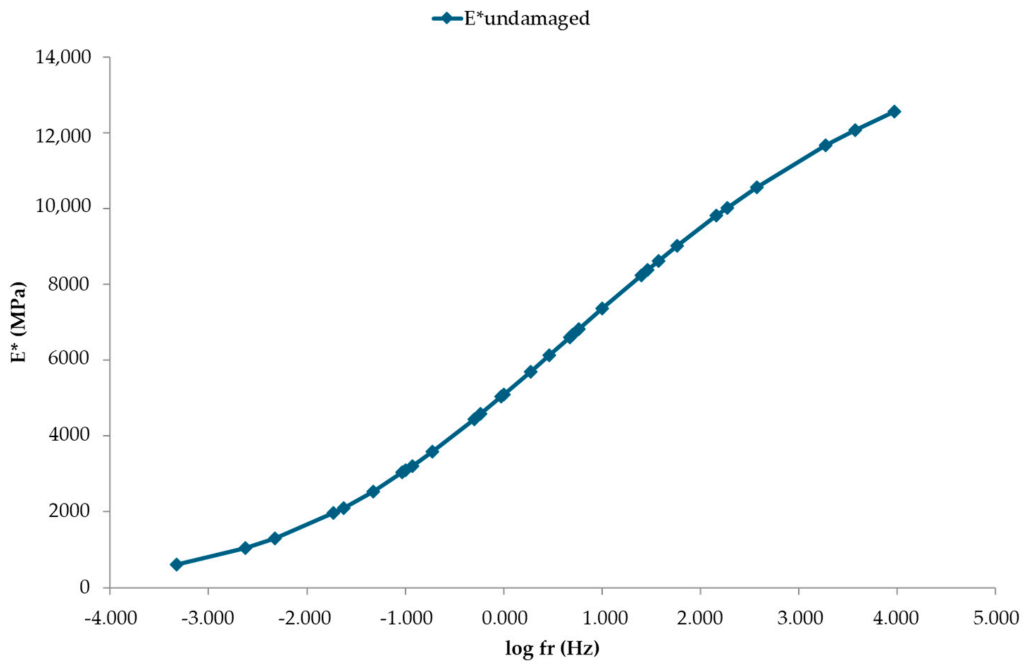

Figure 7. Undamaged HMA E* master curve.

3.2. Development of the Field E Master Curve*

3.2.1. Damage Estimation

For the estimation of damage d_j, the estimated undamaged HMA E* needs to be defined at the field temperature at a frequency corresponding to the load pulse of the FWD. The FWD frequency was determined through the time history (Figure 8).

