Practical verification of the theory behind long-life asphalt pavements

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ABSTRACT

Traditional asphalt pavement design is based on a mechanistic–empirical approach which identifies the strain at critical locations in the pavement structure to safeguard the road against fatigue and structural deformation. However, research has shown that when roads are well built above a certain threshold, structural damage is non-existent with rutting confined to the surfacing, an ideal and economic design solution. The existence of these 'long-life' pavements challenges the current design and maintenance methodologies and suggests a need for a radical approach to pavement design. Although findings from global research have verified that a threshold effect for pavements does exist, there is limited real life data to support this theory. This paper, sponsored by Highways England, aims to demonstrate the threshold effect as well as develop a radical approach to flexible pavement design and maintenance, using the threshold concept. Three instrumented road sections of varying thicknesses were designed, built, and trafficked under varying wheel loads and speed. The results demonstrated classical pavement deterioration through both rutting and fatigue cracking. However, one of the sections showed no deterioration and the associated strains illustrate the threshold effect. In addition, a methodology is presented which involves the development of a robust model that predicts tensile asphalt strains directly from falling weight deflectometer (FWD) measurements which could be used as a tool to identify long life pavements on the English Strategic Road Network (SRN).

Keywords: Design of pavement, Fatigue Cracking, Performance testing, Permanent Deformation

1. INTRODUCTION

Traditional approaches to flexible pavement design include a mechanistic-based multi-layer analysis of pavement structures with identification of stress and strains at critical locations within the structure. The latest techniques focus primarily on the material properties and their behaviour at varying temperatures and climate conditions. Although these approaches are quite comprehensive and thorough, they require extensive laboratory testing and this is where these techniques tend to 'fall down' as the performance of pavement materials under laboratory testing conditions is significantly different from the performance of pavement materials in the field. The fact that a 'shift factor', which can vary from 2-2000, is required to relate laboratory to field predicted results simply highlights the need for a more simplistic approach.

This paper follows on from earlier work on alternative approaches to pavement design [1]. This work has looked at the current approaches to pavement design, in particular those used in the UK, highlighted their drawbacks, and presented an alternative approach which would not only focus on the behaviour on in-service roads (rather than analytical models), but also help identify threshold strains that signify long life behaviour of flexible pavements.

2. BACKGROUND

The current UK pavement design method, which is based on empirical performance data obtained from long-term monitoring of experimental pavements that were built on the primary road network, is described in Transport Research Laboratory (TRL) Report LR1132 [2]. From the resulting trafficking (20 million equivalent 80kN standard axles (msa)), only trial sections of 185mm thickness or less achieved failure. The design life of thicker pavements was then extrapolated based on these performance trends.

Closer inspection of the performance data showed that none of the trial sections failed by fatigue cracking. Furthermore, research carried out by the Highways Agency in the 1990's on roads that carried much more traffic than the experimental sections, showed no indication of classical fatigue cracking, with the majority of cracking initiating at the surface, with rutting confined to the top 100mm of the asphalt. This research therefore confirms that when roads are well built above a certain threshold, structural damage is non-existent with rutting confined to the surfacing. This behaviour has led to the term 'long life pavements' and suggests that a threshold condition exists for pavements below which fatigue damage is minimal. However, there is limited data to support this theory, and in particular, to determine the threshold level.

In recognition of existing pavement behaviour of which we are more certain of, this research paper aims to build upon this knowledge and the concept of an alternative approach to pavement design, taking into account the existence of long life pavements, and uses data from experimental trial sections under accelerated pavement testing and in-service roads to define the threshold condition.

3. METHODOLOGY

In order to demonstrate the threshold effect, asphalt pavements of varying thickness were designed and constructed in an accelerated pavement test facility and instrumented with asphalt and subgrade strain gauges to help capture the pavements response under repeated trafficking at increased load levels. In addition to recording the critical stresses and strains within the pavement, the stiffness of the pavement at various stages of the trafficking was captured using deflection measurements recorded under an FWD.

Once the accelerated testing of the trial sections was complete and the resulting data was analysed, the following methodology was used firstly, to develop an alternative approach to current pavement design methods, and secondly, to demonstrate the threshold condition;

1. Using the data recorded from the accelerated testing, develop a robust model that can predict critical tensile strains at the bottom of the asphalt layer directly from FWD measurements both before and during PTF trafficking. Such a tool could be used to determine the threshold strain of any major flexible pavements exhibiting long life behaviour, which currently exist on the strategic road network.
2. Examine the trends in pavement performance i.e. structural deformation and fatigue cracking and determine the corresponding threshold strains of pavements which show little or no deterioration (if any).

4. ACCELERATED TESTING OF TRIAL SECTIONS

Experimental trial sections were constructed in the Pavement Test Facility (PTF) at TRL in December 2010. The trial sections comprised of three fully flexible pavement sections with asphalt thicknesses (25mm SMA over HDM50) of 100mm, 150mm and 200mm for sections 1, 2 and 3 respectively, as shown in Figure 1. Each section had a nominal thickness of 225mm layer of Type 1 sub-base overlying a clay subgrade with a design CBR of 2.5%. Core samples were obtained from un-trafficked areas for stiffness modulus testing of the asphalt layers but these results were not available at the time of going to press.

