Published Project Report PPR253

Investigation of the Effects of Pavement Stiffness on Fuel Consumption

by E Benbow, J Iaquinta, R Lodge and A Wright

Published Project Report
PPR253
Investigation of the Effects of Pavement Stiffness on Fuel Consumption

by E Benbow, J Iaquinta, R Lodge & A Wright

PPR 253

PUBLISHED PROJECT REPORT
Investigation of the Effects of Pavement Stiffness on Fuel Consumption

Version: Final

by E Benbow, J Iaquinta, R Lodge & A Wright (TRL Limited)

Prepared for: Project Record: Task No 3/302_057 Influence of Pavement Construction on Fuel Efficiency
Client: Highways Agency (Mr J Williams)

Copyright TRL Limited July 2007

This report has been prepared for the Highways Agency. The views expressed are those of the author(s) and not necessarily those of the Highways Agency.

Published Project Reports are written primarily for the Customer rather than for a general audience and are published with the Customer’s approval.
This report has been produced by TRL Limited, under/as part of a Contract placed by the Highways Agency. Any views expressed are not necessarily those of the Highways Agency.

TRL is committed to optimising energy efficiency, reducing waste and promoting recycling and re-use. In support of these environmental goals, this report has been printed on recycled paper, comprising 100% post-consumer waste, manufactured using a TCF (totally chlorine free) process.
CONTENTS

Executive summary 1

1 Introduction 3

2 Rolling Resistance 3

3 Equipment 4

3.1 The PTF 4
3.2 Instrumentation 5
3.3 Data acquisition 7

4 Initial Trials Evaluating the Equipment 8

4.1 Trials 8
4.2 Analysis - assumptions 8
4.3 Analysis – evaluating rolling resistance 8
4.4 Conclusions of initial trials 10
  4.4.1 Notes on the influence of unwanted variability in the measurements 11

5 Test Pavements for Investigating Rolling Resistance 12

5.1 Design 12
5.2 Properties 12
  5.2.1 Profile 12
  5.2.2 Texture 13
  5.2.3 Deflection 14

6 Trials of Rolling Resistance 15

6.1 Long (24 hour) trials 15
  6.1.1 Procedure 15
  6.1.2 Results from long trials 16
  6.1.3 Compensating for external factors 18
6.2 Further (Short) trials 19
6.3 Discussion 19
6.4 Further investigation of the influence of texture on rolling resistance 20

7 Further Potential Uses of Instrumentation 22

8 Conclusions 24

9 Implications for Fuel Consumption on the Network 25

9.1 Effect of Stiffness 25
9.2 Effect of Texture 26
9.3 Effect of Climate Change 27
9.4 Cost of Construction versus Fuel Savings 27
10 Recommendations 28

References 28

Acknowledgements 29

Appendix A. Recommendations of Task 1 for Instrumentation of the PTF 30

Appendix B. Results from the initial trials 31

Appendix C. TRL PTF Pavement Construction 34

C.1 Pavement 1 (Flexible) 34
C.2 Pavement 2 (Rigid) 34
C.3 Pavement 3 (Flexible – for Texture trial) 36
C.4 Surfacing Requirements 37
C.5 Pavement Specification 37
  C.5.1 Permitted Pavement Options- Schedule 1 37
  C.5.2 General Requirements- Schedule 2 37
  C.5.3 Permitted Construction Materials 38
  C.5.4 General Requirements for Construction Materials- Schedule 4 38
  C.5.5 Requirements for Construction Materials- Schedule 5 38
Executive summary

Investigation of the Effects of Pavement Stiffness on Fuel Consumption

by E Benbow, J Iaquinta, R Lodge and A Wright

Scope of the Project

The objective of this work is to determine whether pavement stiffness has a significant influence on the energy required to travel along a pavement, and hence whether the construction of stiffer pavements could deliver tangible benefits in fuel consumption. The research has been carried out in three tasks:

Task 1: Investigate the techniques needed to measure rolling resistance on the Pavement Test Facility (PTF) and develop equipment to this end.

Task 2: Demonstrate the ability of this equipment to obtain measurements for rolling resistance that behave in a manner that would be expected from results from international research and the capability to measure the small changes in rolling resistance that would likely be seen between two pavements of significantly different stiffness.

Task 3: Investigate the difference in rolling resistance, and therefore corresponding fuel consumption, of both rigid and flexible pavements.

The work described in this report presents the results of Task 3, and also summarises the work carried out in Tasks 1 and 2.

Summary

Work carried out by TRL and others has shown that stiffer pavements may assist in delivering lower levels of vehicle fuel consumption. It has been suggested that increases in pavement deflection of 60-100µm could increase fuel consumption by up to 28%. However, these figures are subject to uncertainty due to the difficulties in carrying out experiments on the road network that enable stiffness to be isolated from other contributing factors. Typically, stiffer pavements are obtained through rigid (concrete) construction techniques. However, the energy consumption and greenhouse gas emissions are lower for the production of flexible as compared to rigid pavements. This could negate some of the advantages of the stiffer pavement. However, since traffic accounts for the major part (as much as 98%, depending on traffic volume, (EAPA, 2004)) of the energy consumption associated with a road, the additional energy consumed in constructing a rigid pavement may not be relevant. It was therefore proposed that work be carried out to investigate the effects of pavement stiffness on fuel consumption.

TRL’s Pavement Test Facility (PTF) was proposed as a test facility to evaluate the effect of stiffness on fuel consumption, because it is able to provide a more stable and repeatable environment than samples of the road network. The objective was to use this facility to determine whether it is more energy efficient to traverse stiff pavements than less stiff pavements. This can be deduced from an assessment of the rolling resistance of the pavement. However, several factors affect rolling resistance, in addition to the stiffness, and stiffness is unlikely to be the largest of these factors. Therefore, there was a need to develop a measurement system within the PTF that would be capable of measuring changes to a small value (the ‘stiffness’ component of rolling resistance) within a large value (the overall rolling resistance).
Task 1 of this project investigated techniques that could be employed to measure rolling resistance in the PTF, and methods to control the additional factors contributing to rolling resistance. Proposals were presented for suitable instrumentation to evaluate the rolling resistance. This instrumentation was developed and initial tests carried out under Task 2 of the project. It was demonstrated that the equipment was able to measure the rolling resistance of reference strips and deliver results in accordance with those reported in the literature. It was also demonstrated that the equipment should have sufficient sensitivity to measure the small differences likely to be associated with differences in stiffness.

Within Task 3, which is described in this report, two test pavements were constructed within the PTF; one was a rigid construction, the other fully flexible but both surfaced with the same thin surfacing system. The deflection, profile and texture, of both pavements were measured. When constructing the test pavements the design was selected such that the rigid pavement should have had a stiffness far greater than the flexible pavement, and the flexible pavement was expected to exhibit a stiffness typical of weak flexible pavements on the network. The deflection measured on the flexible pavement was of the order that would be expected for its construction. However, that measured on the rigid pavement was much higher than would have been expected but this may have been due to the method of construction that was necessary within the PTF. The difference in deflection between the two pavements was around 28µm, with a 50kN load at a temperature of 9.7°C.

To obtain the same texture on both pavements, the same surface course was laid on both pavements simultaneously. This process delivered surfaces on each pavement that had a difference in texture of only 0.15mm (flexible was 0.15mm higher than the rigid pavement).

Because initial trials of the instrumentation showed that temperature has a significant effect on the reported rolling resistance, and couldn’t be controlled to sufficient accuracy, trials were run for 24 hours on both pavements, to deliver data from both pavements from which data segments collected under comparable conditions could be extracted. In addition to this variability due to temperature, it was found that there was also variation in the loading applied between test runs due to a degree of unexpected behaviour of the PTF.

Following the extraction of data collected under common temperature conditions, and after correction for the effects of the wheel load and pavement texture, it was found that the average coefficient of rolling resistance measured on the rigid pavement was 5x10⁻⁴ (5.6%) lower than that obtained on the flexible pavement. However, there was significant overlap between the datasets from the two pavements. This result provides evidence that there is a difference between the coefficient of rolling resistance between flexible and rigid pavements but the evidence does not show that the difference is statistically significant.

Further work was carried out to investigate the capability of the instrumentation to measure the effect of texture on rolling resistance. Two further pavements were constructed, consisting of the same subgrade, sub-base and base but with different surfaces layers. One surface consisted of 30% 0/10mm HRA, whilst the other was a 0/10mm DBM. Thus, the pavements were equivalent apart from the surface layer. The HRA surfaced pavement had an SMTD of 0.16mm, whilst the DBM had an SMTD of 0.6mm.

A difference of 5x10⁻⁴ (3.6%) was identified by the instrumentation between the coefficient of rolling resistance on the textured and untextured surfaces. The range of textures considered in this initial investigation encompasses only a small part of the range of textures present on the network. However, comparison of the results obtained in this initial investigation of the effect of texture with the results obtained on the flexible and rigid pavements suggests that pavements having significantly different constructions (rigid vs. flexible), but the same texture, may demonstrate similar differences in rolling resistance to pavements having similar construction and different textures. In relation to the network, this would suggest that to reduce fuel consumption on existing pavements, it would be more cost-beneficial to change the texture than to reconstruct to increase the pavement’s stiffness.

It is proposed that the instrumentation could be applied in the further investigation of the effects of texture on rolling resistance.
1 Introduction

Work carried out by TRL (McKeown, 2002) and others has shown that stiffer pavements may assist in delivering lower levels of vehicle fuel consumption. Within this work, a model was constructed which showed that pavement deflection had an influence on truck fuel economy. The model, derived from limited data, predicts that all other factors remaining equal, if the level of deflection was to increase from 60 to 98 µm, then the fuel economy would increase by 28%. However, this figure was derived from the fact that the model was only able to explain 72% of the variability in the fuel consumption measurements from variations in texture, gradient and profile and thus should be treated with caution.

Typically stiffer pavements are obtained through rigid (concrete) construction techniques. However, the energy consumption and greenhouse gas emissions are lower for the production of flexible pavements compared to rigid pavements. This could negate some of the advantages of the stiffer pavement. However, since traffic accounts for the major part (as much as 98%, depending on traffic volume, (EAPA, 2004)) of the energy consumption associated with a road, the additional energy consumed in constructing a rigid pavement may not be relevant. It was therefore proposed that work be carried out to investigate the effects of pavement stiffness on fuel consumption.

As noted above, the results of previous work, investigating the fuel consumption on different pavement constructions, have been subject to doubt due to the challenging nature of the experiments performed on live network sites. Therefore TRL’s Pavement Test Facility (PTF) was proposed as a test facility because it was thought able to provide a more stable and repeatable environment than the road network, whilst still presenting conditions that can be considered reasonably representative of those experienced on the network. The objective was to use this facility to determine whether it is more energy efficient to traverse rigid pavements, which can be deduced from an assessment of the rolling resistance of the pavement. However, several factors affect rolling resistance, in addition to the stiffness. Furthermore, stiffness is unlikely to be the largest of these factors. Therefore, there was a need to develop a measurement system within the PTF that would be capable of measuring changes to a small value (the ‘stiffness’ component of rolling resistance) within a large value (the overall rolling resistance).

