Development of a performance-based surfacing specification for high performance asphalt pavements

Prepared for Highways Agency, Quarry Products Association and Refined Bitumen Association

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Executive Summary

This report describes research sponsored by the Highways Agency, Quarry Products Association and the Refined Bitumen Association. Previous work, funded by the sponsors, demonstrated that well-constructed flexible pavements, built above a threshold strength, will remain structurally sound for longer than their design lives provided that deterioration is treated in a timely manner. In these heavily trafficked, *long-life* roads, deterioration will normally take the form of cracks developing at the surface or deformation occurring in the surface course and the layer immediately beneath. Maintenance treatments will therefore be principally concerned with replacing the surfacing.

The overall objective of the research described in this report is to improve the performance of asphalt surfacing under the more demanding conditions that are likely to be encountered in the future. This entailed the development of a performance-based specification for the surfacing, comprising the surface course and binder course or upper roadbase, recognising that the surface course should not be treated in isolation. This is especially the case for thin surfacings, which place greater demands on the binder course or upper roadbase on which they are laid. Performance-based specification offers great potential to both the Industry and the Customer. It will encourage better mix design, give the Industry more freedom to produce more commercially attractive designs and the Customer assurance that the pavement will not deteriorate prematurely.

The development of the surfacing specification was carried out in three parts:

- The performance requirements and role of the asphalt surface layers were reviewed.
- A trial was carried out, using the TRL accelerated pavement test facility (PTF), to investigate the behaviour of pavement design solutions that have the potential for performing well under aggressive loading conditions.
- Trials of a draft surfacing specification developed from the TRL PTF trial were carried out under contractual conditions as part of road maintenance or road construction schemes.

As part of the initial review, the role of the various asphalt layers was clarified and redefined. In particular, the redefinition of the function of the binder course recognises that its role depends on the thickness and nature of the wearing course and the intensity of the traffic. For example, a heavily trafficked road with a thin wearing course may require an 80 mm thick binder course that is resistant to deformation whereas lower in the road, conventional roadbase macadam may be adequate.

Following this initial review, the performance of a number of surfacing systems incorporated into long-life pavements were investigated in a controlled environment in the TRL PTF with a view to identifying means of achieving better in service performance. These trials were carried out under simulated extreme traffic loading in which the pavement was trafficked with a heavy, slow-moving, canalised wide-base single tyre at a high pavement temperature. The asphalt materials used in this trial were tested using practical laboratory performance tests that had the potential to be used in contractual situations, and the results from these tests were correlated with the performance of the materials in the PTF. The results from each pavement test section were also compared with a control pavement that was constructed using traditional surfacing materials.

The draft specification developed from the PTF trials was tested and refined under contractual conditions in three trunk road resurfacing contracts The feedback from these road trials ensured that the final specification was both practicable and economic.

The proposed new specification for the asphalt surfacing will ensure that future roads designed for heavy traffic will continue to have excellent deformation resistance even under extreme trafficking conditions. The specification will encourage better design of the asphalt surface course and the binder course and, should any problems occur in the future, it will be possible to review the performance criteria.

As a result of European harmonisation of standards, the terms ‘surface course’ and ‘binder course’ will soon replace the terms ‘wearing course’ and ‘basecourse’ which have traditionally been used in the UK. Throughout this report the terms surface course and binder course have been adopted, but the term roadbase has been retained for the main structural layer.

1 Introduction

This report describes research sponsored by the Highways Agency, Quarry Products Association and the Refined Bitumen Association. The overall objective of this research was to ensure that asphalt pavements continue to perform well even under the more demanding conditions that are likely to be encountered in the future. Increased traffic, higher axle loads and greater use of super-single tyres are some of the factors that need to be taken into account.

Previous work for the sponsors demonstrated that deterioration in well-constructed flexible pavements, built above a threshold strength, is normally confined to the surface layers and that these roads will have a very long structural life. In these heavily trafficked, *long-life* roads, deterioration will normally take the form of cracks developing at the surface or deformation occurring in the surface course and the layer immediately beneath. Maintenance treatments will therefore be principally concerned with replacing the surfacing.