During construction, asphalt base and subgrade strain gauges were incorporated into the trial sections. The base gauge recorded the horizontal tensile strain at the bottom of the asphalt layer. The subgrade gauge recorded the vertical compressive strain at the top of subgrade. The layout of the three trial sections showing the strain gauge location is presented in Figure 2. The gauges were numbered from 1 to 18 (Section 1 – 1 to 6, Section 2 – 7 to 12 and Section 3 – 13 to 18).

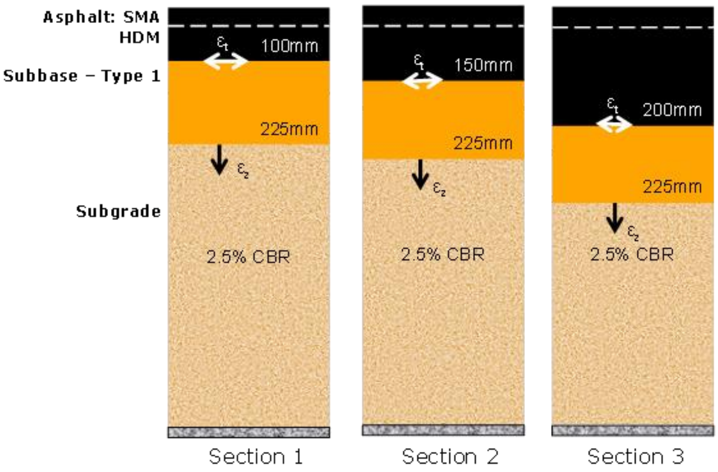

Figure 1. Design thicknesses of the trial sections

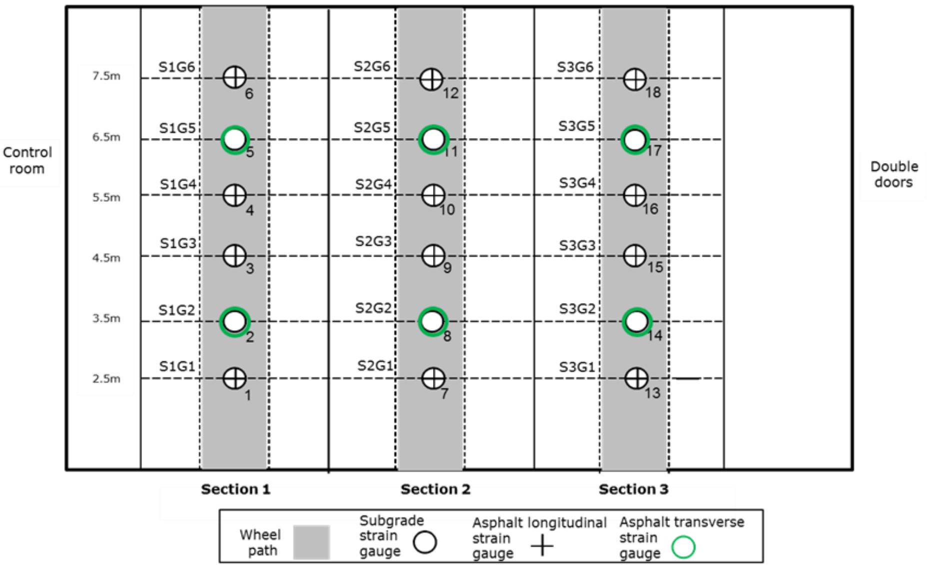

Figure 2. Layout of the PTF trial sections

As is often the case with instrumented pavements, a number of the asphalt and subgrade gauges failed to respond during the initial testing (7 asphalt and 2 subgrade gauges), which is most likely due to the effects of the laying and compaction processes of the pavement layers on the instrumentation, which is extremely difficult to mitigate against.

PTF trafficking of the trial sections was performed using blocks of loading cycles (5,000-10,000 passes) starting at 30kN at 15 km/h, using a super-single wheel, whilst simultaneously recording the pavement response. Prior to trafficking and after each loading block was completed, FWD surveys of the trial sections were performed at loads varying from 19 – 53kN, except on section 1 whereby the maximum FWD loading was 35kN due to its thin nature. The pavement response was also recorded under the FWD loading. This process was repeated after each increase in PTF wheel loading. Rutting and cracking was monitored with optical levelling and visual assessment. Loading was increased equally on each section based on the performance of the thinnest trial section (S1).

4.1 Results from accelerated pavement testing

The results of PTF trafficking trials are as follows:

- Section 1 (100mm thick) failed from high rutting (>20mm) and cracking after approximately 30,000 passes under loads varying from 30-50kN. This is equivalent to approximately 0.05msa.
- Section 2 also failed from high rutting (>20mm) and cracking after 75,810 passes under loads varying from 30-65kN (0.3msa).

- However, Section 3 showed no signs of deterioration from trafficking after 80,904 passes with loads varying from 30-65kN (0.34msa). Note that the last 40,000 passes were performed at 65kN.
  Ideally, PTF trafficking on section 3 would have continued for much longer but unfortunately this was halted due to project budget and timeline constraints.