An investigation was completed under Task 1 of this project into the techniques that could be employed to measure rolling resistance in the PTF (Wright and Lodge, 2004). Methods to control the additional factors contributing to rolling resistance were also investigated, so that these could be controlled or measured, and hence be catered for when assessing the effects of stiffness on rolling resistance. This investigation proposed instrumentation for the PTF to evaluate the rolling resistance. This instrumentation was developed and initial tests carried out under Task 2 of the project. The implementation and results of these are described in Sections 2 to 4.

The remainder of this report describes the final task of this project (Task 3), which has included the construction and testing of two pavements within the PTF (one rigid, the other flexible), to quantify the effects of stiffness on rolling resistance, and hence fuel consumption.

2 Rolling Resistance

The energy used in moving a load across a surface is related to the rolling resistance incurred by the wheel at the surface and at the axle. The rolling resistance, \( F_r \), is defined as the force opposing movement and results in the loss of energy (or energy consumed) per unit of distance travelled. \( F_r \) is related to the loading of the wheel (axle) via the Coefficient of Rolling Resistance, \( C_{rr} \), according to equation 1.

\[
\text{Coefficient of Rolling Resistance} \ (C_{rr}) = \frac{\text{Rolling Resistance} \ (F_r)}{\text{Test Load} \ (L_m)} \quad [1]
\]
As it should be possible to control or measure the Load, the variable and possibly uncontrollable factors influencing the energy consumed are contained within the Coefficient of Rolling Resistance. The goal of this project is to determine the significance of pavement stiffness on the energy used in traversing the pavement. However, this will be combined with several other factors that all contribute to the rolling resistance. These factors are contained within the reported value of $C_{rr}$. Initial work, carried out in Task 1 of this project (Wright and Lodge, 2004), determined that the coefficient of rolling resistance of a pavement is affected by:

- The speed of traversing the pavement
- The longitudinal profile
- The gradient
- The transverse profile
- The texture profile
- The temperature
- The aerodynamic drag
- The tyre pressure
- The pavement stiffness.

The requirement was therefore to develop equipment that enables the evaluation of the rolling resistance, and a test programme that either eliminates, controls or measures the influence of the contributing factors so that the influence of stiffness can be extracted. The equipment and programme are described in the following sections.

### 3 Equipment

#### 3.1 The PTF

The TRL Pavement Test Facility (PTF), Figure 1, consists of a wheel mounted in a carriage, which itself is suspended from a pair of rails mounted on a gantry positioned approximately 2m above the pavement surface. The carriage is attached to a motor via cables so that the carriage may be pulled along the rails to traverse a 10m strip of pavement. The motor is able to accelerate the carriage to 20km/h over the first 1.5m of the 10m strip, and then maintain the carriage speed at 20km/h for the next 7m before decelerating the carriage to 0km/h in the final 1.5m of strip. This operation can be carried out in both directions on the test strip. An hydraulic ram is mounted in the carriage between the wheel and the rails so that the vertical load on the wheel may be increased up to 8000kg. To enable experiments to be carried out on different strips of test pavement the entire carriage and gantry assembly is mounted on a further set of rails that enable the assembly to be moved along an array of test strips. A number of devices, including sensors and loggers, were installed in the PTF, to deliver an accurate evaluation of the coefficient of rolling resistance.
Figure 1: Picture of the PTF showing the rig, the concrete strip and the two platforms

Note that, when referring to the PTF, the view of the PTF gantry shown in Figure 1 is defined as being taken from the double door end of the PTF. Figure 1 shows the PTF with the control room on the far side of the PTF gantry (the door into the control room can be seen in the centre of the photograph). When the PTF gantry is viewed from the far side of the gantry, we define the view as being taken from the Control Room end of the PTF. The PTF consists of a carriage and wheel (Figure 2), suspended from a gantry, that is traversed across the width of a test strip (Figure 1). Key characteristics of the PTF that proved particularly useful for this study were:

- The ability to achieve high trafficking rates in two directions;
- The ability to apply controlled vertical wheel loading, in 5kN increments;
- The ability to test at controlled speeds from 5 up to 20km/h;
- The ability to manually control the tyre inflation pressure from 414 up to 1034kPa (60-150psi);
- The ability to control the pavement temperature and achieve minimum temperature exchange with the outside world;
- Zero wind effects (restricting aerodynamic drag);
- Virtually horizontal pavement strips (extremely small gradients);
- A path of travel very close to a perfect straight line (with limited wandering).

3.2 Instrumentation

The PTF carriage and wheel were equipped with a number of sensors (see Figure 2 and Figure 3) to measure:

- the force applied by the ram through the rod ends on each side of the wheel, using strain gauges (along AC in Figure 5);
- the force in the two arms holding the wheel axle, using load cells (along AB in Figure 5);
- the acceleration of the moving assembly with a high sensitivity three-axis accelerometer;
- the arm angle ($\alpha$ in Figure 5) with a digital rotary encoder, directly mounted on the pivot point;
- the rotational angle of the wheel with another rotary encoder, connected to the wheel by a pulley and a belt;
- the temperature of the surface of the tyre (in contact with the pavement) via a pyrometer;
- the temperature of the surface of the pavement with another pyrometer;
the ambient temperature, in the proximity of the accelerometer and also the two pyrometers. The ambient temperature was also manually measured using a thermocouple placed a few centimetres above the middle of the trafficked strips, when the PTF was stationary.

In addition to these sensors, a remotely controlled artificial load (from PCM Electronics and Frazer Nash) was installed, taking the form of a motor and pulley (Figure 2). This equipment was not required for the purpose of measuring rolling resistance but allowed the introduction of a small resistant couple (variable between 0 and 100N) at the wheel hub. This artificial load (artificial rolling resistance) could be used to introduce an additional rolling resistance to that presented by the pavement, and hence enable the assessment of the sensitivity of the equipment, and derive a degree of calibration. The artificial load could be changed remotely by the operator whilst the PTF was in operation.

The implementation of this equipment followed the recommendations of Task 1 (Wright and Lodge, 2004), which, for reference, are summarised in Appendix A.

Figure 2: Sensors mounted on the PTF, as seen from the “control room”.
3.3 Data acquisition

The multiple channel data acquisition system shown in Figure 4 exploited synchronized hardware connected to a host computer over an Ethernet link (TCP/IP connection). The first unit was an analogue logger from Scalar Technologies Limited, providing information from the rod ends, load cells, accelerometer and non-contact temperature sensors. The second unit was a digital logger from Softronic Systems Limited, supplying the clock trigger (to synchronize the acquisition of the various signals), the location of the wheel (right platform, pavement, or left platform) determined by a set of optical devices, and the two rotary encoders for the wheel and arm angles. This digital system also ran software to control the artificial load, which could be set from zero to full load in increments of $1/3$ load.
4 Initial Trials Evaluating the Equipment

Before using the above equipment to evaluate rolling resistance it was necessary to evaluate its suitability for this measurement, and in particular the potential to measure small variations in rolling resistance on pavements with varying stiffness. The results of these trials are reported by Benbow et al. 2006. This section summarises the results of these trials.

4.1 Trials

A number of trials were carried out, which determined

1) How long the temperature of the tyre took to reach a steady state condition on a rigid concrete pavement (to control the influence of temperature).

2) How the system would behave when external influences, such as load and speed, were varied (both in an ordered manner and also randomly) on a rigid concrete pavement (to control the influence of load and speed).

3) Whether a difference between rolling resistance measured on a rigid pavement and that measured on a flexible pavement could be measured with the equipment (to assess sensitivity).

The majority of these trials were carried out over a smooth rigid reference pavement that is present at the control room end of the PTF (Figure 1). However, a number of tests runs were also carried out on an existing (uncharacterised) flexible pavement that had been constructed for the purposes of other PTF experiments.

4.2 Analysis - assumptions

The primary stage of analysing the data from the initial trials was to develop a method to quantify the rolling resistance from the measurements provided by the instrumentation. This required a number of basic assumptions:

- The pavement, on which the majority of the tests took place, is horizontal
- The wheel is always in contact with the surface, and in rotation without slip
- The instrumented arms and rod ends are perfectly rigid
- The temperature of the pavement is constant along its length
- The two identical arms holding the wheel are inclined at the same angle.

Because the calculation of the rolling resistance from the sensor data is complicated, several further assumptions were made. In particular, there are contributions to the rolling resistance which are not easily measurable, for instance aerodynamic drag and inertial forces. In order to take account of these contributions, it was necessary to assume that the inertial forces were equal and opposite in both directions (and thus would cancel out when combining a right-to-left and left-to-right pass), and that the contribution from the aerodynamic drag was negligibly small in comparison to the other contributing forces.

4.3 Analysis – evaluating rolling resistance

Figure 5 shows a schematic of the geometry of the measurement system as installed on the PTF, assuming that motion take places from right to left. Note that Figure 5 is not to scale, and the angles, as well as distance d, are exaggerated for the sake of clarity.
Figure 5: Simplified representation of the forces in balance for a right to left motion.

Note the following definitions (refer also to Figure 3)

- The arm is AB. For simplicity, this has been represented by a line in Figure 5 but actually has a thickness, \( t \), of approximately 100mm.
- The ram is AC.
- \( r \) is the radius of the tyre.
- A is the centre of the wheel (also considered as the centre of gravity of the system).
- B is the arm pivot point.
- C is the ram pivot point.
- The angle between the arm AB and the x-axis is \( \alpha \).
- The angle between the ram and the z-axis is \( \beta \).

One rotary encoder provides the angle of the arm, \( \alpha \). Simple geometrical considerations allow the computation of the ram angle \( \beta \), given the length of AB, the fixed vertical distance between the top of the ram and the arm pivot - BCV, as well as the thickness \( t \) of the arm, using the following equation:

\[
\tan(\beta) = \frac{AB \times [1 - \cos(\alpha)] + t \sin(\alpha)}{BCV - AB \sin(\alpha) - t \cos(\alpha)} \tag{2}
\]

The system of mass \( m \) moves with a velocity \( \vec{V} \) and an acceleration \( \vec{a} \) (which is not null).

The weight is \( \vec{W} = mg \), where \( g \) represents gravity.

\( \vec{F} \) is the force driving the carriage and wheel assembly, measured in the load cells in the arms (which are pushed during the travel from right to left and pulled from left to right).

\( \vec{L} \) is the load applied by the ram, which is always directed downward nearly vertically (\( \beta \) is about 2°).

The tyre deforms and the friction can be modelled as a force \( \vec{R} \) applied at a distance \( d \), slightly in front of the projection of the centre of gravity of the wheel (Miege and Popov, 2005). This force can
be split in two components, namely a vertical force $\vec{S}$ directed upward, which is the reaction of the surface, and a horizontal force $\vec{Fr}$ opposed to the motion.

With these notations, the balance of forces becomes:

$$m\ddot{a} = \vec{F} + \vec{L} + \vec{R} + \vec{W}$$

[3]

By projection on the x-axis (in the horizontal plane, parallel to the direction of travel) we obtain (in algebraic notation):

$$ma_x = F_x + L_x + Fr$$

[4]

and along the z-axis (vertical):

$$ma_z = F_z + L_z + S + W_z$$

[5]

The accelerations, $\ddot{a}_x$ and $\ddot{a}_z$, can be obtained from the accelerometer, which is mounted on one of the arms. Since the accelerometer is mounted on one of the arms and these are at an angle, a rotation has to be made to get the components along the true x, y and z-axes.