Until fairly recently, a hot rolled asphalt surface course (HRA) with a dense bitumen macadam or HRA binder course has traditionally been the main form of surfacing in the UK. Experience has shown that conventional HRA is capable of performing well over a wide range of conditions and it also uses less high quality aggregate than, for example, stone mastic asphalt. However, many new surface course materials have been introduced in recent years that are potentially beneficial to road performance. These include thin surfacings, which can be used to provide rapid maintenance treatments to restore skid resistance and riding quality and to reduce tyre noise.

In recent years, and particularly during the hot summers of 1995/96, there have been several incidences of excessive rutting in both newly laid and mature HRA. A number of reasons for this have been suggested, for example: higher than normal summer temperatures; increased use of wide single tyres; increased congestion; and a steady increase in the average axle weight. Furthermore, early life rutting has occurred in a number of maintenance schemes soon after opening to traffic. The factors responsible for this are believed to be the opening of the road too soon after laying when the material is still warm, often in adverse hot weather conditions, and slow, canalised traffic due to contra-flow traffic management being in force for maintenance work on the opposite carriageway. It is now prudent to develop material specifications to ensure that these conditions do not result in poor performance of the surfacing.

The performance of the surfacing will depend on the surface course and the underlying layer which, together, form a surfacing system. This is especially true for thin surfacings, the use of which can result in greater demands on the binder course or upper roadbase on which they are laid. The introduction of a performance-based specification for the surfacing, comprising the surface course and binder course or upper roadbase, will allow the most cost-effective use of the various types of surfacing materials. It will also acknowledge that the surfacing layers should not be treated in isolation to one another.

This form of specification offers great potential to both the Industry and the Customer. It will give Industry increased freedom to produce more commercially attractive designs for the surfacing and the Customer will be assured that the pavement will not deteriorate prematurely. The research has focused on identifying the requirements for an asphalt pavement to prevent unacceptable rutting. This has entailed:

- Assembling information on the rutting behaviour of fully flexible pavements in order to establish which layers are at greatest risk.
- Examination of the role of the surface layers and, in particular, the binder course or upper roadbase.
- Using the TRL accelerated pavement test facility to investigate the behaviour of rut-resistant pavement design solutions that have the potential for performing well under aggressive traffic loading and high pavement temperatures.
- Conducting specification trials of rut-resistant systems as part of road maintenance or road construction contracts.

The feedback from the road trials ensured that the performance-based specification developed was both practicable and economic.

2 Review of surfacing requirements

Until fairly recently, the most widely used surface course material on flexible pavements on the UK's high speed trunk roads and motorways has been hot rolled asphalt (HRA) with a surface layer of pre-coated chippings that resist polishing. This has resulted in high macro- and micro-textures which provide and maintain a high level of skid resistance. The HRA usually has low air voids content which minimises binder ageing and hardening. However, in order to accept and retain the pre-coated chippings, the asphalt consists of a bituminous mortar in which the larger aggregate particles are dispersed rather than being in contact with each other. Consequently, the deformation resistance of this material depends principally on the properties of the binder and the characteristics of the fine aggregate rather than on interlocking coarse aggregate.

Deformation within the binder course can also form a major component of surface rutting. Traditionally, the binder course, whether of HRA or dense bitumen macadam (DBM), has been formulated using a recipe specification with no specific controls on strength or air voids content. Depending on the particular constituents, the binder course material may be as susceptible to deformation as the surface course but its lower in-service temperature, due to the thermal insulation of the surface course, usually results in acceptable performance. The binder course has the least detailed specification of any of the asphalt pavement layers and consideration should now be given to including requirements that ensure adequate deformation resistance.

As a consequence of the increased occurrence of rutting in asphalt surfacing during the hot summers of 1995 and 1996, three developments have already taken place:

- A performance-related specification clause for HRA (Clause 943), based on properties of the in situ material, was included in the 1998 edition of the *Specification for Highway Works* (Highways Agency *et al.*, 1998). It specifies the material in terms of the maximum wheel-tracking rate and depth, a range of air voids content and minimum binder content.
- Surface course materials such as stone mastic asphalt (SMA) and thin asphalt surfacings are being used more frequently in place of HRA.
- The revision of Clause 929 in 1998, introduced control of the compaction of macadam binder courses and road bases by air voids rather than by Percentage Refusal Density (PRD). The maximum permitted air voids are now slightly lower than would have been the case when compaction was controlled by PRD.

