Analytical Redesign Approach for Flexible Pavement Using Non-Destructive Tests

A. Loizos, V. Papavasiliou & C. Plati
Laboratory of Pavement Engineering, National Technical University of Athens (NTUA), Athens, Greece

ABSTRACT: The present paper presents the methodology and the results of an analytical redesign approach for a new typical flexible pavement of a four-lane dual carriageway highway within a Public Private Partnership (PPP) concession system. Prior to the construction of the pavement, a trial section was constructed taking into account the outcome of an analytical pavement design procedure. On the surface of the pavement, Non Destructive Testing (NDT) was carried out using the Falling Weight Deflectometer (FWD). In respect to the measured deflections, a back-analysis was applied, in order to assess the modulus values of the AC, the unbound layers and the subgrade. A strain response analysis was undertaken and the calculated critical strains using the in situ collected data were evaluated. Following the results of the analytical redesign procedure, it was concluded that the in situ characteristics of the materials differ from the material input data used for the mechanistic pavement design. Taking advantage of the calculated in situ characteristics it may be possible to achieve more reliable results in terms of a rational analytical pavement design approach.

KEY WORDS: Redesign, non-destructive tests (NDT), FWD, strain response analysis.

1 INTRODUCTION

Pavement engineers frequently utilize analytical tools to assist in analyzing pavement structures, taking into consideration the in-service condition of the road. Such tools facilitate the establishment of a performance-based design, capable of extending the service life of roads. An ideal design tool consists of a structural model capable of predicting the state of stresses and strains within the pavement structure under the action of traffic and environmental loading.

Fatigue performance models can calculate or predict the total number of Equivalent Standard Axle Load repetitions (ESALs) to a structural fatigue cracking failure. These models, using actual performance field data, calculate the total number of repetitions to failure using expected in situ material properties. However, field data is not available until the pavement is constructed. For this reason, pavement engineers often use conservative material property values to ensure that the design will meet or exceed calculated traffic predictions in terms of ESALs [COST 333, 2000]. Therefore, the pavement may often be overdesigned.

In order to investigate the issue above, an experiment was performed, based on a trial section, where the analytical redesign approach was introduced. The present paper presents the methodology and the results by introducing an analytical redesign of a new typical flexible pavement, based on in situ material properties. The pavement is to be constructed for a four-lane dual carriageway highway within a Public Private Partnership (PPP) concession system. Prior to the construction of the highway pavement, a trial section was constructed taking into account the outcome of an analytical pavement design procedure. On the surface of the pavement Non Destructive Testing (NDT) was carried out by the Laboratory of Pavement Engineering of the National University of Athens (NTUA) using the Falling Weight Deflectometer (FWD).

In respect to the measured deflections using the FWD, a back-analysis was applied in order to assess the modulus values of the AC, the unbound layers and the subgrade of the pavement. The aim of the investigation was the comparison of the mechanical properties of the different layers of the constructed pavement with the design data.

In respect to the analysis results of the in-situ collected data, a strain response analysis was undertaken and the calculated critical strains using the in situ collected data were compared with the related ones using the analytical pavement design data. The aim of this analysis is to investigate a potential reduction of the pavement layer thicknesses, however without reducing the bearing capacity for the predicted number of Equivalent Standard Axle Loads (ESALs) during the design life of the pavement.

The benefits of the redesign approach are pronounced in this paper. The impact of the unbound granular material is also demonstrated. The main findings of the data analysis concerning the conducted field-testing are presented and discussed in the present paper.

2 PAVEMENT DATA COLLECTION AND MODELING

The analytical pavement design data of the pavement (taking into account a total number of $3*10^7$ ESALs) were considered for the asphalt concrete (AC) layers a stiffness modulus of 4500 MPa based on laboratory data [CEN, 2005]. Furthermore, for the unbound granular material a modulus of 400 MPa and for the subgrade a modulus of 200 MPa was considered for the purpose of the analysis. Considering a total unbound granular layers thickness (h_2) of 40 cm, the calculated total thickness of the AC layers was h_1 = 22 cm (see Figure 1a).