The design parameters used to predict against such failures as rutting and fatigue cracking are the early life vertical compressive strain at the top of the subgrade and the early life horizontal tensile strain at the base of the asphalt layer. To this end, this research study aimed to examine the ‘trends’ in the early life strains and the corresponding predicted lives to failure.
Traditional methods of strain calculations at critical locations within the pavement include estimation of layer stiffnesses with back calculation and then forward calculation of strains using linear elastic models. However, the back-analysis approach does not distinguish between asphalt layers of varying stiffness and often provides values that seem illogical and somewhat unreliable. Therefore, a more direct approach is used in this study whereby asphalt base strains are predicted using a model based on the relationship between measured FWD deflection bowl parameters and strain. The following section describes the methodology for the model development which enables us to examine the trends in pavement performance in full.

6. ANALYSIS

6.1 Strain data analysis and model development

Earlier unpublished work [3] describes an alternative approach to derive regression equations relating the stresses and strains in the pavement to the characteristics of the measured deflection bowl. FWD deflections are simply the accumulated transient vertical strains and so a regression equation relating vertical strains in the pavement structure to the shape of the deflection bowl is quite logical. Furthermore, the horizontal strain at the bottom of an asphalt surfacing layer is closely related to the curvature at the centre of the deflection bowl, provided that the layer below the asphalt is much less stiff than the asphalt.

As described earlier, FWD surveys were performed above each gauge location under variable loads both prior and during PTF trafficking of the trial sections. The strains recorded from the bottom of the asphalt layer were then related to various FWD deflection bowl parameters. The deflection bowl parameters considered in the analysis are presented in Table 1. A cross-sectional view of a typical FWD deflection bowl which illustrates these parameters is given in Figure 3.

Table 1. FWD deflection bowl parameters

Parameter name	Mathematical definition	Units
Surface curvature index (SCI)	$d_0 - d_{300}$	microns
Base curvature index (BCI)	$d_{600} - d_{900}$	microns
Base damage index (BDI)	$d_{300} - d_{600}$	microns

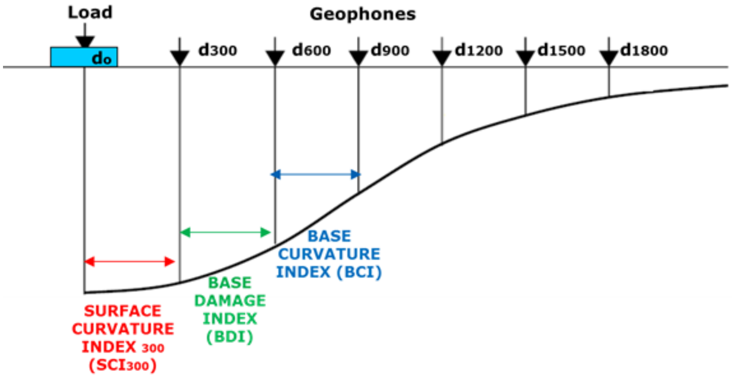

Figure 3. Typical FWD deflection bowl and some of the measured parameters

The BDI and SCI parameters were chosen for the current analysis as previous research suggests that BDI and SCI are more sensitive to the behaviour of the asphalt layers [4]. Using the relationship between measured asphalt strains and SCI (both normalised to 40kN), we predicted the tensile strain at the bottom of the asphalt layer using a simple linear regression. The predicted values compared well with actual measured strains recorded under the FWD loading, as shown in Figure 4, with a standard error (SE) of 26 $\mu\varepsilon$.

Although the linear regression analysis of single FWD parameters predicted the asphalt strain reasonably well, it was believed to be too simplistic and may not be suitable for a wider range of pavements. To improve the accuracy of strain prediction using SCI, multiple regression analysis was carried out which includes asphalt thickness (H_{AC}) and central FWD deflection (D_0). The resulting relationship reduced the standard error to 20 με.

$$\varepsilon_t(predicted) = 16.99 + 0.37SCI + 0.159D_0 - 0.0764H_{AC} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . TRL1$$

Where ε_t (predicted) = predicted strain at the bottom of asphalt base in microstrain, SCI and D_0 in microns, and H_{AC} in mm.