These developments raised several questions:

- Will Clause 943 be sufficient to produce a rut resistant pavement for all traffic conditions?
- Will alternative thin surface courses perform better than Clause 943 HRA?
- Will the revised binder course specifications ensure sufficient deformation resistance? and, if not,
- Will more stringent binder course criteria be required when thin surface courses are used?

The review described in the following sections has helped establish a better understanding of the relevant factors controlling surfacing performance and to provide a basis for designing the pavement trials that were subsequently been conducted in the TRL pavement test facility (PTF) to aid the development of a surfacing specification.

2.1 Performance of asphalt surfacing

Deterioration of a pavement should be judged in terms of how it affects the ability of the pavement to carry a given level of traffic economically, safely, comfortably and at an appropriate speed. Two modes of structural deterioration are generally recognised. These are cracking and permanent deformation. However, not all forms of deterioration affect the structure of the pavement; for instance, a road may become unsafe if the resistance to skidding of its surface drops below a prescribed level.

The most common form of deformation, known as rutting, is the development of depressions in the wheel path caused by movements of the pavement materials under traffic loading. The ruts appearing on the surface can be an accumulation of deformation from all the pavement layers. Significant deformation that occurs deep in the pavement is a symptom of overall structural inadequacy. Deformation arising in the asphalt surfacing only is a result of the asphalt lacking sufficient internal stability for the conditions under which it has to operate and is not, therefore, a structural problem related to the overall strength of the pavement.

Cracking that initiates at the underside of the roadbase is considered to be a fatigue phenomenon and a criterion to guard against this possibility is included in all modern analytical pavement design methods. However, recent investigations (Wu, 1992; Nunn, 1994; Schmorak and Van Dommelen, 1995) have failed to find positive evidence of this form of deterioration in thicker, well-constructed roads. Investigations reported by Leech and Nunn (1997) have shown that cracking in such roads initiates at the surface and propagates downwards.

At the 8th International Conference on Asphalt Pavements there was much more acceptance of surface initiated cracking than hitherto. Witczak *et al.* (1997) pointed out that surface cracking occurs widely although the models developed as part of the United States Strategic Highways Research Program (SHRP) failed to model cracking from the surface downwards. Also, Nishizawa *et al.* (1997) reported that theoretical fatigue does not agree with field experience for thick asphalt pavements and proposed that the fatigue criterion is not valid for traffic-induced tensile strains less than 200 micro-strain. They also concluded that in thick asphalt pavements rutting is usually caused by plastic deformation in the asphalt rather than in the subgrade. These conclusions are very similar to those of Nunn *et al.* (1997) for well-constructed asphalt pavements built above a threshold strength. This conclusion is also supported by a recent review of pavement design methods in which experts from 22 European countries were asked to rank the most common forms of deterioration in their roads (Nunn and Merrill, 1997). Rutting originating in the asphalt layers and cracks initiating at the surface were ranked 1 and 2 out of 12 possible modes of deterioration. Fatigue cracking and structural deformation were ranked 7 and 9. Frost heave, low temperature cracking and studded tyre wear were the only forms of distress ranked lower.

2.1.1 Rutting

Nunn *et al.* (1997) demonstrated that ruts appearing at the surface of roads designed for heavy traffic are generally the result of deformation occurring predominately in the top 100 mm of the road. This implies that more stringent deformation criteria should be applied to the surfacing and that these criteria can be relaxed for the lower asphalt layers.

Deformation is an extensive phenomenon in which all elements of the layer contribute to the overall rutting. In the mechanistic approach to modelling, a suitable response model is supplied with data in the form of a constitutive equation. Both the model and the equation can be very complex, recognising that the pavement layers behave as non-linear, visco-elasto-plastic materials, and a 3-dimensional representation is required to integrate the elemental responses to the moving wheel load.