For the introduction of the redesign approach, a trial section approximately 250 m long was constructed. Both the component materials and the related layer mixes used for the construction of the trial section were the same as the anticipated ones to be used for the construction of the highway pavement. A reduced total AC thickness has to be introduced, in order to be able to study progressively the bearing capacity of the pavement. For the purpose of the investigation, the trial section was constructed up to the level of 18 cm total AC layers thickness. The reduced total AC thickness (by 4 cm) is mainly based on pavement engineering judgment, taking into account the pavement cross-section and construction aspects as well. For the estimation of the bearing capacity of the pavement, in situ NDT using the FWD were performed at eleven specific test points of the trial section.

A detailed back-analysis was performed using the Elmod software [Dynatest, 2006]. The horizontal (tensile) strains at the bottom of the AC layers (ε_r), as well as vertical compressive strain at the top of the subgrade (ε_z) (see Figure 1), were calculated using a multi-layer linear elastic analysis [BISAR, 1998]. The load used for the calculations was a 65 kN single wheel (in accordance with the maximum allowable in Greece axle load of 13 ton) with a 150 mm radius. Strains were also calculated using the analytical pavement design data following the related pavement model (Figure 1b).

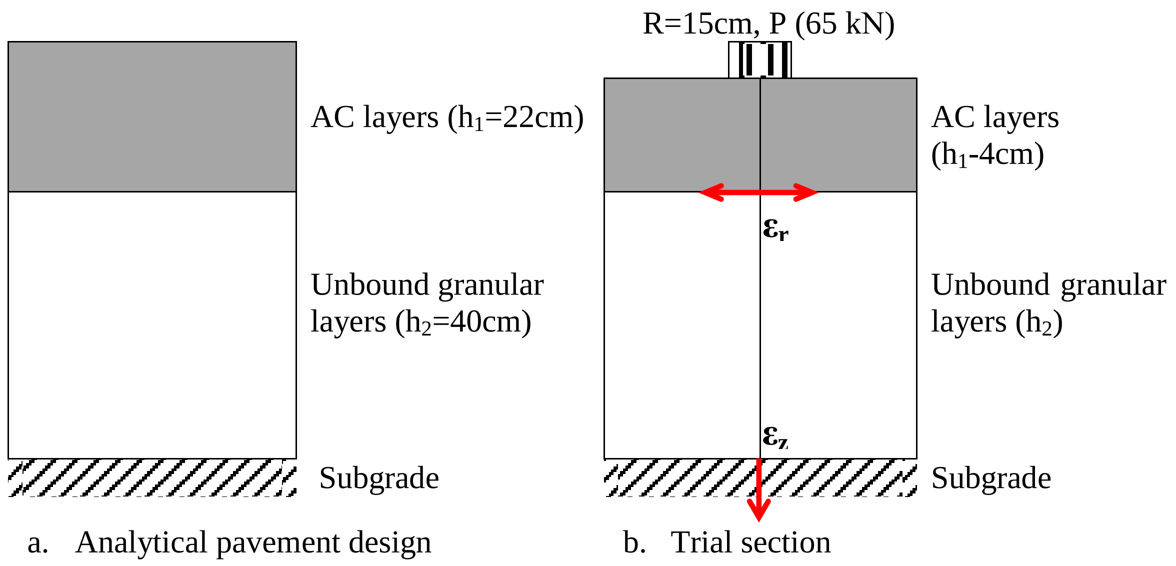

Figure 1: Pavement modeling (cross-section).

The back-calculated pavement layers moduli as well as the calculated strains using the in situ collected data were compared with the related ones from the analytical pavement design. The criterion used for evaluation of the structural equivalency (against fatigue) of the constructed pavement (in respect to the initial designed) was the strain comparison. If the in situ calculated strains are equal or lower than the related ones using the design data, the constructed pavement can be considered as equivalent or superior to the initially designed pavement. Thus, the redesign of the constructed pavement is completed and the total thickness of the AC layers can be considered as sufficient to carry the predicted ESALs.