Now considering the horizontal relationship in the two directions of travel gives:

- from right to left
  $$-ma_{x_{RL}} = -F_{x_{RL}} - L_{x_{RL}} + Fr_{RL}$$

[6]

- from left to right
  $$ma_{x_{LR}} = F_{x_{LR}} - L_{x_{LR}} - Fr_{LR}$$

[7]

with $F_x = F \cos(\alpha)$ and $L_x = L \sin(\beta)$.

It was assumed that the friction is the same in the two directions, and since the aerodynamic drag was neglected, the rolling resistance, $D$, is defined by $D = Fr_{LR} = Fr_{RL}$, that is, by combining Equations 5 and 6:

$$D = \frac{1}{2} \left( -m \left( a_{x_{RL}} + a_{x_{LR}} \right) + \left( F_{x_{RL}} + F_{x_{LR}} \right) + \left( L_{x_{RL}} - L_{x_{LR}} \right) \right)$$

[8]

The values of rolling resistance are expected to generally lie in the range of a fraction to several hundreds of kN.

Note: For all trials the arm angle ($\alpha$, Figure 5) was positive, i.e. the arm was higher at the wheel axis end than the end joining it to the PTF carriage. As expected, when the vertical load was increased the angle of the arm decreased linearly, ranging between 10 and 13°. Similarly, the rams always stayed to the left of the vertical (if viewing the PTF from the same side as displayed in Figure 5), ranging between 1.8 and 2.5° ($\beta$, Figure 5). This meant that, since the geometry of the system remained the same for the whole of the trial, the same calculation could always be used to obtain rolling resistance.

4.4 Conclusions of initial trials

Summary results of the initial trials are shown in Appendix B. The trials demonstrated that rolling resistance increases linearly with increasing wheel speed, in accordance with previous research (Bendtsen, 2004 and Popov, 2002). This behaviour was reliable up to and including test speeds of 15km/h. For higher speeds the behaviour was not as expected, and no definite reason was identified for this deviation in behaviour. Thus, it was concluded that the speed should be limited to a maximum of 15km/h during the final trials (Section 6).
Similarly a linear increase in rolling resistance was observed with increasing wheel load for loads below 30kN, in agreement with the literature (Bendtsen, 2004, Popov, 2002). However, for higher loads the system became non-linear and the behaviour differed from that for smaller loads. It was concluded that this behaviour was likely to arise from the fact that the instrumented arms are not perfectly rigid, and applying large wheel loads causes a degree of bending, thus distorting the measurements. Improving the rigidity of the arms was not an option, due to the effects that this would have on their sensitivity, thus it was concluded that the load should be maintained at or below 25kN for the final trials.

The variation of the coefficient of rolling resistance (Crr) with tyre inflation pressure on an asphalt surface was in good agreement with that typically reported in the literature (Wong, 2001). However, when the equipment was tested on a concrete surface, although the relationship was in reasonable agreement with that expected, the overall values were often slightly lower than those obtained for asphalt.

It was shown that the temperature of the tyre took 1½ hours of trafficking to reach a steady state with the pavement temperature. This “warm-up” time would need to be taken into account when designing the final trials (Section 6). The relationship between the tyre/pavement temperature and the rolling resistance was also in agreement with the literature. However, it was noted that an increase of ~1°C caused a decrease of ~0.00005 in the coefficient of rolling resistance. Estimates of the effect of stiffness on rolling resistance showed that the difference in the coefficient of rolling resistance, between a flexible and rigid pavement, could be as little as 0.0002. Therefore, for the final trials, it would be necessary to ensure that the standard deviation of the tyre temperature, between trials, did not exceed 2°C (otherwise the effects on the rolling resistance from stiffness would be overwhelmed by the effect of temperature).

Finally, tests with the artificial load showed that the measurements, as well as the processing techniques, were reliable, and that the system should be capable of accurately measuring small changes in rolling resistance.

4.4.1 Notes on the influence of unwanted variability in the measurements

Many precautions were taken to eliminate as much noise as possible from the measurement data. Many sources of noise were present, some that could be minimized and some that could not be controlled. In particular, the electrical noise generated by the 50Hz power supply was found to be significant but was reduced by using sheathed cables. Ferrite bead inductors were snapped around all cables potentially broadcasting radio signals. The decision to transmit information (between the loggers onboard the moving carriage and the host computer) via the Ethernet network also substantially reduced potential interference. Further safety measures were to properly bond the sensors and use dampers to attach the instrumentation to the carriage, etc. However, the heavy machinery of the PTF comprises many parts in motion: motors, pulleys, rope scroll wheels, cables, plates, more or less connected by virtue of the construction, but all of them vibrating at their own frequency and sometimes with large amplitudes, and it was not possible to control the noise emanating from these sources. There are also several control mechanisms continuously adjusting the speed of the carriage and when necessary the vertical load. Accordingly, obtaining data absolutely free of noise was unachievable.

Indeed, when the data from the trials was inspected, the forces measured at each point across the pavement in the rod end strain gauges and the arm load cells clearly displayed large oscillations. It was subsequently found that these could be attributed to the speed regulation system, and to the horizontal wander of the wheel. This wander of the wheel could just be a feature of the PTF, but could also be due to the fact that the instrumented arms are not perfectly rigid. To minimise the effects of this it was concluded that data used for analysis should be restricted to that obtained from the middle 2-3m strip.

One implication of the noise is that suitable filtering needs to be applied to remove the noise from each pass. This would be essential if an accurate value of rolling resistance is desired at individual
measurement points (e.g. every few cm) along the length of the test strip. However it was felt that it
would not be practical to attempt to obtain such values. Indeed, even with filtering the rolling
resistance calculated at any particular intermediary point within a pass would be particularly doubtful
because the values are so unstable. Therefore an approach was taken such that values of the rolling
resistance were obtained that corresponded to an average over a large number of passes over the
middle 2-3m of the test strip.

5 Test Pavements for Investigating Rolling Resistance

5.1 Design
The test pavements were constructed in situ in the PTF test bed for the purposes of assessing the
effect of stiffness on rolling resistance. These were constructed to the standards set out in the DMRB
(Volume 7: HD25/94 and HD26/06), with a number of additional criteria:

- One strip shall have considerably higher stiffness than the other. However, the strips shall not
  have constructions that are completely unrepresentative of types that may be used on the
  trunk road network.
- The running surface provided as the top layer will be the same for both test strips, providing a
  surface sufficiently robust to ensure consistency throughout the testing phase.
- The longitudinal profile at the running surface should be such that the effects on the rolling
  resistance are minimal, whilst also minimising the vibration and noise effects in the rig i.e.
  there should be no profile features present that are larger than ±5mm in height.
- It will be necessary for both strips to have the same longitudinal profile, to avoid introducing
  variability due to different energy losses created by different profiles.

Two pavements were constructed, one of a flexible construction, the other of rigid construction, both
adhering to the guidelines laid out above. The pavements were constructed as described in Appendix
C, using CRCP for the base of the rigid pavement, asphalt for the base of the flexible pavement. Both
pavements were surfaced with a proprietary thin surfacing system, using a 14mm Hitex PSV 55-65
(commonly referred to as PSV 60).

The two pavements were laid adjacent to each other within the PTF and the surface course was laid on
both pavements simultaneously, in order to achieve similar levels of texture and profile.

5.2 Properties

5.2.1 Profile
The longitudinal profile of both the rigid and flexible pavements was measured with the ARRB
walking profiler (ARRB Transport Research Ltd., 1996).

For the rigid pavement, the profile of the concrete base layer was measured, before the surface layer
was laid. Measurements were made along the longitudinal line to be trafficked in the centre of the test
strip and at ±300mm on each side of this line. The results are presented as a shaded surface in Figure
6. There are clear longitudinal undulations with a small transverse “bump” around the middle,
probably due to the constraints of the PTF structure. Generally, concrete is vibrated during
construction to ensure that the resulting surface is horizontal but this was not possible within the PTF.
Despite not being completely flat, the initial trials had concluded that profile amplitudes in the range
of ±5mm were acceptable for these trials, and the measured profile fell easily within these limits. In
an ideal situation, the concrete would have been flat in both directions but it was not considered
feasible to improve the surface further, once laid, and the addition of the thin surfacing was, in any case, expected to significantly improve this aspect of the final surface profile.

![Figure 6: Longitudinal profile of the stiff concrete course (before surfacing)](image)

Due to the timetable of construction, it was not possible to measure the profile of the base layer of the flexible pavement, thus no such results can be presented here.

Profile measurements were taken, once the surface course had been laid on both pavements, both along the central longitudinal line of trafficking and also along the two lines equally spaced between the middle and edges. The corresponding central profiles are displayed in Figure 7.

![Figure 7: Longitudinal Profiles of the rigid (stiff) and flexible pavements, measured from left to right, when viewing the PTF as in Figure 1](image)

As can be seen, the profile of neither pavement is flat and there is a small gradient running up from left to right. However, in the initial trials, it was found that, due to the influence of the PTF’s speed regulation system on the wheel, only the data collected from the middle 2-3m of the test bed was useable. If only this middle section is considered, then the profiles are fairly flat and similar to each other – see the non-hatched area on the graphs in Figure 7. Thus, since the profiles are comparable over the length of interest, this should affect the results from each pavement equally. Also, the two pavements are fairly flat in this length, and the profile is within the tolerance specified for pavement construction, so it is feasible to again make the assumption that the pavements are horizontal.

### 5.2.2 Texture

The texture of the pavements was measured using a circular texture meter (Flintsch, 2003, Nippo Sangyo, 2006). As with profile, the texture was measured along 3 longitudinal lines – the intended
line of trafficking (centre) and two lines lying midway between the centre and the edges. Three measurements were made at each location.

The pavements were trafficked for a few hours each before measurement of the texture, to reduce the effects of the stickiness/reflection of the fresh bitumen on the texture readings. Thus, the PTF was run for 3 hours on each pavement and then the texture measured. The results are contained in Table 1. Since the texture measured at each line across the width of each pavement was consistent, only one result has been presented for each pavement.

<table>
<thead>
<tr>
<th>Pavement</th>
<th>SMTD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid</td>
<td>1.10 mm</td>
</tr>
<tr>
<td>Flexible</td>
<td>1.25 mm</td>
</tr>
</tbody>
</table>

Table 1: SMTD measurements made on both pavements, after trafficking for 3 hours each.

As can be seen, the rigid pavement has 0.15mm deeper texture than the flexible, over the lengths where the data analysis will concentrate. The difference is surprising given that the surface course was laid at the same time on both pavements, using the same material and the same machine. However, it was hoped that the difference in SMTD would not be large enough to significantly affect the assessment of rolling resistance. Certainly previous research (Descornet, 1990) and results found in Section 6.4 would suggest that this is the case.

5.2.3 Deflection

The deflection of both pavements was measured using the FWD (Falling Weight Deflectometer). Deflection measurements were made every 0.5m along the longitudinal centre line and the two lines mid-way between this and the pavement edges. Two load levels were used – 50kN and 75kN, to represent those usually used to measure deflection of in-service flexible and rigid pavements respectively. The average values of central deflection measured by the FWD, with measurements normalised to 50kN and 75kN (as appropriate), are presented in Table 2.