Simpler models have been developed by Shell (1978) and ESSO (1983) as sub-systems of their pavement design methods. These models use linear elastic theory and only consider the on-axis stresses and strains directly under a circular wheel load of uniform pressure. The material characteristics are determined using a uniaxial creep test.

Nunn (1985) demonstrated that a model that only considers the on-axis behaviour is unlikely to predict the observed distribution of deformation, the majority of which occurs in the upper asphalt layers. An on-axis, linear elastic response model generally predicts large compressive radial stresses at the surface as a result of the pavement flexing. The Poisson's ratio effect of these horizontal compressive forces produces a vertical tensile contribution to the strain at the surface. Under some conditions, this can exceed the vertical compressive strain due to the compressive vertical stress and lead to the prediction that the surface course will become thicker. The opposite happens at the underside of the asphalt layer. Here, high radial tensile stresses which, coupled with a vertical compressive stress, can result in a relatively high predicted vertical deformation in the lower roadbase.

More recent work by Hopman *et al.* (1997), Weissman and Sousa (1996) and others has demonstrated that the greatest dissipation of energy is off-the-axis of the wheel load, near the surface and below the edge of the tyre. An on-axis model will not include this very significant area and will therefore be unlikely to give reliable predictions (see Section 2.2.2).

Other more sophisticated attempts have been made to model pavement rutting but none have achieved universal acceptance. The complexities of modelling deformation and characterising material were highlighted in the early 1980s when TRL embarked on the development of a model with Imperial College (Dougill *et al.*, 1986). A non-linear visco-elasto-plastic model was developed and laboratory studies were undertaken to determine the non-linear deformation parameters of asphalt.

Hopman (1997) has developed a 3-dimensional linear, visco-elastic model of the road in which a Burgers' model is used to characterise material behaviour. Models of this type are likely to provide insight into the understanding of deterioration mechanisms that cannot be explained using conventional strain criteria. If, for example, dissipated energy is taken as a measure of the development of deterioration, Hopman's model shows that deterioration can progress faster in the upper part of the road structure than lower down, as indicated by the conventional strain criteria.

2.1.2 Surface cracking

Cracks can initiate at the surface of mature flexible pavements and propagate downwards. To date, this form of deterioration has received little attention from researchers. The mechanism of surface cracking is complex and there is no satisfactory explanation of this phenomenon. It is likely that ageing of the uppermost layer of the surface course progressively reduces its capacity to withstand tensile conditions induced by thermal and tyre forces.

The majority of these cracks are either transverse or longitudinal. The transverse cracks are likely to be caused solely by thermally induced stresses while the longitudinal cracks are caused by both traffic and thermal stresses. Many nominally similar flexible roads do not crack at the surface even when old, which suggests that the ageing characteristics of the surface course will play a crucial role.

The information on crack investigations in the UK has been summarised by Leech and Nunn (1997). This showed that cracks in thick flexible pavements, although having been present for many years, were generally still confined to the surfacing. On some sites these cracks had progressed into the top of the roadbase, but no instances of cracking through the full thickness of asphalt were found in roads with more than 200 mm of asphalt. Rheological tests on recovered binders from the surface course showed that the greatest ageing occurred in the top few millimetres of the layer. Although ageing appears to be a causal factor it was not possible to identify the material or any binder characteristic that could be linked to the cracking susceptibility of the surface course.

Pavement modellers have often cited high levels of strain energy dissipation occurring near the surface as an indicator of potential surface cracking (Hopman, 1997; Rowe *et al.*, 1997). Energy dissipation can only result from the strain response lagging behind the stress. This behaviour occurs with a visco-elastic pavement response model. The greater the viscous component the greater will be the phase lag and hence the calculated dissipated energy. It is suggested that the dissipated energy is causing crack development but, in a highly viscous pavement, this energy is more likely to cause deformation in the structure rather than cracking. Surface cracking is more likely to occur in age-hardened structures in which the asphalt has a relatively small viscous component.

2.1.3 Other modes of deterioration

In addition to rutting and surface cracking other types of deterioration can affect HRA surfacing. These include loss of chippings, fretting and loss of skid resistance.