3 DATA ANALYSIS

3.1 Back-calculated moduli

The back-calculated AC layers moduli of the trial section were corrected to the reference temperature according to reference (Baltzer and Thompson 1994). The minimum back-calculated moduli values were for the AC layers 4608 MPa, for the unbound granular layers 607 MPa and for the subbase 292 MPa.

The results at every test point are presented in Figure 2(a) for the AC layers, in Figure 2(b) for the unbound granular layers and in Figure 2(c) for the subgrade. The related analytical pavement design values are also presented in the above Figures.

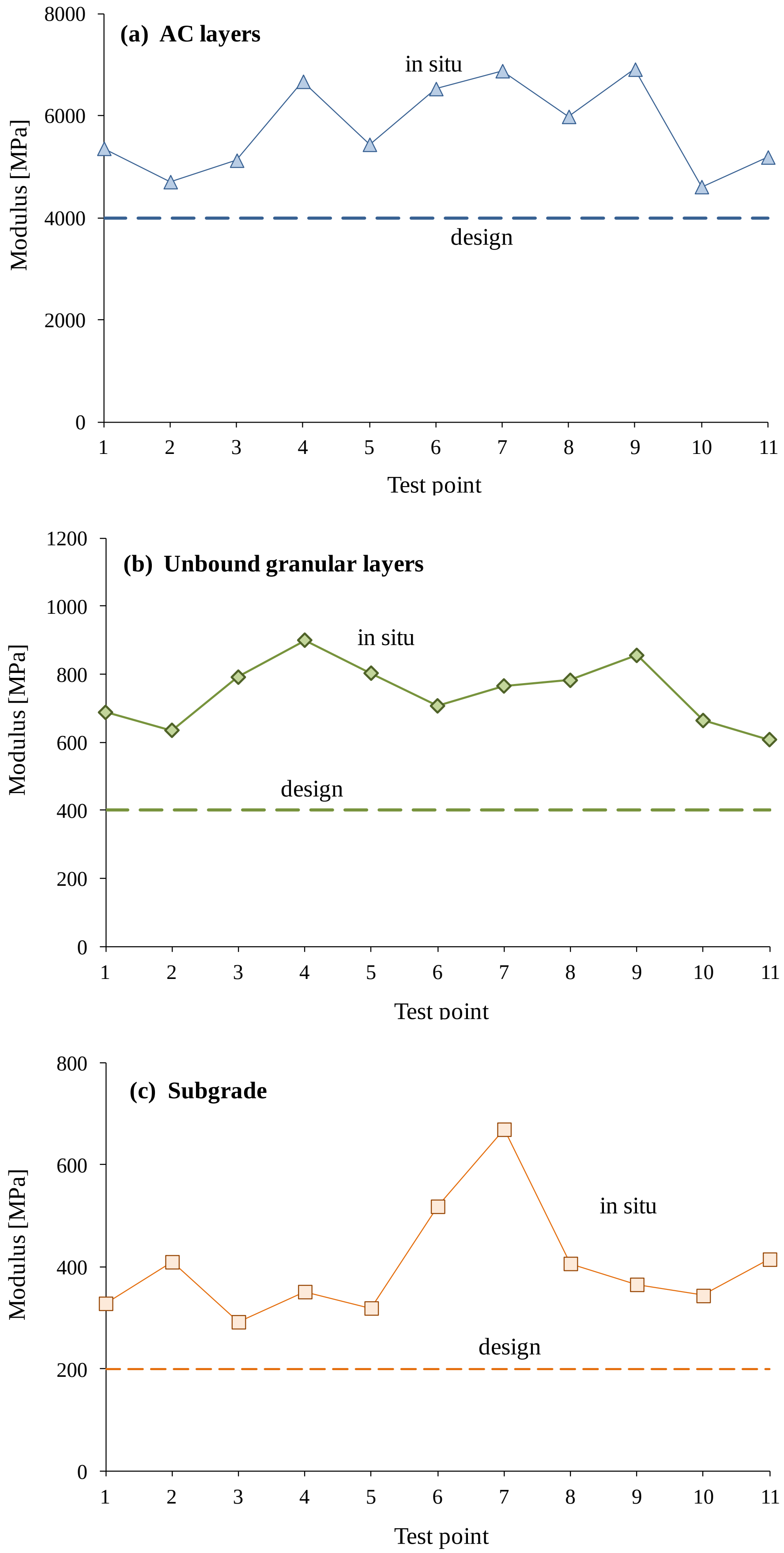

Figure 2: Back-calculated layer moduli.

As it can be seen, during measurements on the surface of the pavement with a total AC layers thickness of 18 cm, the back-calculated layers moduli were higher than the related ones from the analytical pavement design. However, due to the fact that according to the pavement design the total AC layers thickness should be higher (22 cm), than the related one of the trial section (18 cm), it is not possible to evaluate the structural adequacy of the pavement of the trial section taking into account the back-analysis results.