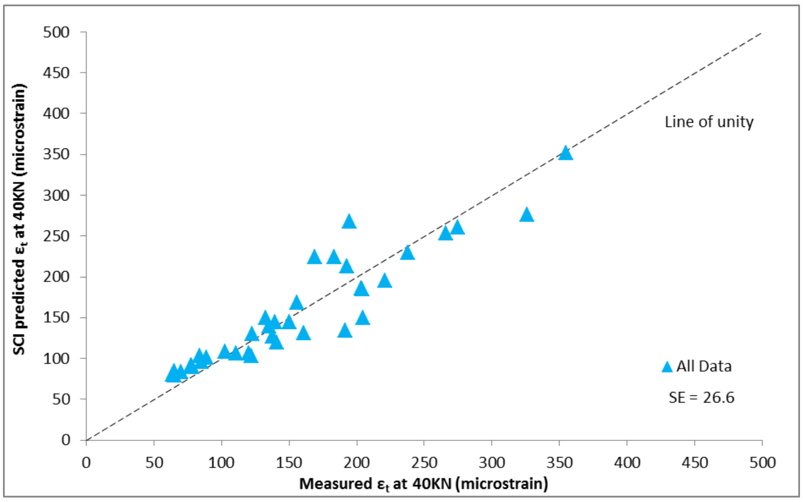

Figure 4. SCI predicted ε_t vs. measured ε_t for PTF trials data

Two other models used to predict asphalt base strain from FWD deflection data include those developed at North Carolina State University [4] and at KOAC-WMD in the Netherlands [5]. These two models use FWD deflections measured under 40kN and 50kN FWD loading respectively to predict tensile strains at the bottom of an asphalt pavement (ε_t) and compressive strains at the top of the subgrade (ε_z) and are presented in Table 2. These models were developed analytically i.e. unlike this research study they do not incorporate 'actual' strain data.

Table 2. Regression equations from NCSU and KOAC studies

Study	Variable	Equation
NCSU	Tensile strain beneath asphalt layer (ε_t)	$Log(\varepsilon_t) = 0.5492*Log(SCI) + 0.3850*Log(BDI) + 0.7812*Log(H_{AC}) - 0.0017*H_{AC} + 1.7353$
	Compressive strain on top of subgrade (ε_z)	$Log(\varepsilon_z) = 0.5321*Log(BDI) + 0.3496*Log(BCI) - 0.1395*Log(H_{AC}) - 0.0006*H_{BC} + 3.9647$
KOAC-WDM	Tensile strain beneath asphalt layer (ε_t)	$Log(\varepsilon_t) = -1.0676 + 0.5618*Log(H_{AC}) + 0.03233*Log(d_{1800}) + 0.4746*Log(SCI) + 1.1561*Log(BDI) - 0.6827*Log(BCI)$
	Compressive strain on top of subgrade (ε_z)	$Log(\varepsilon_z) = 2.4859 + 0.3458*Log(SCI) + 0.1664*Log(d_{1800}) - 0.6875*Log(H_{AC} + H_{RB} + H_{SB}) + 0.4743*Log(BDI)$

Where H_{AC}, H_{RB}, and H_{BC} = thickness of the asphalt layer, aggregate base layer, and sub-base layer (mm) respectively. FWD deflection bowl parameters (SCI, BDI, BCI, etc.) are in mm for the NCSU models, and in microns for the KOAC models. For comparative purposes, Figure 5 presents the predicted strains from the TRL, NCSU and KOAC models compared with the actual strains measured under the FWD loading.

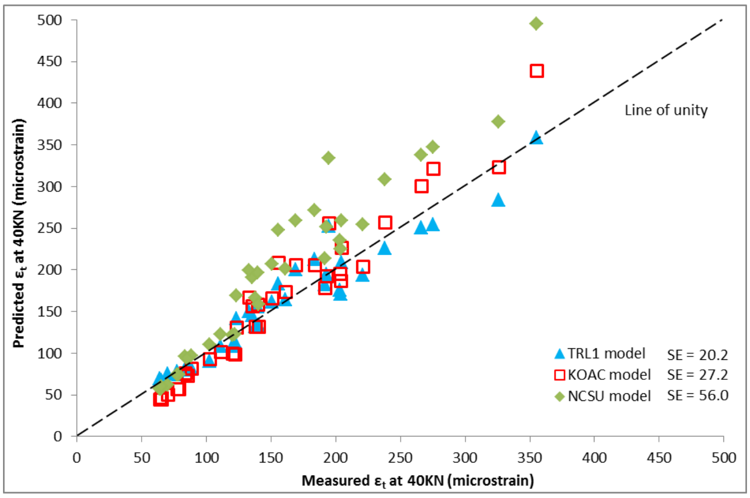

Figure 5. Predicted vs. measured εt for PTF trials data

6.2 Identifying the Threshold Condition

6.2.1 Trends in Rutting

Figure 7 presents the rutting measurements from each trial section under variable PTF loading, which were taken at each gauge location across the 10m trial section (18 locations total, i.e. 6 in each section). Sections 1, 2, and 3 are represented using the colours blue, red, and green respectively, while the different symbols represent rut measurements taken at each of the six gauge locations within each section throughout the trafficking phase. Using the fourth power law, the increase in PTF wheel loading was accounted for by converting 'wheel passes' into equivalent standard axles (ESA). The progression of rutting in each trial section was then plotted against ESA, as shown in Figure 8. All three trial sections experienced early 'consolidation' before a linear increase in rutting with trafficking is shown, as would be expected. Limited rut measurements were taken in Section 3 as intermediate checks between 50,000 and 300,000 ESA suggested that there was very little rut development.