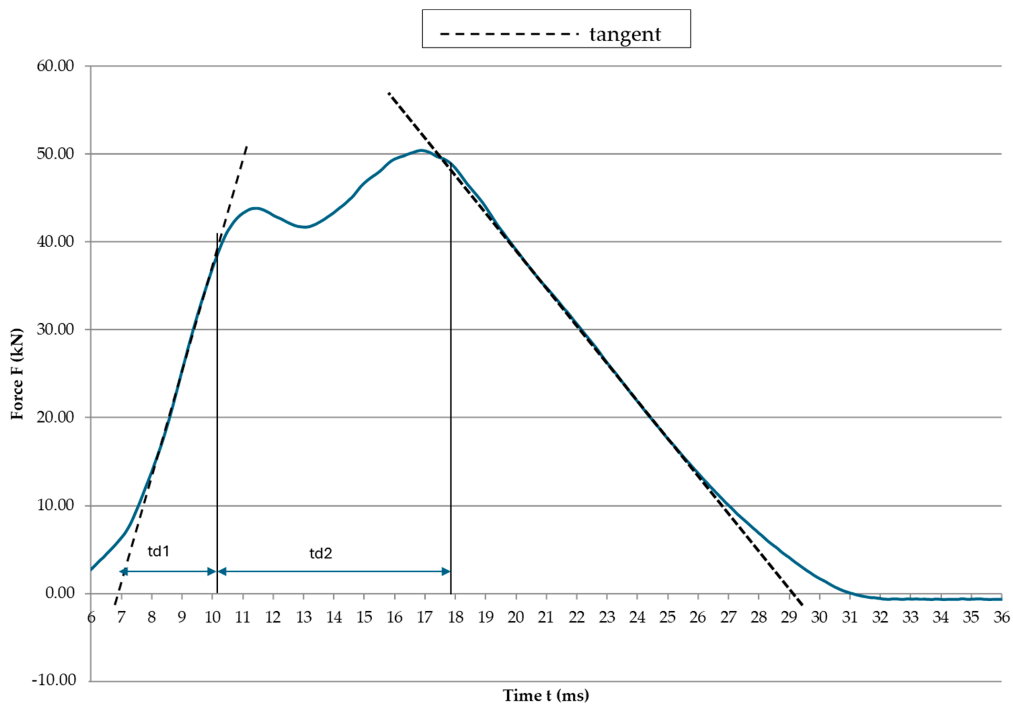

Figure 8. FWD time history.

Since the load pulse is imperfect sinusoidal, the approach described in [29] is applied. Equations (4)–(7) were used for the determination of the FWD frequency (f_{FWD}).

$$t_{b1} = \frac{2t_{d1}}{\pi} \tag{4}$$

$$t_{b2} = t_{d2} \tag{5}$$

$$t_b = t_{b1} + t_{b2} \tag{6}$$

$$f_{FWD} = \frac{1}{2\pi t_b} \tag{7}$$

where t_{b1} and t_{b2} are the individual load durations (ms) defined graphically from duration times t_{d1} and t_{d2} (as noted on Figure 8), t_b is the total loading time (ms), and f_{FWD} is the loading frequency (Hz). It is noted that in Equation (6) t_b is expressed in s.

The concluded FWD frequency (f_{FWD}) was 16.3 Hz. This is in accordance with international experience [29,30]. The estimated undamaged E* at the field temperature of 9.5 °C and loading frequency of 16.3 Hz is equal to 11,039 MPa. The estimated damage dj is equal to 0.036.

It should be noted that initially an effort was made to incorporate the Witczak equation in the analysis for the estimation of the E* of the asphalt base layer mix as well. However, by doing so, the construction of the field master curve was not feasible, since the estimated damage appeared to have negative value. This was due to the fact that the estimated undamaged E* at the field conditions was smaller than the backcalculated modulus of the HMA layers. Therefore, no further analysis could be performed.

3.2.2. Determination of the Field E* Master Curve

According to step 6 of Figure 1, α' is found equal to 2.72087 considering that α is equal to 2.823081 as shown in Equation (3). Then, the field HMA master curve was determined by replacing parameter α with α' in step 6 of Figure 1. In Figure 9, both E*undamaged and E*field master curves are presented.