For this reason, the structural evaluation of the pavement should be done, by comparing the induced critical strains ε_r and ε_z (see Figure 1) in the body of the pavement with the related ones_using the data from the analytical pavement design (thresholds). The analysis results and the related discussion points are included in the following subsection 3.2.

3.2 Strain response analysis

The back-calculated moduli as well as the thicknesses of the different pavement layers of the test section were used for the forward calculation of the strains in the pavement (see section 2). The analysis results for every test point are presented in Figures 3 and 4 for the horizontal (tensile) strain at the bottom of AC layers (ε_r) and the vertical compressive strain at the top of the subgrade (ε_z) respectively.

The calculated critical strains using the analytical pavement design data (thresholds) were at the bottom of AC layers: ε_r = 142.6 microns (tension) and at the top of the subgrade ε_z = 178.5 microns (compression). These are shown in Figures 3 and 4 respectively.

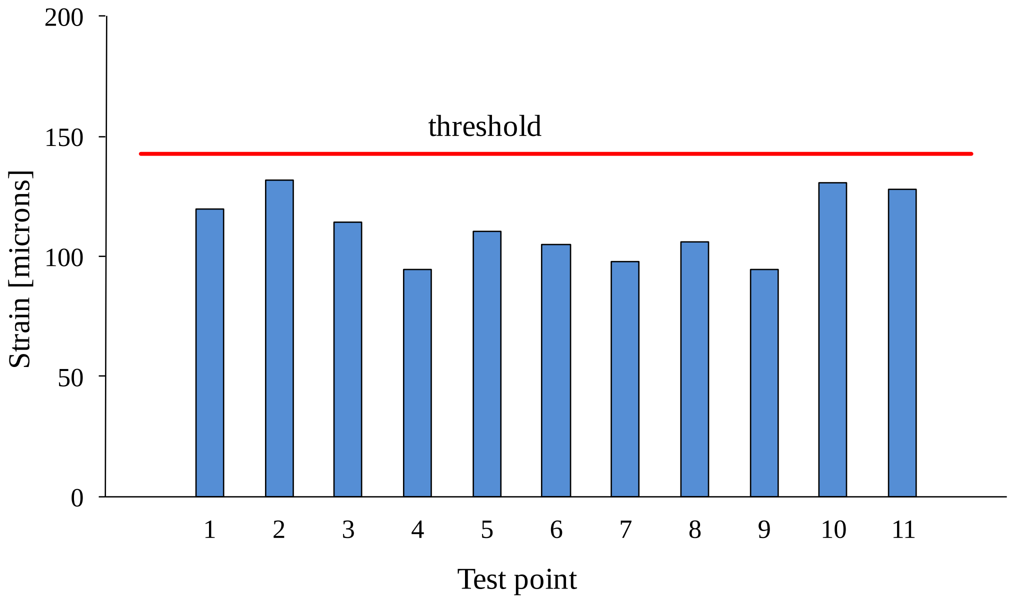

Figure 3: Horizontal (tensile) strains at the bottom of AC layers (ε_r).