<table>
<thead>
<tr>
<th>Pavement</th>
<th>Temperature at 100mm for these tests (°C)</th>
<th>Deflection at 50kN (microns)</th>
<th>Deflection at 75kN (microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid</td>
<td>9.2</td>
<td>245</td>
<td>390</td>
</tr>
<tr>
<td>Flexible</td>
<td>9.7</td>
<td>273</td>
<td>438</td>
</tr>
</tbody>
</table>

Table 2: Average central deflection measurements for both pavements

The flexible pavement was designed to be the weakest structure permitted within the DMRB, Volume 7 HD26 (DMRB, 2006), for HA roads, with a total design life of 1 msa. If the measured deflection of 273 microns, at a loading of 50 kN and a temperature of 9.7 °C, is adjusted to the equivalent standard temperature of 20°C then the expected deflection would be around 500 microns. Although this might appear a large value in comparison to the more normal range found on heavily trafficked HA motorways, of around 100 to 200 microns, it should be remembered that the total thickness of asphalt materials is only 210mm and a 125 penetration bitumen was used in the main layers. In fact, if the standard HA deflection design method is applied to the adjusted deflection measurement then a total estimated pavement life of around 1 msa is obtained, corresponding to the original design brief.

In contrast, the results for the rigid pavement are more surprising on initial inspection, as they are significantly higher than the average deflections, of around 50 to 100μm, for rigid CRCP pavements on the network. However, it should be noted that there are a number of features in the standard CRCP design that were modified when constructing the pavement within the PTF, due to concerns over damage to the PTF pit and also the effect that cracking would have on the pavement’s properties. It was thought that if cracks did develop in the pavement then these would lead to the pavement being
weakened and thus a decrease in its stiffness. Also, it was considered possible that the cracks would affect the profile of the pavement, which, as discussed in Section 5.2.1, was not desirable.

The following features were not standard for the CRCP pavement constructed within the PTF:

- The steel reinforcement was not anchored at either end and the CRCP slab was deliberately isolated from the surrounding walls (of the PTF pit) by a 12mm thick flexible material. This was to protect the walls of the PTF pit from the concrete slab expanding too much and thus causing damage.

- The CRCP slab was isolated from the underlying layer with a double layer of polythene, to reduce the friction between the two layers and thus constraining strains, in an attempt to avoid cracking in the slab.

Both of these measures would undoubtedly have reduced the chance of cracking in the in rigid layer, however, they increased the chance of the pavement deflecting.

Without restraint from the edges, there is a possibility that the whole pavement is able to move up and down rather than deflect in the normal manner. Thus, the total deflection is more dependent than usual on the strength of the foundation. In addition, the double layer of polythene under the CRCP layer may also have increased the overall deflection. However, a simple back analysis suggests an upper layer stiffness of 18Gpa for the CRCP pavement and around 7Gpa for the flexible pavement. Thus, there is a clear difference in the stiffness of the upper layers of the pavements.

6 Trials of Rolling Resistance

As discussed above, the initial trials assessing the capability of the equipment (Section 4) confirmed the large influence of temperature on rolling resistance. Hence it was important, during the trials of the measurement of rolling resistance on the test pavements, to either control the ambient temperature, the pavement temperature and the temperature of the tyre, or ensure that datasets were obtained where all three of these temperatures were in the same range (so that datasets could be compared).

In the PTF Infra-red heaters can be used to control the temperature of the pavement at 100mm depth. However, it is not possible to control the ambient temperature within the PTF, and it was also not possible to control the temperature of the surface of the pavements, nor the tyre temperature, since these depend on ambient temperature. Thus it was concluded that it was not practical to attempt to control the temperature.

Therefore, long (24 hour) trials were designed, as discussed in Section 6.1, so that, during trials on different pavements, the temperature of the components should stabilise and therefore comparable conditions of temperature should exist.

6.1 Long (24 hour) trials

6.1.1 Procedure

Following the completion of the initial trials (Section 4), it was necessary to remove the instrumentation from the PTF, to accommodate the needs of other research projects using the PTF. Following re-fitting of the instrumentation for the long trials, checks were carried out, using the smooth concrete reference pavement at the control room end of the PTF, to establish satisfactory performance of the instrumentation. This involved calibration of the horizontal arm reference angle and encoder scaling, manually checking the tyre pressure, and ensuring that the data behaved as would be expected, with and without the artificial load.

Furthermore, prior to the long trials, the rigid and flexible test pavements were trafficked for 3 hours each, to reduce the effects of the new surface on the measurements of rolling resistance (e.g. from a “sticky” coating).
Trials were then undertaken on the test pavements by trafficking continuously, using a tyre pressure of 827kPa (120psi), speed of 15km/h, wheel load of 25kN and no artificial load, for 24 hours on each pavement. It was planned that the two pavements should be trafficked for 24 hours 3 times each, in order to obtain a robust dataset, where there would be an overlap of temperatures, from which values could be obtained and used for analysis.

6.1.2 Results from long trials

An observation that was made during the long trials was that there appeared to be a linear relationship between the tyre temperature and the coefficient of rolling resistance, for the range of temperatures measured, on both pavements. As can be seen in Figure 8, for the flexible pavement, the slope of the line was 1.9x10^-4/°C whilst for the rigid it was 1.7x10^-4/°C, giving an average of 1.8x10^-4/°C for both pavements. This is in broad agreement with literature, where it was found that the coefficient of rolling resistance, of a car tyre, running on a smooth surface was linearly related to tyre temperature, with a slope of 1.34x10^-4. However, it was not possible to establish such a relationship between the coefficient of rolling resistance and the temperature of the pavement or the ambient temperature. This made it difficult to develop correction factors for these variables that could be used to normalise the data from each pavement to compensate for temperature. Therefore, it was hoped to obtain a dataset from both pavements where all temperatures were the same.

![Figure 8: Relationship between rolling resistance and tyre temperature](image)

When the temperature data, from the 24 hour trials, was analysed and areas of overlap between the two datasets extracted, it was found that there were approximately 1200 passes made in each direction on both pavements, where approximately common conditions could be established. These being a tyre temperature of 11°C, pavement temperature between 10.0 and 11.3°C, and ambient temperature between 7.1 and 7.4°C.

However, whilst these trials had successfully achieved a common set of temperatures, the instrumentation showed that the PTF was not successfully maintaining a consistent loading throughout the period of the trials. The inconsistency in the load commenced after approximately 200 passes, and varied by ±1kN thereafter, as can be seen in Figure 9. Unfortunately this problem had not been identified during the initial trials of the instrumentation, and it was concluded that a fault had been introduced into the PTF’s loading system during the research carried out on other projects between the date of the initial trials and the date of the trials on the test pavements. Analysis of the
data from the instrumentation showed that variation in load resulted in the rigid pavement being trafficked with 0.2kN less load than the flexible pavement.

![Wheel load measured on flexible pavement](image)

**Figure 9:** Wheel load applied versus time

The data collected during the conditions of common temperature was collated and evaluated to determine the coefficient of rolling resistance on each test pavement. Because of the variation in load described above the coefficient obtained on each pavement must be considered in relation to the load applied. Figure 10 presents the measured coefficients of rolling resistance for each pavement, measured with a load of 29.1±0.1kN being applied to the rigid pavement, and 29.3±0.1kN being applied to the flexible pavement. For these datasets, the average coefficient of rolling resistance on the rigid pavement was 8.33x10^-3 and on the flexible 8.78x10^-3. However, as can be seen from Table 3 and Figure 10, the values obtained in the two datasets overlap substantially and the two cannot be clearly separated from each other. The average values and standard error bars have been added to Figure 10 for information.

![Coefficient of rolling resistance for flexible and rigid pavements](image)

**Figure 10:** Coefficient of rolling resistance for flexible and rigid pavements (relative to load)
6.1.3  Compensating for external factors

It has been noted above that a difference in load was observed between tests of the rigid and flexible pavements. Although the difference was not large (0.2kN), it will have an effect on the measured rolling resistance. Furthermore, assessment of the surface properties of the test pavements (section 5.2.2) showed that there was a difference in the surface texture depth of the test pavements of 0.15mm.

The effects of wheel load and texture on rolling resistance has been reviewed in previous research (Popov 2002, Benbow et al. 2006, Descornet 1990) and relationships estimated. Use of the literature enables us to evaluate the influence of these factors as follows:

- A decrease in wheel load of 0.2kN should lead to a decrease in the coefficient of rolling resistance of approximately 8x10^-6 (Popov 2002, Benbow et al. 2006).
- A difference in texture depth of approximately 0.15mm should lead to an increase in the coefficient of rolling resistance, of 3.2x10^-5 (Descornet 1990).

Adjusting the figure given for the flexible pavement, in Table 3 using these estimates, revises the results of Table 3 to obtain the results displayed in Table 4.

<table>
<thead>
<tr>
<th>Pavement</th>
<th>Average Coefficient of rolling resistance</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid</td>
<td>0.008326</td>
<td>0.000616</td>
</tr>
<tr>
<td>Flexible</td>
<td>0.008822</td>
<td>0.001077</td>
</tr>
</tbody>
</table>

Table 3: Coefficients of rolling resistance from 24 hour trials

<table>
<thead>
<tr>
<th>Pavement</th>
<th>Average Coefficient of rolling resistance</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid</td>
<td>0.008326</td>
<td>0.000616</td>
</tr>
<tr>
<td>Flexible</td>
<td>0.008822</td>
<td>0.001077</td>
</tr>
</tbody>
</table>

Table 4: Coefficients of rolling resistance from 24 hour trials, including theoretical correction for differences in load and texture

Whilst the average coefficient of rolling resistance on the flexible pavement now differs slightly more from that on the rigid pavement, there is still substantial overlap between the two datasets. Due to the necessary method of extraction of the data, it was not possible to separate the datasets further and no obvious statistical technique could be applied.

The difference between the averages measured on the two pavements, is approximately 0.0005, half of the standard deviation measured on the flexible pavement, which could be said to be significant. However, since it would be extremely difficult to reproduce the experiment, with exactly the same temperatures and other conditions, the reproducibility of the results cannot be proved. Thus, since it is not possible to reduce the noise of the dataset further, no obvious statistical method exists to separate these datasets further and thus it is not possible to determine if this result is significant.

Thus, whilst it can be proposed that, for our test pavements, an increase in deflection of ~250µm (at 50kN/700kPa loading and 20°C) will result in an average increase in coefficient of rolling resistance of the order of 5x10^-4, since the overlap between the datasets obtained during these trials is significant, this result cannot be considered conclusive.
6.2 Further (Short) trials

Following the observation of a variation in the load applied by the PTF during the long (24 hour) trials, further testing was carried out over short lengths of time (in an attempt to obtain datasets where the load was relatively stable). This approach was considered to be less desirable than the long trials because of the greater difficulty in obtaining overlapping datasets covering equivalent temperature conditions. The approach taken here was to carry out the trials with minimum delay between each test in an attempt to maintain temperature stability and obtain an overlap in temperatures.

Furthermore, to ensure that the system was behaving correctly measurements were taken both with and without application of the artificial load. Thus, the procedure, described in Table 5, was carried out three times on each of the rigid and flexible pavements, and the PTF reference concrete test pavements. The order of the pavements selected for trafficking varied for each set of three trials.