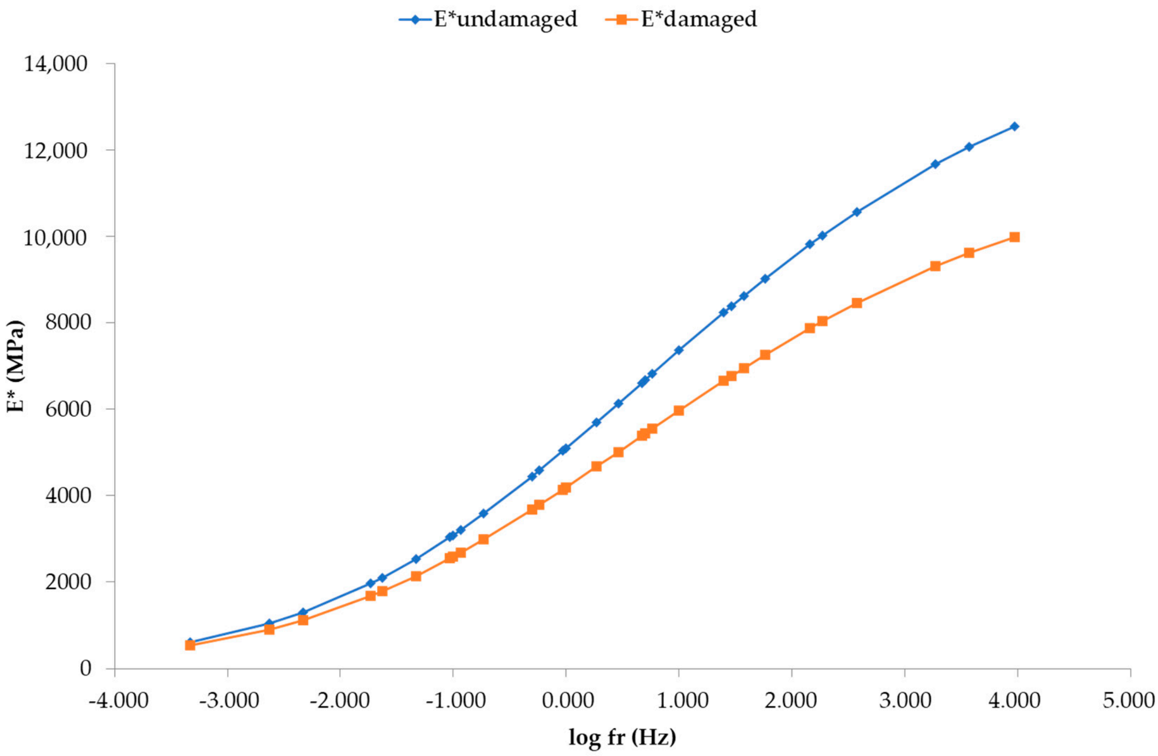

Figure 9. E*undamaged and E*field master curves.

Damage and consequent deterioration of the HMA layers condition are rather small due to the fact that the operation time of the investigated pavement is three years, and no distresses were observed on the pavement surface.

3.3. Validation Process

Further analysis was performed in order to investigate whether the methodology followed can produce accurate results as far as the E*field master curve is concerned. Given that cores taken were in good condition with no distresses observed and the thickness of the asphalt layers was 15 cm, they were tested in the lab and the dynamic modulus was determined for various loading conditions, as described earlier. These values represent the actual field E* as determined in the lab (E*core). Therefore, the E*field master curve, which was determined with the process being investigated, is compared to the E*core. Figure 10 shows the E*undamaged and the E*field master curves in comparison with the one which was developed using the E*core measurements in the lab (E*core). The E*core master curve is described mathematically by Equation (8).

$$logE^* = 0.521715 + \frac{2.742355}{1 + exp(-1.595648 - 0.473622 log fr)} \quad (8)$$