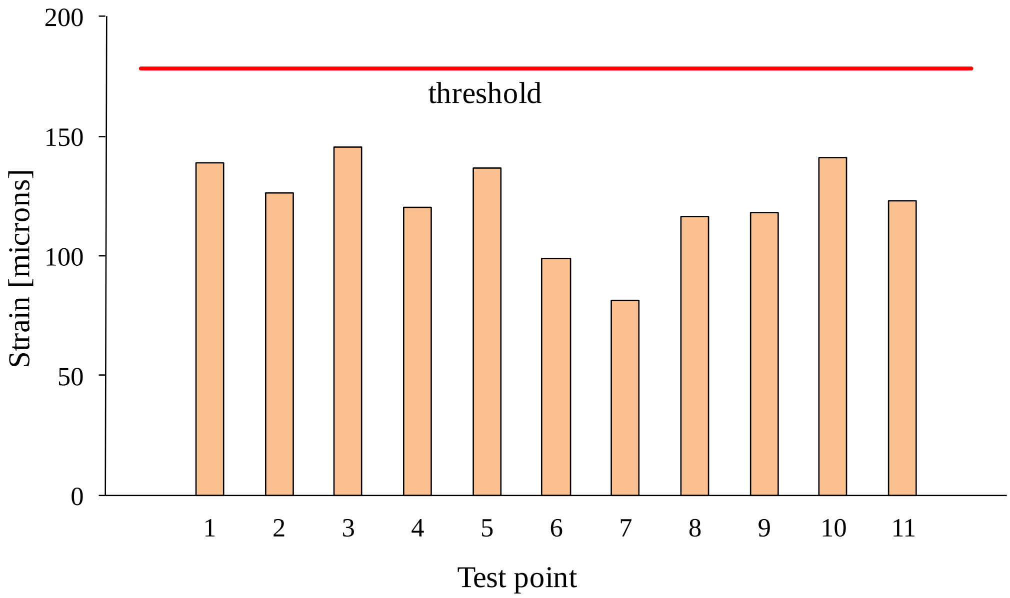

Figure 4: Vertical compressive strains at the top of the subgrade (ε_z).

As it can be seen, during measurements on the surface of the pavement with a total AC layers thickness of 18 cm, the calculated strains based on in situ material properties were lower in comparison with the related ones using the analytical pavement design data (with a total AC layers thickness of 22 cm).

According to the above results, the pavement can be constructed with a reduced total AC layers thickness, than initially estimated during the analytical pavement design procedure. Consequently, it can be concluded, that it is possible to construct a more economic highway, without a reduction in the structural adequacy of the pavement. Moreover, for the completion of the pavement surface, the "owner" of the highway (concessioner) can make decisions about the type of the wearing course, considering only techno-economic issues.

For the estimation of the minimum thickness of the total AC layers (min h_1) and the unbound granular layer (min h_2), however without exceeding the strain thresholds, an additional strain response analysis was conducted. The aim of this analysis procedure is to estimate the potential reduction in material quantities for the construction of the highway pavement.

To achieve this goal, the analysis was conducted at two specific test points of the trial section, where the maximum strains were calculated. In the case of the total AC layers thickness (h_1), the maximum horizontal (tensile) strain at the bottom of AC layers (ε_r) was calculated at test point #2 (see Figure 3). In the case the unbound granular layer (h_2), the maximum vertical compressive strain at the top of the subgrade (ε_z) was calculated at test point #3 (see Figure 4). For the strain response analysis, the in situ material properties of the pavement layers were used, however with reduced thicknesses, in comparison with the ones of the trial section. The analysis was done in three phases:

- During the first phase, the minimum total AC layers thickness (min h_1) was estimated, aiming not to exceed the threshold of the maximum horizontal (tensile) strain at the bottom of AC layers (ε_r). The first strain response analysis was carried out using the in situ material properties at the test point #2 (with h_2 = 40 cm).
- At the second phase, the minimum unbound granular layer thickness (min h_2) was estimated, aiming not to exceed the threshold of maximum vertical compressive strain at the top of the subgrade (ε_z). Using the min h_1 (estimated at the first phase), the second

strain response analysis was conducted using the in situ material properties at the test point #3.