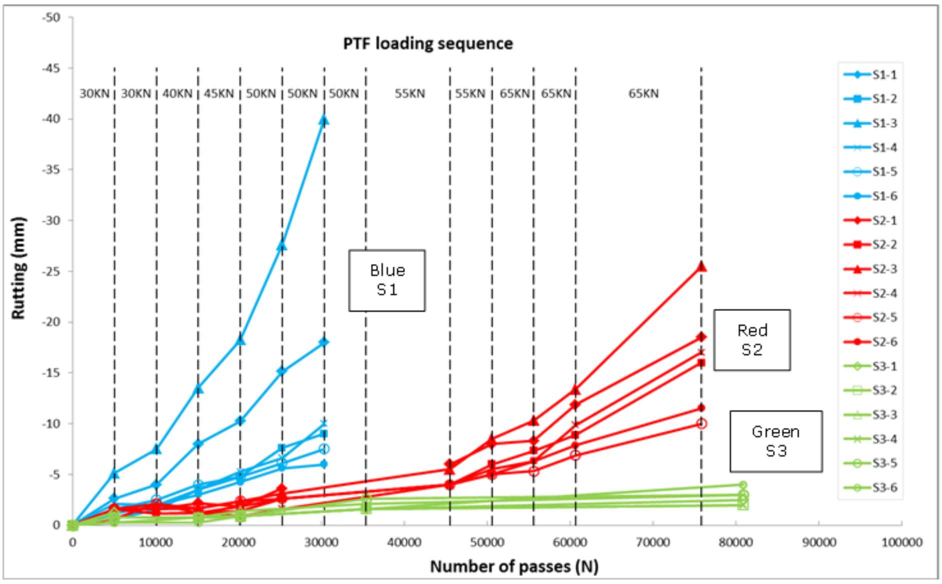

Figure 7. Trial section rutting measured under variable PTF loading

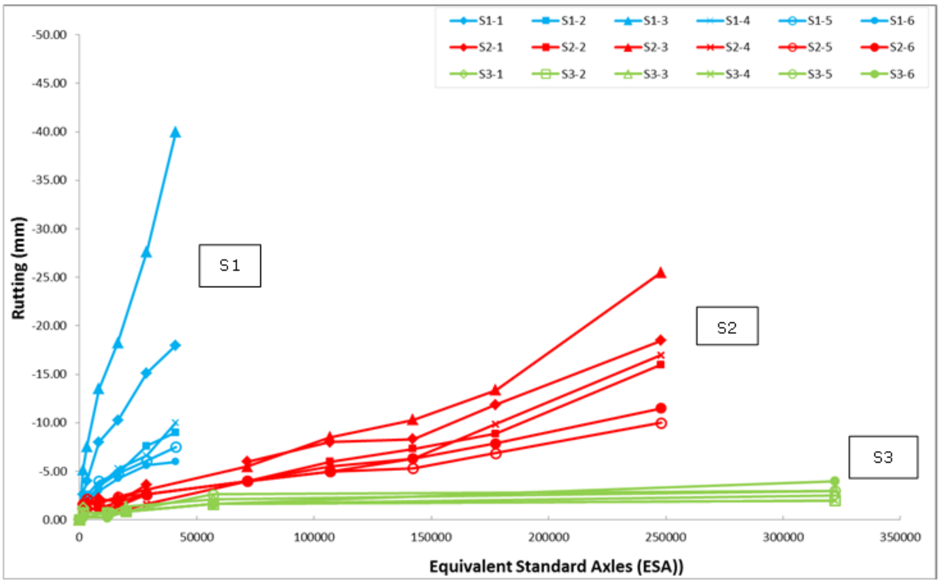

Figure 8. Rutting vs. ESA using fourth power law

The linear rate of rutting vs. ESA and the slope of this linear relationship represents the rate of deterioration by rutting, at each gauge location. The linear relationship was then used to estimate the life to a 10mm rut, at each of the test points, in some cases by means of extrapolation, and is shown in Table 3.

6.2.2 Relating rutting to subgrade strain

As discussed earlier, it was difficult to establish robust rutting trends for Section 3 as trafficking was necessarily restricted as a result of the financial and time constraints of the trafficking phase. However, it was considered that the trends in the subgrade strains may provide additional information about the subsequent performance of the sections.
Figure 9 presents the dynamic subgrade strains for the sections, where the data has been fitted to exponential trendlines. It can be seen that the subgrade strains largely mirror the pavement rutting shown in Figure 7. Subgrade strains in Section 3 actually seem to stabilise with trafficking. Increasing dynamic strain in the subgrade (under a constant load) will normally only result from the decreasing stiffness of the bound layers above it, either through increasing temperature or the development of cracking. As the pavement temperature remain broadly similar during trafficking it is likely that the increasing subgrade strains in Sections 1 and 2 indicate deterioration of the bound layers. Section 3 showed virtually no increase in subgrade strain with trafficking.