<table>
<thead>
<tr>
<th>Wheel load</th>
<th>Tyre pressure</th>
<th>Speed</th>
<th>Number of passes</th>
<th>Artificial load</th>
</tr>
</thead>
<tbody>
<tr>
<td>25kN</td>
<td>827kPa (120psi)</td>
<td>15km/h</td>
<td>110</td>
<td>Full</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>110</td>
<td>1/3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>110</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>110</td>
<td>2/3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>110</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>110</td>
<td>Full</td>
</tr>
</tbody>
</table>

Table 5: Order of application of artificial load during short trials

Unfortunately, although these trials were designed to minimise the fluctuation of tyre, pavement and ambient temperature, it became apparent that this was not the case, with differences of up to 3°C in the temperatures. Although the results of the long trials (section 6.1.2) showed a linear relationship between the tyre temperature and coefficient of rolling resistance, and thus it could have been possible to scale the results to a fixed tyre temperature, it was not possible, in these short trials, to obtain a comparable relationship to compensate for the effects of ambient and pavement temperatures. Therefore, since correcting for tyre temperature would not enable us to obtain accurate results, and might lead to results where the influence of pavement and ambient temperature obscured the very small change expected due to stiffness, it was not possible to obtain any further data from these short trials.

6.3 Discussion

The long (24 hour) trials have shown that the coefficient of rolling resistance measured on the flexible pavement was typically 5x10^-4 higher than that obtained on the rigid pavement. Given the magnitudes of typical coefficients of rolling resistance, this difference cannot be considered to be large and because the two datasets overlapped to a significant extent, this result is not statistically conclusive. Furthermore, when considering the measured coefficients of rolling resistance on each pavement type note should be taken of the observations made when characterising the properties of the pavements (Section 5), as discussed below.

When constructing the test pavements the designs were selected such that each pavement would exhibit a stiffness typical of certain rigid and flexible pavements, respectively, on the network. The rigid pavement should have had a stiffness far greater than the flexible pavement, and the flexible pavement was chosen to be a relatively weak structure but still expected to exhibit stiffness typical of the weaker flexible pavements on the network. The deflection measured on the flexible pavement, whilst not generally found on the network, was of the order expected for such a relatively weak structure (1msa traffic load). However, the deflection measured on the rigid pavement was far higher than was expected. This would suggest that perhaps the method of construction practiced within the PTF led to the rigid pavement being less stiff than it should have been.
For the rigid pavement it is noted that CRCP pavements constructed on the network are typically anchored at each end of the concrete slab. However, when considering the construction of this pavement within the PTF there was concern that anchoring of the pavement could damage the PTF pit, and would also lead to increased crack induction. It was concluded that cracking may have an undesirable effect on the profile of the pavement, and potentially weaken it. Therefore it was decided to not implement anchoring within the construction.

A conclusion that may be drawn from this is that it is difficult to construct a rigid pavement within the constraints of the PTF that displays behaviours consistent with those obtained from pavements on the network. Producing a pavement that displays such behaviour will require revision to the construction processes applied in the PTF.

It has not been possible to fully explain the relatively high level of the FWD measurements on the rigid pavement. It is our opinion that the level of the deflection readings from the FWD on the rigid pavement were largely as a result of the concrete slab being able to move both horizontally and vertically within the PTF’s pit. However, inspecting the bowl shape from the deflection readings, for both pavements, suggests that the rigid pavement had an upper layer stiffness significantly greater than the flexible pavement. The results of the trials show that the effect of this on rolling resistance is not significant.

A further observation made in Section 5 was that there was a difference in surface texture between the two test pavements. This occurred despite stringent controls on the surface laying and the fact that the same surface was laid on both pavements at the same time. As discussed above, it is known that texture has an effect on a pavement’s rolling resistance, and this is likely to dominate over the influence of stiffness (which these trials have shown to be small and difficult to quantify). At the end point of our experiments into the effect of stiffness on rolling resistance further work was commencing (on a separate project) in the PTF on a test pavement that had been constructed using a single foundation but two different surfacings. It was felt that this offered a good opportunity to extend the trials of rolling resistance to determine whether the instrumentation could be used to investigate the effect of texture on rolling resistance. This is discussed in Section 6.4.

### 6.4 Further investigation of the influence of texture on rolling resistance

The pavement tested was fully flexible and constructed so that the same base, sub-base and sub-grade ran the whole length of the pavement, whilst the surface layer changed halfway along its length. The pavement’s construction is discussed in detail in Appendix C.

At one end was an unchipped Hot Rolled Asphalt (HRA) (30% 0/10mm), whilst the other half was a 0/10mm Dense Bitumen Macadam (DBM) surface course (Figure 11). Since the HRA was unchipped, it had a very low texture until ruts started to form and the pattern of the tread of the tyre started to be imprinted on it. The texture of each half of the pavement was measured (prior to trafficking) using the circular texture meter, and the SMTD of each half was found to be 0.16mm for the HRA end and 0.60mm for the DBM i.e. a difference of 0.44mm. Comparison of these measurements with the known distribution of SMTD values obtained on the HA network, shown in Figure 12, shows that the SMTD of the unchipped HRA is an extremely low value in network terms, and not generally found on the network. Also an SMTD of 0.6mm or less, which is still quite low, would only be found on about 6% of the network.
The deflection of the pavement was measured with the FWD and the deflection at d1 (normalised to 50kN and with a temperature of 8.7°C at 100mm depth) was found to be 247µm on the DBM side and 240µm on the HRA side i.e. of a similar order to the rigid pavement used above. The apparent higher level of stiffness of this pavement is probably due to the fact that the pavement was constructed with thicker surface and base layers (see Appendix C) than the flexible pavement used in the stiffness comparison.

Profile measurements carried out over the test strip using the Walking Profiler showed a bump at the location of the surface change in the middle of the pavement. This was found to cause the PTF test wheel to bounce for a short time after traversing the bump. Thus, instead of being able to use the middle 3m of the length for the analysis (as used in the main trials), only 1m of data was available for analysis from each side of the surface change.

Tests were carried out at a load of 25kN, speed of 15kmh and tyre pressure of 827kPa i.e. the same conditions as the trials carried out on the rigid and flexible pavements. However, due to the requirements of the research project for which these pavements were constructed, it was necessary to carry out the tests whilst the pavement was being heated, using infra-red heaters, to a temperature of 35°C at 100mm below the surface. Despite this higher temperature in the lower layers of the pavement, the surface temperature was not much higher than the surface temperature measured during the trials on the flexible and rigid test pavements above.

Figure 13 shows the coefficient of rolling resistance obtained on either side of the surface change as the trafficking of the pavement increased. It can be seen that the coefficient of rolling resistance (Crr) for both sides of the pavement varied with time, as the ambient (and therefore tyre) temperature changed. However, the coefficient of rolling resistance is significantly higher on the textured half of the test strip. Because the test pavement was constructed with two different textures along its length it was possible to take measurements almost simultaneously (the PTF’s wheel traversed both surfaces in
one pass) and therefore these were taken at approximately the same temperatures, wheel load and speed, which resulted in two datasets being collected that were directly comparable. Also, the pavement had similar profiles on both halves, and only the surface layer differed between the two halves. Thus the measured difference in the rolling resistance can only be attributed to the texture.

From the data shown in Figure 13 the trials suggest that an increase of 0.44mm in the SMTD leads to an increase of $5 \times 10^{-4}$ in the coefficient of rolling resistance. This is consistent with that estimated in the literature (Descornet 1990). It is also consistent with the average difference in the coefficient in rolling resistance observed between our rigid and flexible pavements. However, whilst there is some overlap between the datasets of the coefficient of rolling resistance measured for two different textures, the datasets are much more distinct from each other than from the rigid/flexible pavement trial, where the dataset for the rigid pavement is a subset of that from the flexible pavement (see Figure 10). Thus there is higher confidence in the difference in rolling resistance calculated for the two halves.

If we consider the distribution of texture depths obtained on the network (Figure 12) we are able to place this result in context. It can be seen that the range of textures considered in this initial investigation encompasses only a small part of the range of textures present on the network. However, comparison of the results obtained in this initial investigation of the effect of texture with the results obtained on the flexible and rigid pavements suggests that pavements having significantly different constructions (rigid vs. flexible), but the same texture, may demonstrate similar differences in rolling resistance to pavements having similar construction and different textures, indicating that texture would probably have the largest influence at the network level.

![Figure 13: Rolling resistance measured on each half of the dual surface pavement](image)

7 Further Potential Uses of Instrumentation

The instrumentation constructed for this project was designed with the primary objective of measuring rolling resistance. However, the trials have highlighted a number of other potential uses for the equipment.

The PTF is frequently used to carry out trials where rutting is a key measure. During these types of trials, the test pavement is trafficked for a set number of passes and then rutting is measured manually,
whilst the PTF is stationary. Trafficking then recommences and the cycle continues. Whilst this gives an accurate record of rut depth, it gives no detail of the shape of the rutting trend e.g. if the rut depth has increased by 1mm after 200 passes, the manual method of measurement gives no indication whether the rut increased in depth linearly over the 200 passes, or whether the deformation took place in the last 20 passes. Furthermore, stopping the PTF to take measurements affects the establishment of equilibrium conditions of temperature within the pavement and tyre.

During the investigation into the effect of texture on rolling resistance, the pavement being trafficked developed ruts. It became apparent that the angle of the arm could potentially be used to calculate the rut depth of the pavement being trafficked. The average arm angle for each 100 passes, measured by the encoder, is shown in Figure 14, with the first 100 passes being displayed as a black line, at the top of the graph, with the last 100 passes being displayed as a feint silver line at the bottom. The middle length of the pavement has been omitted, due to the wheel bouncing over the surface change in this length. As can be seen, the pavement height measured by the arm angle encoder decreases over time, as ruts formed in the pavement and the ruts in the DBM side are deeper, which was as observed.

It is felt that this change in height could be used as a proxy for rut depth measurement but in this work, the encoder, from which the height measured was derived, was neither calibrated nor targeted at this application and some further changes were needed to provide an exact measure of rutting. Since these changes were out of the scope of the project, they were not implemented. However, they could be easily implemented for future experiments.

![Figure 14: Pavement height measured by arm angle encoder](image)

If the arm encoder could be used to calculate rut depth in the PTF, this would enable continuous rut depth data to be collected over the duration of the experiment, without the need to regularly stop the PTF to manually measure the rut formation (thus greatly reducing experiment time).

Further uses could also include:
- Use of the arm encoder to measure the profile in the pavements, and the change of profile as an experiment progresses.
- Use of the pyrometers to continuously record pavement and/or tyre temperature.
8 Conclusions

This work has developed instrumentation for the measurement of rolling resistance on test pavements constructed within TRL’s Pavement Test Facility (PTF). Earlier, in Task 2, trials of the instrumentation had shown that it is capable of measuring differences in rolling resistance as small as those obtained between pavements of significantly different stiffnesses.

For Task 3, two pavements were constructed within the PTF, in order to measure the effect of pavement deflection on rolling resistance. One was constructed with a CRCP base, and the other with an asphalt base, but both with the same subbase, subgrade and surface course. When constructing the test pavements the design was selected such that the rigid pavement should have had a stiffness far greater than the flexible pavement.