Both workmanship and climatic factors affect the process of securely embedding pre-coated chippings into the asphalt. If the chippings are rolled in when the asphalt is too cool, or excess chippings have been applied, there will be inadequate chipping embedment which will lead to plucking out and loss in the very early life of the surface. The loose chippings may cause vehicle damage and lead to areas with insufficient chippings to provide an adequate level of skid resistance.

Prevention of this form of deterioration is a matter of good workmanship, which ensures that the mat temperature during rolling is appropriate, the specified application rate is followed and the chippings are evenly distributed.

Fretting is the loss of the fine aggregate from the mortar which can result in the subsequent loss of coarse aggregate particles or chippings. Fretting generally occurs in winter, in materials that are nearing the end of their service life. It is a cold-temperature phenomenon associated with the binder (Child, 1997) and it is also influenced by the type of asphalt mixture.

During the first few years of service, the skid resistance of HRA decreases as the surface polishes. Subsequently the skid resistance stays more or less constant but with fluctuations from summer to winter. Generally, away from junctions where the SCRIM investigatory levels are relatively low, skid resistance is not a serious problem on motorways and dual carriageways, except where chipping loss or fretting has occurred. However, at or near the approaches to junctions, skid resistance can be a problem because the SCRIM investigatory levels are higher and the braking or turning traffic has a greater polishing effect on the chippings. This often requires more frequent resurfacing or the use of a high friction surfacing.

2.1.4 Summary

i The principal modes of distress associated with traditional asphalt surface courses are rutting and surface cracking.

ii No universally accepted mechanistic models of pavement rutting and surface cracking have been developed.

iii Rutting in the asphalt layers is primarily caused by permanent deformation occurring in the surface and binder courses.

2.2 Recent experience

In recent years, a number of factors have combined to cause greater incidences of excessive rutting in both newly laid and mature HRA surfacing. These are:

- Higher summer temperatures.
- Increasing use of wide-base single tyres.
- Reduced vehicle speeds owing to increasing traffic flows and disruptions at roadworks.

There is also a perception that average axle weights have been increasing.

In 1999, EC Directive 95/53/EEC increased the allowable maximum gross vehicle weight of articulated vehicles with 5 or more axles from 38 to 40 tonnes and also increased the maximum axle load, normally the drive axle, from 10.5 to 11.5 tonnes. These changes are likely to increase the risk of deformation.

These issues are discussed in the subsequent sections.

2.2.1 Temperature

Temperature data from a site near Birmingham for the period 1981 to 1996 was used to determine the year to year variation and any long-term trends. The mean maximum daily air temperatures for the hottest calendar month, usually July, are plotted in Figure 2.1.

The mean value of 22.3°C for this period was 0.3°C above the trend established during the period 1931 to 1960 (Booth, 1961). However, the hottest calendar month does not show the whole picture. Since records began 340 years ago (in 1659) the summers in recent years have been amongst the hottest on record. In the last 25 years, 1976 saw the hottest summer since 1659, with 1995 being the 3rd and 1983 the 5th hottest.

The data in Figure 2.1 shows that there are substantial differences in the monthly average (of up to 6°C) between the hottest and coolest periods. In 1995, the hottest month, August, had a maximum daily temperature of 32°C. This would have resulted in a pavement surface temperature substantially in excess of 50°C.

Temperature measurements at various depths in TRL experimental pavements at Alconbury and Crowthorne have been reported by Forsgate (1971). The maximum temperatures reached, based on the averages of both sites, are given in Table 2.1. The air temperatures for the period when these measurements were made were close to the 30-year average and do not represent conditions in the exceptionally hot years of 1983 or 1995. In these years, the mean maximum daily temperatures were about 4°C higher than the long term means. Consequently the maximum temperatures to be expected in hot years would be at least 4°C higher and these are also shown in Table 2.1.

Table 2.1 Observed and estimated maximum pavement temperatures

Depth (mm)	*Measured temperature (average year) (°C)*	*Estimated temperature (hot year) (°C)*
0	53	>57
20	47	>51
40	42	>46
90	39	>43

The records show that the UK climate has generally been warmer in recent years. If these conditions persist, or are part of a trend towards warmer conditions, they will aggravate asphalt deformation problems.