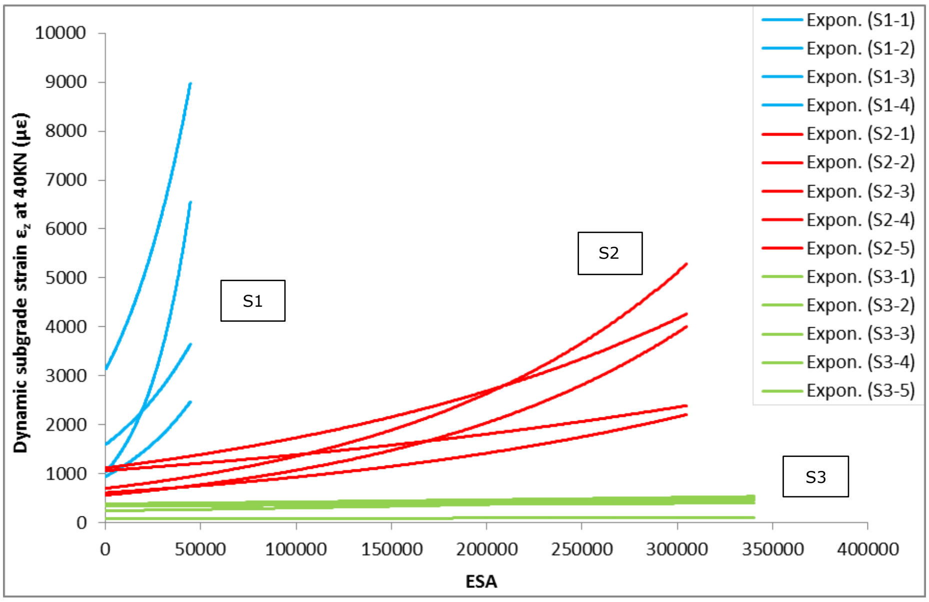

Figure 9. Dynamic subgrade strain ε_z against trafficking for PTF trial sections

‘Permanent’ subgrade strain, ε_Z’, i.e. the element of total subgrade strain that is not recoverable, is closely related to deformation in the subgrade during trafficking since such non-recoverable elements accumulate to create the permanent deformation. The permanent subgrade strain results for Section 3, presented in Figure 10 reveal a common trend in behaviour in that after 0.24msa, five out of the six gauges (S3G6 stopped working after 0.05msa) show that the permanent strains appear to have stabilised. This behaviour indicates that although the deformation has not entirely stopped, it has reduced to almost a negligible amount. More importantly as there is no increase in permanent subgrade strain this indicates that there is also no deterioration in the bound layers above (at this point in trafficking) and therefore signifies long-life behaviour. These results are summarised in Table 3. The estimated rutting life in Section 3 is shown to be well over 1msa to greater than 7msa. The subgrade strains presented are those measured under 40kN FWD loading and predicted using the NCSU model presented earlier, and represent early life strains i.e. before trafficking commenced. It should be noted that the final phase of trafficking on Section 3 was at a wheel loading of 65kN which is more than 50% over the allowable loading permitted in the UK for the type of tyre used for the trafficking.

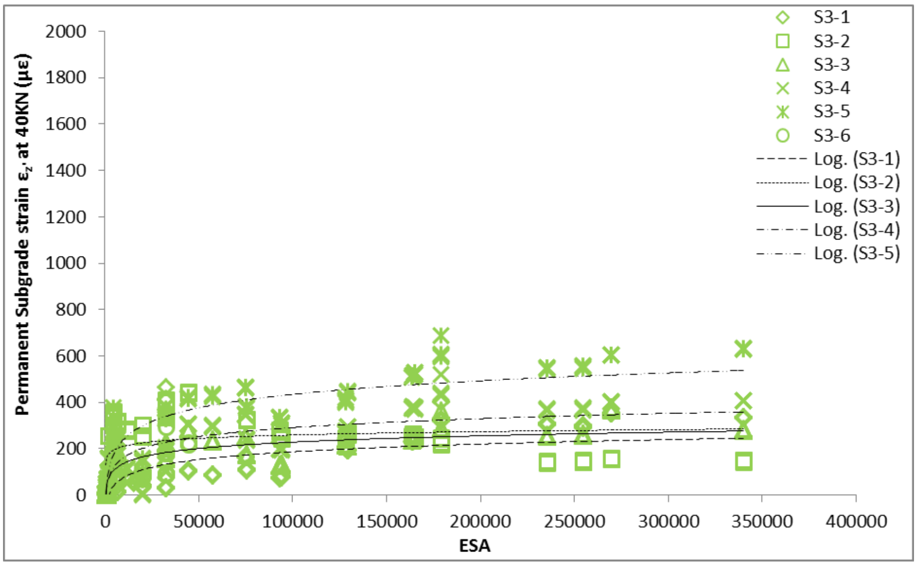

Figure 10. Section 3 permanent subgrade strain $\varepsilon_{z'}$ (normalised to 40KN load) against trafficking

Table 3. Early-life subgrade strains under 40KN and rutting life of PTF trial sections

PTF trial section	Subgrade Gauge	Early life subgrade strain (at 40KN)		Rutting life at 10mm
		Measured (με)	Predicted (με)	msa
1	S1-1	NA	1117	0.03
	S1-2	685	866	0.06
	S1-3	NA	1314	0.01
	S1-4	945	1003	0.05
	S1-5	NA	850	0.01
	S1-6	717	731	0.10
2	S2-1	803	584	0.16
	S2-2	814	578	0.19
	S2-3	653	567	0.12
	S2-4	490	514	0.18
	S2-5	574	462	0.30
	S2-6	452	463	0.24
3	S3-1	235	245	>**7.17**
	S3-2	246	234	>**7.17**
	S3-3	262	267	>**7.17**
	S3-4	228	252	>**3.05**
	S3-5	249	223	>**3.05**
	S3-6	250	269	>**1.12**

Note: NA = No data available due to strain gauge failure

6.2.3 Trends in Fatigue cracking

Figure 11 shows predicted base strain (using the TRL1 model) against trafficking, and the locations of eventual failure by fatigue cracking in Sections 1 and 2 are highlighted. Figure 12 focuses on the horizontal strain for Section 3 during trafficking and here we can see no significant increasing trend in strain for five of the six gauges with trafficking. The average early life strain for these five gauges is 76με.