The deflection measured on the flexible pavement was of the order that would be expected for this type of pavement, i.e. designed for a traffic load of 1msa on a relatively weak subbase. However, the deflection measured on the rigid (CRCP) pavement was a lot higher than would have been expected. This may have been due to the construction methods employed in the PTF for this pavement. As discussed in Section 5.2.3, the CRCP slab was not anchored at either end, as it would be when constructed on the network, and this may have allowed the slab to move vertically. Also, a double polythene sheet placed between the slab and the base layer, to help prevent cracking, may have also allowed the slab to move horizontally, which would also have an affect on the deflection measured by the FWD. Thus the deflection difference between the pavements was only 28 microns at the temperature of the tests.

To obtain the same texture on both pavements, the same surface course was laid on both pavements simultaneously. This process delivered surfaces on each pavement that had a difference in texture of only 0.15mm (the flexible length was 0.15mm higher than the rigid length). Although the difference cannot be ignored, previous work had suggested that such a small change in texture should have a small effect on the rolling resistance.

During Task 2, trials of the instrumentation showed that temperature has a significant effect on the reported rolling resistance. Because heating the pavements to maintain the temperature would not have controlled the other variables of ambient temperature and tyre temperature, trials were run for 24 hours on both pavements, to deliver data from both pavements from which data segments collected under comparable conditions could be extracted. However, due to a degree of unexpected behaviour of the PTF, it was found that there was also variation in the loading applied between test runs.

The effect of varying wheel load on the coefficient was also known from previous research. Thus, following the extraction of data collected under common temperature conditions, the data was corrected for the effects of the difference in wheel load and pavement texture. This resulted in greater separation between the average measured coefficients of rolling resistance on each pavement and it was found that the average coefficient of rolling resistance measured on the rigid pavement was $5 \times 10^{-4}$ lower than that obtained on the flexible pavement. However, despite the corrections, there was still significant overlap between the datasets from the two pavements. (It was found, during Task 3, that the data collected on pavements with textured surfaces contains more noise than that collected on smooth surfaces such as the PTF’s reference concrete strip). Therefore although this result provides some evidence that there is a difference between the coefficient of rolling resistance between flexible and rigid pavements, the evidence does not support a conclusion that the difference is statistically significant.

Following the completion of the trials on the flexible and rigid pavements further work was carried out to investigate the capability of the instrumentation in measuring the effect of texture on rolling
resistance. A pavement was constructed with the same base layers for the whole length but half of the length had an unchipped HRA surface (SMTD 0.16mm), whilst the surface of the other half was DBM (SMTD 0.6mm). Thus, during one pass of the PTF, data was collected from both surfaces, giving a dataset where the temperatures and wheel loads were identical and thus highly comparable from each surface type.

A difference of $5 \times 10^{-4}$ (3.6%) was identified by the instrumentation between the coefficient of rolling resistance on the textured and untextured surfaces. The range of textures considered in this initial investigation encompasses only a small part of the range of textures present on the network. However, comparison of the results obtained in this initial investigation of the effect of texture with the results obtained on the flexible and rigid pavements suggests that pavements having significantly different constructions (rigid vs. flexible), but the same texture, may demonstrate similar differences in rolling resistance to pavements having similar construction and different textures. In relation to the network, this would suggest that to reduce fuel consumption on existing pavements, it would be more cost-beneficial to change the texture than to reconstruct to increase the pavement’s stiffness (since it is much cheaper to resurface than to reconstruct).

During these texture trials, it was also demonstrated that it may be possible to continuously measure rut depth whilst trials are being carried out, using the measured angle of the arm, which would result in continuous rut depth data, as well as reduced experiment time, due to the lack of need to stop the PTF to make manual measurements. A number of other further potential uses were also identified.

9 Implications for Fuel Consumption on the Network

Pavement properties, such as longitudinal profile, stiffness, texture and gradient all affect the rolling resistance a vehicle experiences when travelling on a road. In the work presented herein, differences in texture and deflection have been discussed in terms of their effect on the coefficient of rolling resistance.

A linear relationship exists between this coefficient of rolling resistance and the fuel consumed (Descornet, 1990):

$$\frac{\Delta F_c}{F_c} = \eta \frac{\Delta C_{rr}}{C_{rr}},$$

Equation 9

where $\eta$ is approximately 0.2, $F_c$ is fuel consumption and $C_{rr}$ is the coefficient of rolling resistance.

Thus, if the fuel consumption (and therefore environmental impact) of a road is to be considered, during the planning stages of new construction or maintenance, the cost benefits of building a more fuel efficient pavement (i.e. stiffer and/or lower texture) should be determined. The following sections discuss the fuel saving versus construction costs, given the kind of difference in rolling resistance seen during the current work.

9.1 Effect of Stiffness

During the trials performed in the PTF, it was found that a decrease in deflection of 28µm (at 50kN load and 9.7°C) resulted in the coefficient of rolling resistance decreasing from 0.0083 to 0.0088, i.e. a difference of $5 \times 10^{-4}$, i.e. a decrease of 5.7% in the coefficient of rolling resistance($C_{rr}$). Using the formula, given in Equation 9, this suggests a decrease of 1.14% in the fuel consumption of vehicles travelling over the two pavements.

As has been discussed earlier in Section 5.2.3, these two pavements are not entirely representative of the HA road network and the difference of $5 \times 10^{-4}$ in the $C_{rr}$ was not found to be statistically significant. However, we can nevertheless estimate the effect of the corresponding decrease in fuel consumption of 1.14% on the annual fuel cost on the HA’s network.
The typical fuel consumption on a given road is proportional to the length of the road, the number of vehicles travelling on it and the fuel consumption rate of a typical vehicle. Thus:

\[
\text{Cost of fuel per km per year (\£)} = \text{Fuel consumption (l/km)} \times \text{cost of fuel (£/l)} \times \text{number of vehicles}
\]

In other words, assuming a cost of £1 per litre of fuel, this equation simplifies to:

\[
\text{Cost of fuel per km per year (£/km)} = \text{Fuel consumption} \times \text{number of vehicles}
\]

If the average fuel consumption on a flexible pavement is 0.1176l/km (~20mpg), then, since it is estimated to be (with all the aforementioned caveats) 1.14% lower on a rigid pavement, it will be 0.1163l/km on such a pavement. According to DfT’s Transport Statistics (DfT 2006) the average annual vehicle flow on each lane is around 2.8M. (Based on 97 billion vehicle km per year covering 35,000 lane km). Thus, the saving in fuel per year on the rigid pavement, compared to the flexible (assuming a cost of £1 per litre) is given by the following equation:

\[
\text{Saving in fuel per year on rigid pavement per km (£)} = \text{Difference in fuel consumption} \times \text{number of vehicles}
\]

\[
= 0.0013 \times 2.8M
\]

\[
= \£3,640/\text{year}
\]

According to Spon’s Civil Engineering and Highway Works Price Book (2004), the cost of building a dual 3 lane rural motorway is of the order of £2.1M to £2.5M per kilometre, i.e. around £0.3M/km per lane. Since the HA road network comprises around 35,000 lane km (DfT 2006), these figures suggest that it would cost around £10.5 billion to reconstruct the whole network.

Thus the cost of reconstructing the network, at a cost of £0.3M/km, could be recovered in fuel savings over 80 years. This, of course, takes no account of other relevant costs such as traffic management, user delays, or inflation.

Since the results gained during the current set of experiments are not statistically significant and an exact relationship between deflection and fuel consumption has not been determined, the effects of reconstructing the network on fuel consumption cannot really be quantified. However, if the difference in deflection between typical flexible and stiff pavements on the network is actually much larger than that observed between the two test pavements, and the fuel consumption is proportional to deflection, then the length of time taken to recover the costs of reconstruction could be significantly reduced.

### 9.2 Effect of Texture

An increase of 0.44mm in the SMTD of one of the pavements in the PTF led to the coefficient of rolling resistance increasing from 0.0135 to 0.014, a difference of 5x10^-4, i.e. an increase of 3.6%. Thus, a decrease of 0.44mm in the SMTD would lead to a decrease in fuel consumption of 0.71%.

However this change in texture level is rather arbitrary as representing the difference between an unchipped hot rolled asphalt, which would never be found on the HA network and a dense bitumen macadam wearing course which is unlikely to be found on the network. The comparison with texture levels found on the HA’s network, and presented in Section 6.4, confirmed this. However, we can nevertheless estimate the effect of the corresponding decrease in fuel consumption of 0.71% on the annual fuel cost on the HA’s network.

If it is again assumed that the average fuel consumption on a flexible pavement is 0.1176l/km (~20mpg), then, since it is estimated to be 0.71% less on a lower texture pavement, it will be...
0.1168l/km on such a pavement. Thus, using the same method and annual vehicle flow, as discussed in Section 9.1, the saving in fuel per year on the higher texture pavement, compared to the lower texture one (assuming a cost of £1 per litre) is given by the following equation:

<table>
<thead>
<tr>
<th>Saving in fuel per year on lower texture pavement per km (£)</th>
<th>Difference in fuel consumption x number of vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>= Difference in fuel consumption x number of vehicles</td>
<td>= 0.0008 x 2.8M</td>
</tr>
<tr>
<td>= £2,240/year</td>
<td></td>
</tr>
</tbody>
</table>

The average cost of resurfacing a road is £16.00/m² (=£51,200 per lane km, assuming an average width of 3.2m)\(^1\), i.e. to resurface the network would cost approximately £1,791m (=£51,200/km x 35,000 km).

Thus resurfacing the whole network, at a cost of £51,200/km, could be recovered in fuel savings in just over 20 years. This, of course, takes no account of other relevant costs such as traffic management, user delays, or inflation.

Note: There may be scope for reducing the texture level on the network providing it was safe to do so but it is difficult to suggest what an acceptable change would be and then there is insufficient evidence from the present study to convert the present result, from the above 0.44 mm change into a reliable prediction for the whole network. However it is interesting to note that a change of 0.44mm in texture level gives an absolute change in Crr similar to that generated by the deflection difference of 28microns found on the stiff and flexible test pavements.

9.3 Effect of Climate Change

It was found, during all trials performed in the PTF, that an increase in tyre temperature leads to a decrease in the coefficient of rolling resistance. The relationship appeared to be linear for the range of temperatures experienced during the trials and the graph of Crr vs. tyre temperature had an average slope of 1.8x10\(^{-4}\) per °C.

The global warming models predict that Britain will experience an average increase of temperature of 1 to 2 °C over the next 50-70 years (http://www.telegraph.co.uk/htmlContent.jhtml?html=/archive/1996/10/25/nglob25.html). Ambient temperature has a large influence on both the tyre and pavement temperature and thus the rolling resistance. Thus, if it is assumed that tyre temperature will increase as per the ambient, and also that the temperature will increase linearly at 0.04°C year; this will result in a reduction in fuel consumption of approximately 0.016 % per year (assuming that such a small change in temperature will have little or no effect on the deflection of the flexible pavements).

9.4 Cost of Construction versus Fuel Savings

When a whole-life cost assessment is carried out, during the planning stages of either new construction or maintenance, the cost of constructing competing designs should be tempered with knowledge of the estimated fuel consumption costs on each pavement design. Thus, it would be recommended that further work should be carried out to attempt to quantify the effect of a range of textures or deflections on the fuel consumption, so that the environmental affect of any pavement can be considered when whole-life costing.