2.2.2 Dual and wide-base single tyres

In recent years, there has been a substantial increase in the proportion of heavy goods vehicles fitted with wide-base single tyres. In the UK, the wide-base single-wheel axles

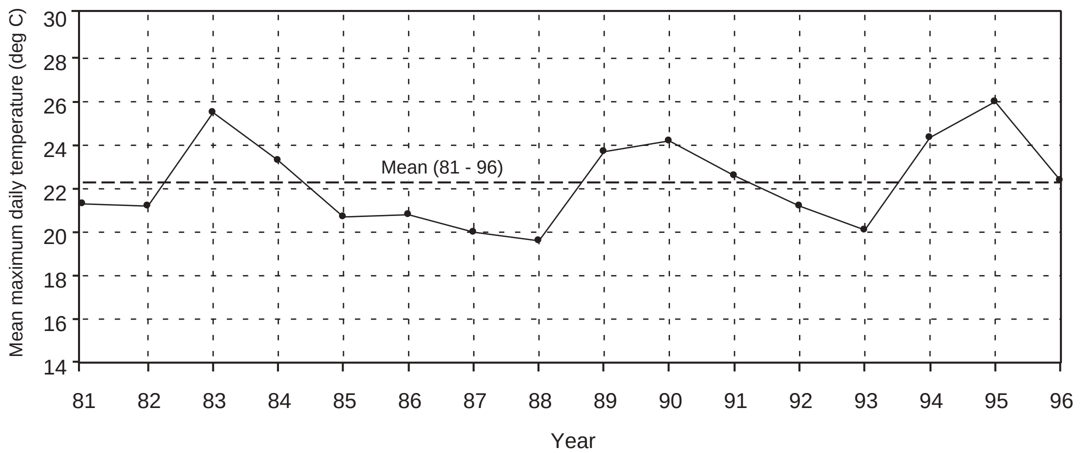


Figure 2.1 Variation of mean maximum daily air temperature for July

are typically found on triple-axle trailers of articulated units. The numbers of these vehicles, expressed as a proportion of all heavy goods vehicles, had more than doubled from 7 to 15 per cent in the period 1986 to 1992 (Society of Motor Manufacturers and Traders, 1995) and this trend has continued.

The tyre-pavement contact area of a wide-base single tyre is approximately 10 per cent less than that of dual tyres carrying the same load, and the tyre inflation pressure is correspondingly higher. This has led to an opinion that axles with wide-base single tyres will cause more wear than dual-tyre axles of the same total weight because of the greater stresses and strains induced in the pavement layers.

On the triple-axle trailer the maximum legal load on all three axles is restricted to 24 tonnes, which results in 8 tonnes per axle, provided that the suspension distributes the load efficiently. A typical wide-base single tyre size is 385/65R22.5. The tractor units have either two or three axles, usually fitted with conventional 295/80R22.5 tyres on all axles, with singles on the steering axle and duals on the load carrying axle(s). The size of wheel and tyre fitted to a trailer axle is controlled only by the axle load and the load rating of the tyre.

An indication of the impact of wide-base single tyres on surface rutting can be obtained from measurements of the distance between the maximum rut depths for the two wheel paths on the nearside lane. In 1982, when the average spacing between the centre of dual wheels on a trailer was 1.86 metres, the peak spacing between the ruts in the two wheel paths was also 1.86 metres (Jordan and Still, 1982). This spacing increased to 1.91 metres in the late ‘80s when the width of a commercial vehicle was increased by 50 mm. The most up to date measurements, given in Figure 2.2, were made in 1999.

This histogram was compiled using a total sample length of 45 km from 7 motorways and dual lane trunk roads. The figure shows that the lateral spacing of the ruts has now increased to 2.075 metres, which is very close to the 2.062 metre spacing between the centres of wide-base singles. This indicates that the wide-base singles are having a dominant effect on the rutting behaviour of the asphalt surfacing. The asymmetry of this distribution can be accounted for by the closer spacing of the dual-wheeled axle assemblies.