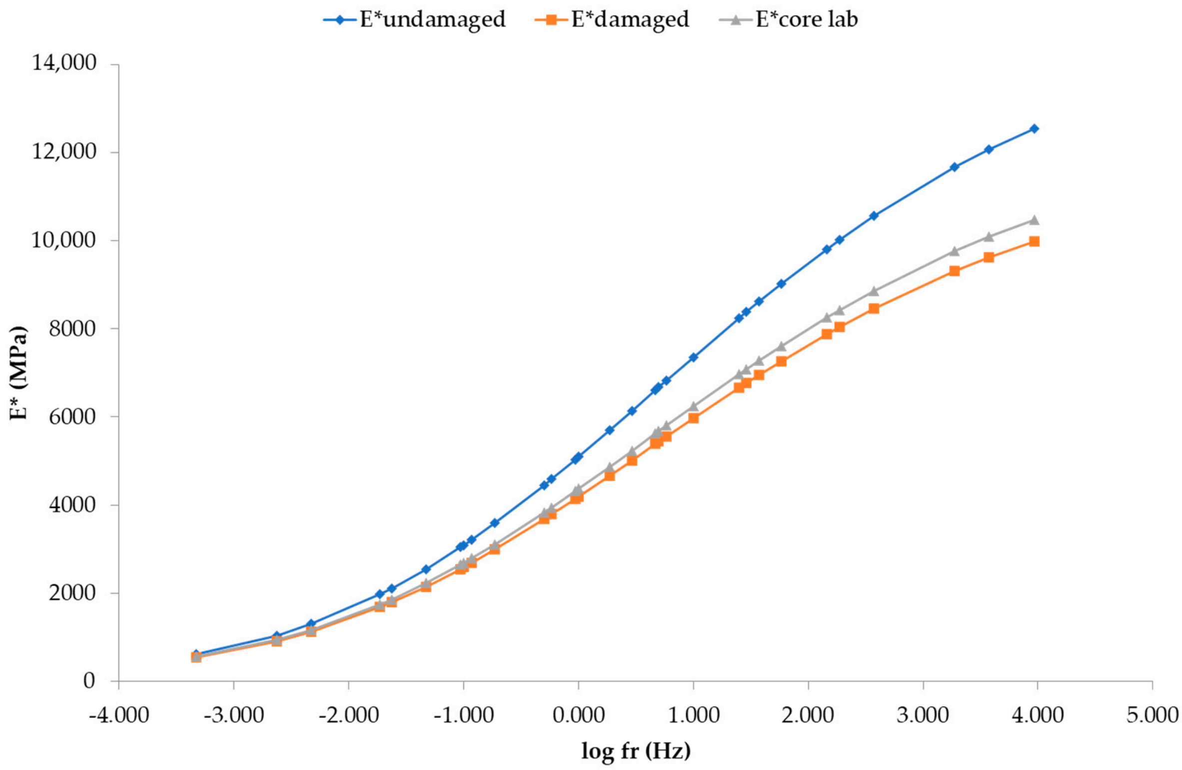

Figure 10. E*undamaged, E*field and E*core master curves.

The values of the two master curves representing the in situ conditions, E*field and E*core, do not seem to differ significantly. *t*-test statistical analysis showed that their difference can be considered equal to 200 MPa for a 95% confidence interval, since the *p* value is greater than 0.005. That means that the field E* is underestimated by a weighted value of 200 MPa following the proposed methodology.

The evaluation process is further assessed through performance indexes of FC and RD, following basic model principles [15]. Simulations with the 3D-Move analysis program were performed for a vehicle moving at 60 km/h [31–33]. Table 1 presents the FC (%) and RD (mm) index values at the end of the analysis period, with the assumption that no maintenance activities will take place and considering both E*field and E*core master curve values.

Table 1. Fatigue cracking and rutting.

Index	E*field	E*core
FC (%)	7.09	7.2
RD (mm)	12.01	11.92

Differences in both estimated fatigue cracking and HMA rutting are not significant, which means that the proposed methodology for the development of the E* field master curve can provide accurate results in terms of HMA layers condition assessment and evaluation.

4. Conclusions

The main findings of the present investigation are the following:

- For the development of the E* field master curve, a reliable and accurate E* prediction algorithm should be used to estimate the undamaged E* master curve. If this is not the case, it may lead to erroneous results or even make further analysis impossible, as in this study. Therefore, the need for local calibration of the E* prediction equation is emphasised.
- The method is also applicable for cases in which the asphalt layers consist of different asphalt mixes (asphalt base layer and wearing course). For the backcalculation, the modelling of the asphalt layers as a single layer is recommended. In this case, the backcalculated modulus corresponds to a composite damaged modulus. For the estimation of the undamaged modulus, more than one algorithm may be activated suitable for the different asphalt mixes. Then, the composite undamaged modulus can be calculated as a function of the modulus and the thickness of each asphalt layer.
- As for the evaluation of the proposed methodology in terms of its accuracy in developing the E*field master curve, the comparative analysis with the E* master curve obtained in the laboratory by testing cores has shown that the methodology is robust and can yield accurate results for the E*field.
- This is also confirmed by the analysis results of the estimated stresses with respect to the FC and RD prediction models incorporated in the present concept approach. Considering the E*field and E*core master curve values as input for the stress estimation, the differences in both estimated fatigue cracking and HMA rutting were not significant.
- The existing asphalt layers E* master curve can be obtained through a single FWD testing and traditional back analysis methods, which is in favour of the efficiency of the proposed approach. Integration of NDT data can provide valuable input parameters for the evaluation of in-service pavements.
- While other methods offer powerful tools for pattern recognition and predictive modelling, the investigated procedure's E*damaged modulus master curve provides significant advantages in terms of integration with traditional practices and robustness.
- The damaged modulus master curve directly integrates with performance prediction models, ensuring that predictions of distress, such as fatigue cracking and rutting, are directly linked to the pavement's mechanical properties.

- It seems that the investigation provides a clear and transparent methodology for developing the damaged modulus master curve, making it easier for engineers to understand the underlying processes and assumptions. This transparency is critical for validating and refining pavement designs.

The results are promising and apply to a certain pavement cross-section and materials. Further research could involve the consideration of various pavement structures and asphalt mix materials. Further investigation into the load frequency of the FWD measuring equipment may also prove beneficial.

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