\(^1\) This cost is based on data provided by HA Managing Agents, in discussion on costs of maintenance on road renewals and summary schemes. The values have been derived from costs of schemes carried out in 2005/06.
10 Recommendations

This work has not shown any strong evidence to conclude that pavement stiffness has a large effect on rolling resistance. However, the results were complicated by the difficulties encountered in constructing pavements that showed behaviours consistent with those expected (given their constructions). Either as a result of the particular method of construction required in the PTF, or some feature of the PTF’s pit, the rigid pavement did not display the level of stiffness expected. If the construction of a rigid pavement were to be required in future (e.g. to confirm the results of this work), it will require modifications to the design and a different method of construction to that used for the experiments discussed herein.

The work has shown, more conclusively, that texture has a potentially larger influence on rolling resistance than stiffness. It would be of benefit to use the instrumentation to further explore this. If such an investigation should take place, it would be beneficial to consider the best use of the equipment, including:

- Removing the ramps at the ends of the PTF, to prevent the wheel from bouncing, as it exits the ramps, thus providing a longer length from which useable data can be obtained.
- Any pavement being investigated should be trafficked sufficiently so that a relationship between the rolling resistance and ambient, tyre and pavement temperature, wheel load and speed can be developed, thus enabling all results to be normalised to report values for exactly the same conditions.
- Alternatively, pavements should be constructed so that two or more types of surface can be trafficked virtually simultaneously. Data collected would then be directly comparable, since the temperature, speed and load would be identical.

References


and


Nippo Sangyo Company (2006): Description of Circular Texture Meter


Acknowledgements

The work described in this report was carried out in the Technology Development Group of TRL Limited. The authors are grateful to Brian Ferne who carried out the technical review of this report, to Benjamin Olobo for pavement design, to Mike Harding and John Chandler for their technical advice on CRCP and also to Dave Blackman, the facility manager of the PTF.
Appendix A. Recommendations of Task 1 for Instrumentation of the PTF

Support Arm: A load cell will be installed in each support arm to measure the force acting along the axis of the arm and is the main source of the rolling resistance information.

Wheel Hub: The wheel hub will be instrumented to enable the rotational position of the wheel to be recorded so that irregularities in the tyre and/or bearings can be analysed. Also, pulses indicating incremental rotation of the wheel will be used to create regular distance pulses as a sample strobe input for the data logger. Further instrumentation will be added to the wheel hub to measure the bearing temperatures.

Wheel Axle: A three axis accelerometer will be mounted on the axle to provide acceleration information that can be used to calculate the forces along the support arm due to the carriage accelerating and decelerating under the influence of the carriage speed control.

Load Ram Pivot: The pivot point of each load ram will be modified to include a load pin that will measure the load being applied by the ram.

Support Arm Pivot: An angular encoder will be installed to measure the angular displacement of one support arm. This shall be used for two purposes. Firstly, the measurement will be used to calculate the change in the force induced along the support arm axis due to the change in geometry of the support arm and load ram. Secondly, it will provide an indication of the axle height above the pavement.

Tyre: If a suitable sensor can be obtained the tyre pressure and internal temperature will be measured continuously. The tyre surface temperature will also be measured continuously using an infra-red temperature sensor fitted to the carriage.

Carriage Location: Four carriage locators in the form of retro-reflective sensors will be mounted on the carriage in pairs and with each pair working with a separate reflector placed to locate either the left or the right end of the pavement. The data logged from the carriage locators will locate the area of pavement under test and confirm the direction of the pass (left-to-right or right-to-left). It will also be possible to use the carriage locators to control data logging so that logging only occurs when the wheel is actually traversing the pavement and not changing direction at each end.

Data Acquisition: A data acquisition system will be required to sample and store the data provided by the above instrumentation. This system will have the following basic specification:

a) Ruggedised construction to enable mounting directly on the PTF carriage and transmission of the data to an off-PTF base system.

b) Minimum 16 simultaneously sampled channels

c) A minimum logging rate capability of 555Hz (sample rate of 555Hz will resolve to 10mm at 20km/h) and a maximum capability of 5,555Hz (1mm resolution).

d) An input for an external distance pulse derived from the rotation of the wheel to trigger samples. The advantage of this approach is that data is distance related and will generate the same number of samples per traverse, regardless of speed. However, it should be noted that tyre pressure and axle load will modify the wheel’s rolling circumference and, therefore, the number of distance pulses per metre. This will be accommodated via re-calibration of the distance measurement for tests carried out under difference load/pressure conditions.

e) External control of recording start/stop for a run

f) Configurable control software to enable samples to be acquired only on the paved area, using signals from the carriage position locators.
Appendix B. Results from the initial trials

Figure 15: Computed rolling resistance (drag) as a function of the artificial load applied at the level of the wheel hub.

Figure 16: When the speed increases, the rolling resistance (drag), created by the tyre, increases linearly (a), as well as the coefficient of rolling resistance (b). However, at extreme speeds (for the PTF 20km/h is a high speed) the system is not stable.
Figure 17: Drag and coefficient of rolling resistance as a function of load.

Figure 18: Coefficient of rolling resistance plotted as a function of the tyre inflation pressure for the concrete (lower curve) and asphalt (upper curve) surfaces.
Figure 19: Effect of changes in temperature on the Coefficient of Rolling Resistance
Appendix C. TRL PTF Pavement Construction

C.1 Pavement 1 (Flexible)

The pavement design for the flexible pavement has been carried out in accordance with the Design Manual for Roads and Bridges (DMRB) Volume 7: HD 26/06 (DMRB, 2006). A required total traffic loading of 1 million standard axles (msa) has been assumed. The total thickness of bituminous material for this design is 210mm.

The flexible pavement design Figure 20 has been designated as PTF1, to be read in conjunction with the specification given in Section C.5.

![Flexible Pavement Construction Diagram](image)

The long term elastic stiffness of DBM125 is in the region of 2500 MPa.

C.2 Pavement 2 (Rigid)

The pavement design for the rigid pavement has been carried out in accordance with the Design Manual for Roads and Bridges (DMRB) Volume 7: HD 26/06 (DMRB, 2006).

The rigid pavement design Figure 21 has been designated as PTF2, to be read in conjunction with the specification given in Section C.5.

For this design:

- T16 longitudinal reinforcement bar spacing is 145mm:
  \[
  (100 \times \pi \times \phi^2 / 4 \times t \times R^2) = (100 \times 3.14 \times 16^2) / (4 \times 230 \times 0.6) = 145\ mm
  \]

- Transverse reinforcement shall be 12mm diameter. At 600mm spacing and shall be at 90 degrees to the longitudinal bars
The incorporation of CRCP into this design for the rigid pavement caused some discussion regarding whether it would be representative of CRCP when it is laid on the network, and whether it would be possible to maintain a similar longitudinal profile and texture profile to the flexible pavement. There were two main issues:

**Anchorage**

When CRCP is laid on the network, it requires anchoring at either end. It was suggested that this anchorage was not required for such a relatively short length and that this lack of anchorage would not affect the key properties of the pavement (e.g. deflection). Thus, anchorage was not used.

**Cracking**

When CRCP is laid on the network, it is generally laid in very long lengths. Since the concrete expands and then shrinks as it cures, this results in cracks appearing roughly 2m apart in the pavement. However, when laid over a relatively short length, such as in the PTF (<10m), these cracks will not necessarily occur.

Two options were considered. The first option would be to induce cracks in the slab, either by laying wood underneath, or by cutting cracks into the slab. However, the introduction of these cracks is not reliable, and since the pavement is being weakened by the inducing method, it may have been that more cracks appear than planned, leading to a much weaker pavement than would be found on the network. Thus, the second option of attempting to obtain a crack-free slab was preferred.

In order to lay a crack-free slab, the slab was laid on a slip layer and at least 28 days were allowed for the slab to cure, before application of the surface layer. The former reduced the likelihood of cracks forming and the latter ensured that, in the unlikely event of a crack forming, this will be small and can be overlaid by the surface layer, thus reducing the effects of the cracking on the profile or texture.
C.3 Pavement 3 (Flexible – for Texture trial)

The design of the flexible pavement, used in the trials on the effects of texture on rolling resistance, is given in Figure 22.

![Diagram of pavement design](image)

**Whilst the lower layers were identical, the surface of the pavement changed half way along its length, as shown in Figure 23. The HRA was a 30% 0/10mm HRA, laid to a nominal thickness of 100mm, consisting of 31.5% 10mm aggregate, 57.5% of sand (h resource) and 11% filler. The bitumen content was 8% (70/100 pen bitumen) and the target air voids was 4%. The DBM was a 0/10mm DBM, laid to a nominal thickness of 100mm, consisting of 31% 10mm aggregate, 31% 6mm aggregate, 37.3% dust and 0.7% filler. The bitumen content was 5.5% (70/100 pen bitumen), and the target air voids was 4%.**

<table>
<thead>
<tr>
<th>B S Sieve</th>
<th>Proposed Target Grading</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.5mm</td>
<td>100</td>
</tr>
<tr>
<td>31.5mm</td>
<td>90 – 100</td>
</tr>
<tr>
<td>20mm</td>
<td>71 – 95</td>
</tr>
<tr>
<td>14mm</td>
<td>58 – 82</td>
</tr>
<tr>
<td>6.3mm</td>
<td>44 – 60</td>
</tr>
<tr>
<td>2mm</td>
<td>24 – 36</td>
</tr>
<tr>
<td>250μm</td>
<td>7 – 21</td>
</tr>
<tr>
<td>63μm</td>
<td>7 – 11</td>
</tr>
<tr>
<td>Binder content</td>
<td>4.0 +/- 0.6%</td>
</tr>
</tbody>
</table>

*The grading for this material is given in Table 6.*
Figure 23: Test strip used to assess effect of texture on rolling resistance

C.4 Surfacing Requirements

The framework that was applied in selecting the “Thin Surface Course System- TSCS” was based on the following considerations:

- Low texture;
- Laid in 30mm lift;
- Interacts well with both a concrete and asphalt substrate;
- Can easily be hand laid.

Based on the above considerations, TARMAC’s “ToughGrip” proprietary TSCS will be used as the surfacing course of both the flexible and rigid pavements.