In contrast, Gauge S3-6 did show an increase in strain between 0.09msa and the end of trafficking. This coincided with the final period of trafficking when the PTF wheel loading was increased to 65kN, which is over 50% more than that normally permitted on the super single tyre configuration used in this study. It is therefore assumed that the result from Gauge S3-6 is atypical and the performance of Section 3 can generally be considered as representing the behaviour of a long-life pavement.

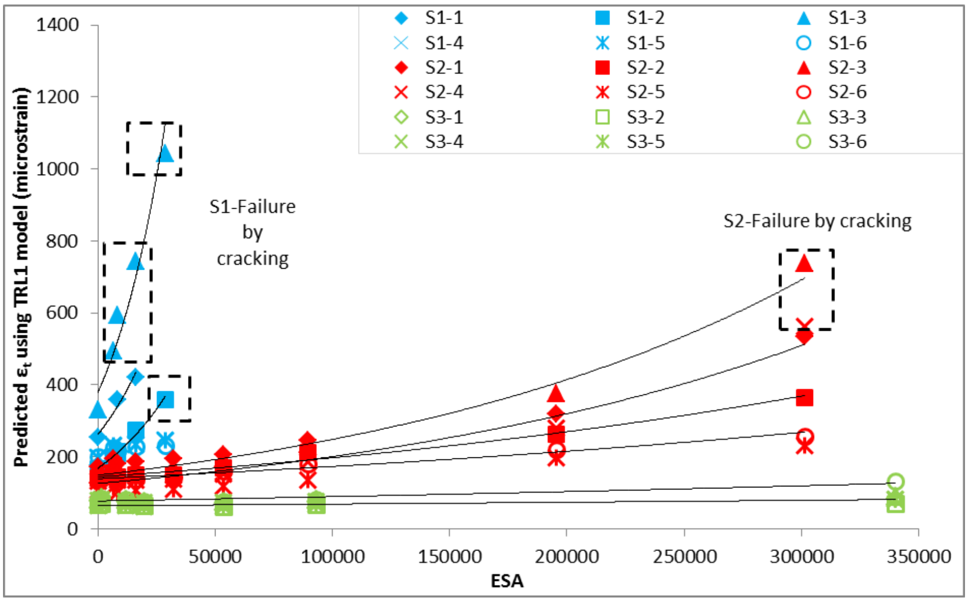

Figure 11. Predicted ε_t under FWD during trafficking (shown as ESA)

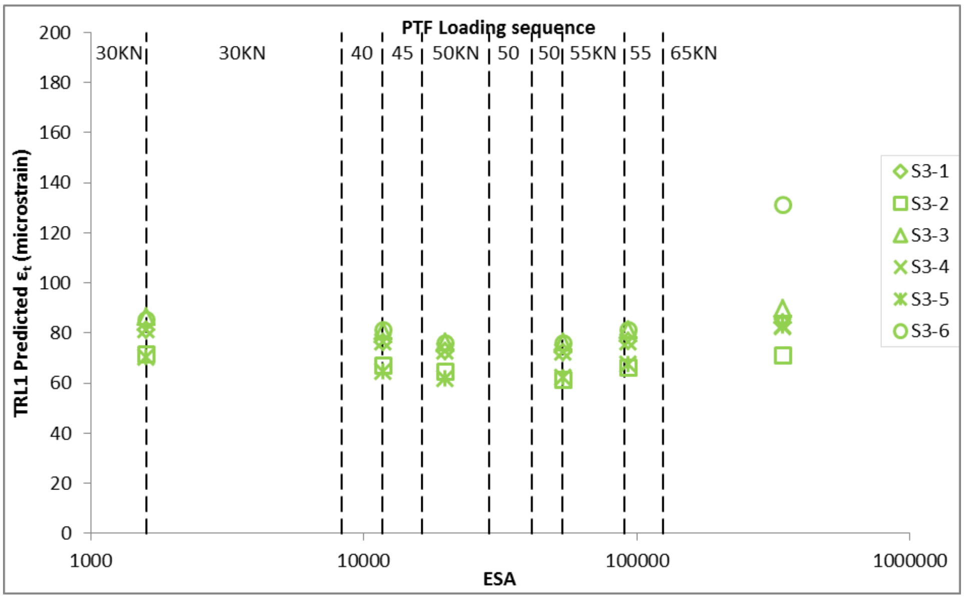

Figure 12. Section 3 predicted ε_t under FWD during trafficking (shown as ESA)

The fatigue lives for each test location have been tabulated in Table 4**Table** below, along with the early life base strains, both measured and predicted values (from TRL1 model). Locations where no cracking was evident have a fatigue life of greater than the number of passes recorded. For example, gauge location S1-1 showed no cracking therefore its fatigue life > 0.4msa.