- At the third phase, a strain response analysis was carried out using the min h_1 and min h_2 (estimated at the two previous phases) and the in situ material properties at the test point #2. The aim of this investigation is to check whether the critical strains (ε_r and ε_z) did not exceed the thresholds, e.g. whether of the bearing capacity of the cross-section with min h_1 and min h_2 is adequate.

The results of the above strain response analysis, as well as the design thicknesses and the strain thresholds are shown in Table 1.

Table 1: Strain response analysis results for minimizing the pavement layer thicknesses.

			Thickness [cm]		Strain [microns]	
			h_1	h_2	ε_r	ε_z
Design thicknesses *& strain-thresholds*			*22*	*40*	***142.6***	***178.5***
Test point (phase)	2	(first phase)	17	40	139.3	132.7
	3	(second phase)	17	35	121.8	**175.3**
	2	(third phase)	17	35	**139.9**	151.8

Taking into account the above results, the highway pavement could be constructed with a minimum total AC layers thickness: min h_1 = 17 cm and a minimum unbound granular layer thickness: min h_2 = 35 cm, in order to fulfill the requirements of the pavement design (without exceeding the thresholds of the critical strains). Consequently, the reduction in materials quantity could be 22.7% for the AC and 12.5% for the unbound granular material.

4 CONCLUSIONS

To balance a long-life pavement performance and optimization of layer thickness construction the possibility of taking advantage of the in situ characteristics of the pavement materials in terms of analytical optimization of pavement design was investigated. To achieve this goal, an analytical redesign approach was introduced, based on a trial section within a PPP highway pavement. The evaluation of the trial section was mainly based on FWD data and related analytical tools.

According to the analysis, the in situ characteristics of the materials differ from the material input data used for the mechanistic pavement design.

Moreover, it is possible to replace the conservative assumptions in terms of the material input data used during the analytical pavement design with the obtained in situ material properties through a redesign approach, in order to ensure that the design will meet the traffic predictions. Taking advantage of the in situ characteristics it may be possible to achieve more reliable results in terms of a rational analytical pavement design approach.

Taking into account the strain response analysis results using the in situ material properties, the highway pavement can be constructed with reduced layer thicknesses, than initially estimated during the pavement design procedure. It seems that it is possible to construct a more rational pavement structure, without a reduction in the structural adequacy of the pavement. For the completion of the highway pavement surface, the “owner” of the highway (concessioner) can make decisions about the type of the wearing course, considering only techno-economic issues.

The above introduced analytical redesign procedure (based on NDTs) can be applied for all climatic conditions. Moreover, the redesign approach, when applicable, may be a useful tool for a rational pavement design and construction approach in terms of a long-life pavement expectation.

REFERENCES

Baltzer, S. and Thompson, H., 1994. *Temperature Correction of Asphalt-Moduli for FWD-Measurements.* Proceedings of the 4th International Conference on the Bearing Capacity of Roads and Airfields, University of Minneapolis, Minnesota, USA.

BISAR, 1998. *BISAR User Manual*. Bitumen Business Group

CEN, 2005. *EN 12697-26: 2005. Bituminous mixtures - Test methods for hot mix asphalt – Part 26: Stiffness*

COST 333, 2000. *Development of New Bituminous Pavement Design Method*. EU Final Report, Brussels, Belgium

Dynatest, 2006. *ELMOD Quick start manual*. Denmark