C.5 Pavement Specification

C.5.1 Permitted Pavement Options- Schedule 1

<table>
<thead>
<tr>
<th>Drawing Ref</th>
<th>Area</th>
<th>General Requirements</th>
<th>Permitted Pavement Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>See Design Notes</td>
<td>PTF1</td>
<td>Schedule 2</td>
<td>A</td>
</tr>
<tr>
<td>See Design Notes</td>
<td>PTF2</td>
<td>Schedule 2</td>
<td>B</td>
</tr>
</tbody>
</table>

C.5.2 General Requirements- Schedule 2

<table>
<thead>
<tr>
<th>Schedule 2 : General Requirements- PTF1 &amp; PTF2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid for checking surface levels of pavement courses</td>
</tr>
<tr>
<td>Surface regularity</td>
</tr>
<tr>
<td>Interval for measurement of longitudinal regularity</td>
</tr>
<tr>
<td>Interval for measurement of transverse regularity</td>
</tr>
<tr>
<td>Whether surface macro texture is required</td>
</tr>
<tr>
<td>Whether measurement of surface macrotexture is required</td>
</tr>
<tr>
<td>Average</td>
</tr>
<tr>
<td>Maximum</td>
</tr>
<tr>
<td>Minimum</td>
</tr>
</tbody>
</table>
C.5.3 Permitted Construction Materials

### Schedule 3: Permitted Construction Materials

<table>
<thead>
<tr>
<th>Pavement Layer</th>
<th>Material Ref</th>
<th>Thickness (mm)</th>
<th>Material Ref</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Treatment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Course</td>
<td>SC- PTF1</td>
<td>30</td>
<td>SC- PTF2</td>
<td>30</td>
</tr>
<tr>
<td>Binder Course</td>
<td>BC-PTF1</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td>B- PTF1</td>
<td>120</td>
<td>B- PTF2</td>
<td>230</td>
</tr>
<tr>
<td>Subbase</td>
<td>SB- PTF1</td>
<td>260</td>
<td>SB- PTF2</td>
<td>260</td>
</tr>
<tr>
<td>Total Thickness</td>
<td></td>
<td>470</td>
<td></td>
<td>520</td>
</tr>
</tbody>
</table>

C.5.4 General Requirements for Construction Materials - Schedule 4

### Schedule 4: General Requirements for Construction Materials

<table>
<thead>
<tr>
<th>Clause</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>801.2</td>
<td>limiting distances for Deposition of unbound mixtures referred to in subclause 801.2</td>
</tr>
<tr>
<td>801.3</td>
<td>limiting distances for Deposition of unbound mixtures referred to in subclause 801.3</td>
</tr>
<tr>
<td>801.7</td>
<td>Whether any material shall not comply with subclause 801.7</td>
</tr>
<tr>
<td>802.4</td>
<td>Whether unbound materials up to 225mm compacted thickness can be spread in more than one layer</td>
</tr>
<tr>
<td>802.14</td>
<td>Thickness of compacted layer</td>
</tr>
<tr>
<td>901.2/942.5</td>
<td>Requirements for resistance to fragmentation, freezing and thawing &amp; cleanliness of aggregates</td>
</tr>
<tr>
<td>901.19</td>
<td>Compaction level of subbase and binder course macadams if different from clause 901.19 requirements</td>
</tr>
<tr>
<td>901.28</td>
<td>PSV of temporary running surface is different from 901.28</td>
</tr>
<tr>
<td>1001.2</td>
<td>Requirements for concrete conformity if different from 1001.2</td>
</tr>
<tr>
<td>1004.7</td>
<td>Testing requirements for concrete slabs</td>
</tr>
<tr>
<td>1028</td>
<td>Requirements for trial lengths</td>
</tr>
<tr>
<td>1033.1</td>
<td>Permission for butt welding</td>
</tr>
</tbody>
</table>

C.5.5 Requirements for Construction Materials - Schedule 5

<table>
<thead>
<tr>
<th>Material Ref</th>
<th>Clause</th>
<th>Description</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB- PTF1</td>
<td>803</td>
<td>Type 1 unbound mixture</td>
<td>Mixtures containing crushed gravel coarse aggregate:</td>
</tr>
<tr>
<td>SB- PTF2</td>
<td></td>
<td>Dense Macadam</td>
<td>MCHW Clause 903.1, 903.3, 929, BS 4987-1</td>
</tr>
<tr>
<td>B- PTF1</td>
<td>903</td>
<td>Bitumen Recipe Mixtures: Dense Base and Binder Course</td>
<td></td>
</tr>
<tr>
<td>BC-PTF1</td>
<td>906</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Macadams

Traffic Count:

Site Definition and Stress Level:

Minimum declared PSV of coarse aggregate:

Maximum AAV of coarse aggregate:

SC-PTF1 Thin Surface Course Systems
Minimum Wheel Tracking Level:

Road/Tyre noise level relative to HRA:

Longitudinal steel reinforcement: 16mm diameter at 145 mm spacing

Transverse reinforcement shall be 12mm dia. At 600mm spacing and shall be at 90 degrees to the longitudinal bars

Continuously Reinforced Concrete Pavement (CRCP)

Anchorages shall be provided at ends and any discontinuities in the pavement: N/A

Expansion joints are required at the approach slabs to anchorages: N/A

6 (11/04) THIN SURFACE COURSE SYSTEMS: INFORMATION TO BE PROVIDED BY THE CONTRACTOR - SCHEDULE 6

[Note to Contractor: Complete one sheet per system or variant of system that may be used]

The Contractor shall provide the following information with his tender:

(i) (11/04) A copy of the British Board of Agreement HAPAS Roads and Bridges Certificate or Certificates for the thin surface course system or systems that are proposed for use in the works, together with a copy of the Installation Method Statement associated with each Certificate [942.1]

(ii) (11/04) For any Certificate that covers several variants of one thin surface course system, proposed variant or variants of the system to be used in the Works [variants of a system occur from any option that results in different values being reported on the Certificate for one or more properties, and could involve changes in nominal maximum aggregate size, aggregate type, aggregate grading, binder type, binder content, fibres or other additives, type and rate of spread of bond coat]

(iii) If requested, or if the thin surface course system is not produced under a Sector Scheme, the proposed component materials to be used in the thin surface course system and their proportions for each proposed system [942.4]

(iv) Proposed source or sources of coarse aggregate together with statement of properties including polished stone value, ten per cent fines value, aggregate abrasion value and flakiness index [942.5]

(v) If regulating material is to used, evidence of its deformation resistance either independently or in combination with the thin surface course system [942.10]
7 (11/04) BINDER DATA REQUIREMENTS [911.2, 929.4, 937.9, 938.1, 943.5 and 943.8] -
SCHEDULE 7

The following data shall be provided to the Overseeing Organisation as required in sub-Clauses 937.9, 938.1, 943.5 and 943.8 and for materials designed in accordance with 911, 929, 944 or 952 in respect of the proposed binder [note: all these Clauses cover materials that are designed by the supplier]. The data should not be more than 6 months old. A table in which the binder data may be recorded is given at the end of this section.

For work carried out for the Highways Agency, a copy of all the data should be handed to the Overseeing Organisation, to be forwarded to: Pavement Engineering Team at Highways Agency, Bedford Office.

I. (05/05) Binder Samples

Bituminous binders shall be sampled from the delivery according to BS EN 58. For modifiers blended with the other component materials of the mixture at the mixer a simulated binder shall be prepared. Such modifiers are generally less intimately mixed with the bitumen and less well dispersed throughout the mixture than when pre-blended. Evidence that the simulated binder offers the same performance as the binder produced when the modifier is added at the mixer shall be provided.

II. (11/04) Penetration

Binder penetration at 25°C (BS EN 1426), 100g 5 sec and at 5°C 200g 60 sec, before and after hardening in the Rolling Thin Film Oven Test (RTFOT) in accordance with BS EN 12607-1, or alternatively, after RTFOT and Ageing in accordance with Clause 923.

III. (11/04) Product Identification Test and Rheological Properties

Results for the binder(s) proposed shall comprise rheological data for each binder in the form of complex shear (stiffness) modulus (G') and phase angle (δ) determined in accordance with Clause 928 for binder as supplied, after RTFOT and Ageing in accordance with Clause 923.

IV. (11/04) Storage Stability Test

All binders shall be stored strictly in accordance with the manufacturer's instructions. Polymer modified binders claimed to remain homogeneous in storage without agitation shall be tested for storage stability in the manner described in Clause 941. The mean of the differences in softening point between the top and bottom samples, of not less than five pairs of such samples shall not exceed 5°C. Manufacturers of pre-blended modified binders shall state what precautions are necessary to ensure that adequate homogeneity is maintained during storage.

V. Photomicrograph

A typical photomicrograph of the modified binder and binder using ultra-violet or other technique to provide maximum contrast of the polymer structure to the binder before modification shall be supplied together with details of sample preparation techniques.

VI. (11/04) Cohesion

Vialit Pendulum cohesion test curve of the binder, in accordance with Clause 930 for the binder as supplied, after RTFOT and after RTFOT and Ageing in accordance with Clause 923.

VII. (11/04) FRAASS Brittle Point

FRAASS brittle point measured using BS EN 12593 shall be provided on the binder as supplied, after RTFOT and Ageing in accordance with Clause 923.
(11/04) **Summary of binder data**

<table>
<thead>
<tr>
<th>Manufacturer of Binder:</th>
<th>Product name</th>
<th>Batch ref:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder type:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Binder source:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Softening point difference in storage stability test</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test</td>
<td>Supplied binder</td>
<td>After RTFOT</td>
</tr>
<tr>
<td>Penetration at 25°C, 0.1 mm (100g and 5 secs)</td>
<td>#</td>
<td>#</td>
</tr>
<tr>
<td>Penetration at 5°C, 0.1 mm (200g and 60 secs)</td>
<td>#</td>
<td>#</td>
</tr>
<tr>
<td>Vialit pendulum cohesion see Clause 939 maximum peak value J/cm²</td>
<td>#</td>
<td>#</td>
</tr>
<tr>
<td>Product identification test</td>
<td>Complex shear (stiffness) modulus (G*) and phase angle (Ø) data. See Clause 928</td>
<td>#</td>
</tr>
<tr>
<td>Fraass brittle point</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other properties the Contractor considers useful</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Where indicated with # the Contractor shall attach a graphical output to this schedule.

8 **(11/04) MIXTURE DATA REQUIREMENTS [919, 929, 944, 952 or 953] - SCHEDULE 8**

The following data should be provided to the Overseeing Organisation as required in sub-Clauses 937.9, 938.1, 943.8 and 943.8 and for materials designed in accordance with 911, 929, 944, 952 or 953 in respect of the proposed mixture as appropriate [note: all these Clauses cover materials that are designed by the supplier].

For work carried out for the Highways Agency, a copy of all the data should be handed to the Overseeing Organisation, to forwarded to: Pavement Engineering Team at Highways Agency, Bedford Office.

I. **Mixing and compaction temperatures**
   Maximum and minimum mixing temperatures should be stated. Maximum and minimum compaction temperatures and any wind chill factor differing from conventional hot rolled asphalt utilising unmodified bitumen shall be stated.

II. **Mix Sensitivity Analysis**
   Wheel-tracking rate for the proposed mixture but with the binder content by mass increased above the target to the maximum binder content anticipated by the Contractor, but not more than + 0.6% above the target.

III. **Repeated Load Axial Test (RLAT) to DD 226 : 1996** (for correlation to performance in terms of deformation).

IV. **Indirect Tensile Fatigue Test (ITFT) - after ageing**, see LINK Protocol (for correlation to performance in terms of fatigue)

V. **Saturation Ageing Tensile Stiffness (SATS)**
Abstract

An investigation has been made into whether pavement stiffness has a significant influence on the energy required to travel along a pavement, and hence whether the construction of stiffer pavements could deliver tangible benefits in fuel consumption. Equipment was developed by TRL to measure rolling resistance in TRL’s Pavement Test Facility (PTF) and during initial tests, this was shown to display the level of accuracy required for such a task. The initial tests also confirmed the expected behaviour, of rolling resistance measurements, when factors such as wheel load, speed and tyre pressure were varied.

Two pavements were constructed within the PTF, both designed to a similar specification to those found on the HA network. One pavement was of a stiff construction, the other flexible and both were surfaced with the same thin surfacing system. Texture, profile and gradient all have a major effect on rolling resistance. Thus the pavements were laid so that the surfaces were as horizontal as possible, which, combined with using the same surfacing course, reduced the effect of differences in these parameters on the measurement of rolling resistance. Hence, the difference in rolling resistance measured on the two pavements would be mainly due to the difference in stiffness between them. A number of trials were then carried out on these pavements to measure this difference.