Table 4. Fatigue life of PTF trial sections and early life subgrade strains at 40KN

PTF section	Gauges	Early life strain (at 40KN)		Cracked	Fatigue life
		measured (με)	predicted (με)	YES/NO	msa
1	S1-1	306	254	NO	>0.04
	S1-2	NA	165	YES	0.03
	S1-3	NA	331	YES	0.03
	S1-4	186	172	YES	0.03
	S1-5	NA	198	NO	>0.04
	S1-6	185	201	NO	>0.04
2	S2-1	217	172	NO	>0.30
	S2-2	NA	141	YES	0.30
	S2-3	141	151	YES	0.30
	S2-4	137	132	NO	>0.30
	S2-5	123	108	NO	>0.30
	S2-6	NA	134	NO	>0.30
3	S3-1	92	79	NO	>0.34
	S3-2	66	69	NO	>0.34
	S3-3	NA	83	NO	>0.34
	S3-4	80	78	NO	>0.34
	S3-5	NA	66	NO	>0.34
	S3-6	NA	81	NO	>0.34

NA=No data available due to non-responsive gauges, msa=million standard axles

7. SUMMARY AND CONCLUSIONS

This study looked at developing an alternative approach to pavement design with particular emphasis on demonstrating and utilising the threshold strength concept. This research builds on previous work commissioned by Highways England which included the construction and trafficking of three instrumented pavement sections in the PTF. One of the key elements of this study was the use of FWD deflection bowl parameters to predict strain at the bottom of the asphalt layer. From the analysis it was found that a strong correlation exists between the measured asphalt base strains and the FWD deflection bowl parameters i.e. SCI and BDI, with SCI showing a slightly better relationship to strain. Using a simple linear regression, reasonable values of asphalt base strains were predicted using the SCI-ε_t relationship. An improved model (TRL1 model) was developed by including additional parameters such as FWD deflection (D_0) and asphalt thickness (H_{AC}). In addition to developing a TRL model, two additional models from published studies were evaluated. The results showed that although these models provided reasonable predictions using data from the PTF trials, they were less accurate than the TRL models. However, it is important to note that the 'external' models were generated from theoretical studies that considered a wide range of structures whereas the TRL models were generated from actual strain measurements but from the limited range of structures built in the PTF.

The observed trends in the PTF pavement performance were examined based on two specific modes of failure; rutting and 'fatigue' cracking. The design parameters used to design against such failures are the early life vertical strain at the top of the subgrade for rutting and the early life horizontal strain at the base of the bound layers for cracking. This study examined the trends in these parameters, the predicted lives to failure, and the corresponding early life strain levels.

The conclusions from this study are as follows:

- The robust model developed from this study predicted asphalt tensile strains from FWD measurements that were comparable to those measured at the PTF trials before trafficking (referred to as early life strains).
    - The TRL model was then used to predict asphalt tensile strains at different stages during and after trafficking.
    - Although the TRL model showed promising results, it requires further development on other calibrated sites prior to their used to predict strains for pavements on the English strategic road network.
- Two models from published studies were also evaluated using PTF trials data.
    - Although these models showed reasonable results, they were less accurate than the TRL model when predicting asphalt base strains.
    - Of the two 'external' models, the NCSU model was more accurate in terms of predicting strains on top of the subgrade. Therefore, this model was used to predict subgrade strains before, during, and after trafficking.
    - These two models also require further calibration prior to being considered for use on the strategic road network.

- This study demonstrated pavement deterioration through both rutting and fatigue cracking in Sections 1 & 2.

The base and subgrade strains recorded in Sections 1 and 2 were strongly correlated with the developments of rutting and fatigue cracking respectively.

- Section 3 showed no significant deterioration in the bound layers despite being subjected to wheel loads of up to 65kN, on an under-designed foundation. This performance illustrates the threshold conditions associated with long life pavements. However, it is important to remember that trafficking on this section was limited to 0.34msa due to resource constraints.

Based on the above conclusions, continued research is being carried out to determine the threshold levels associated with existing long life pavements on the English strategic road network. Future work will be considering the application of this approach in the assessment of existing heavily trafficked road pavements and the design of new ones.

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REFERENCES

[1] Is now the time to revise our thoughts on flexible pavement design?, Nunn, M., Carswell, I., James, D., Fourth E & E Conference, Copenhagen, 2008.

[2] The Structural Design of Bituminous Roads, Powell W.D., Potter J.F., Mayhew H.C., and Nunn M.E., TRL LR1132, Crowthorne, UK, 1984.

[3] Cost-Effective Maintenance Decisions with the Falling Weight Deflectometer, Rolt, J., TRL Unpublished Report UPR/IE/170/66, Crowthorne, UK, 2006.

[4] New relationships between falling weight deflectometer deflections and asphalt pavement layer condition indicators, Xu, Bing, Ranjithan, R. and Kim, R., Transport Research Record 1806, National research Council, Washington, D.C., 2000.

[5] Full structure diagnosis of low volume roads, Van Gurp, C., Bode, A., Wennink, M. and Molenaar, A., Proceedings of the 5th Int. Conference on the Bearing Capacity of Roads and Airfields, Trondheim, Norway, 1998.