2.2.3 Pavement wear attributable to tyre type

Several studies into the relative effects of single and dual tyres on flexible pavements have been undertaken and most concluded that the wide-base single wheel is more damaging. However, the majority of these involved far thinner pavements than those normally used on UK trunk roads and the focus of the investigations was on the structural effects on the pavements and not on surface deformation. Where more than one pavement thickness was considered, the additional structural damage due to the wide-base single wheel decreased with increasing pavement thickness.

Addis (1992), Bonaquist (1992), Huhtala *et al.* (1992) and Sebaaly (1992) examined the measured strains induced in asphalt pavements of different thicknesses by single and dual wheels in instrumented pavements. Their studies concluded that wide-base single tyres produce more structural damage than dual wheel assemblies based on calculations of fatigue damage in the asphalt layer or structural deformation in the subgrade, using the measured traffic-induced strains rather than by direct measurement of any pavement damage.

Corté *et al.* (1994) carried out pavement trials in the circular test track at the Laboratoire Central des Ponts et Chaussées to investigate the rutting of different asphalt materials under loading by wide-base single and conventional dual tyres. They concluded that the wide-base single tyres caused more rutting and that the relative effect is very dependent on the type of asphalt mixture. The more sensitive the mixture is to rutting, the more pronounced the effect appears to be.

Within the European Community there is much interest in the effect of wide-base single tyres. The Directorate

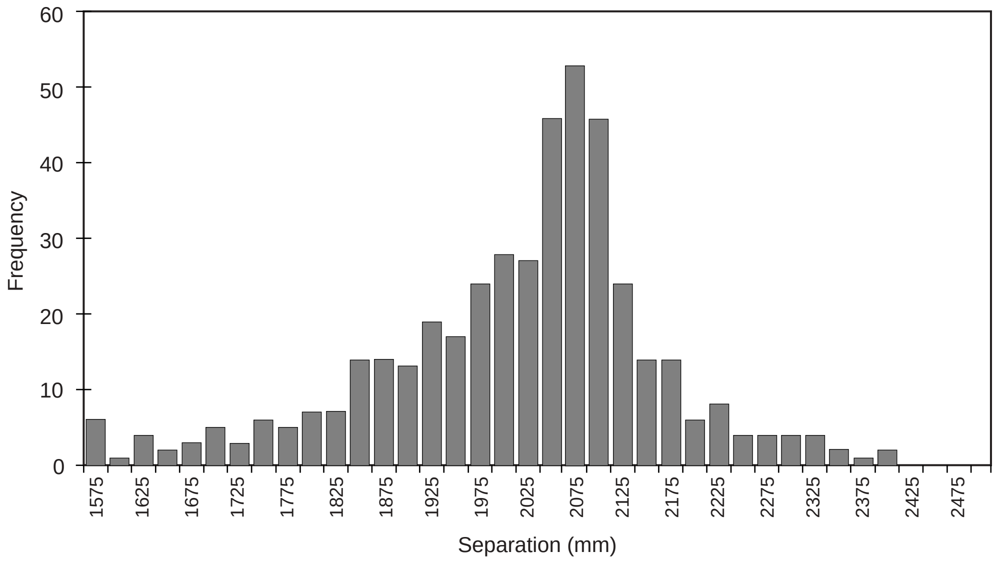


Figure 2.2 Distribution of the transverse separation of wheel-track ruts

General of Transport within the European Commission is supporting COST Action 334 (CO-operation in the field of Scientific and Technical research) on the effects of wide-base single and dual tyres (Addis *et al.*, 1999). This Action, which involves 16 European countries, is examining the economic, environmental and safety implications of the increased use of wide-base single tyres. This on-going programme is also assessing future trends in tyre technology. Tyre technology is advancing rapidly, and new tyre sizes and materials are being introduced frequently. As a result of commercial pressures, tyre manufacturers are responding to the wishes of their clients by the introduction of lower weight, smaller diameter tyres. COST Action 334 points out that this may have adverse consequences for the road infrastructure. In a complex commercial and regulatory environment, the economic balance between the advantages to vehicle operators of the use of different tyre types, and their possible disadvantage to road authorities with respect to possible increased pavement wear, needs closer examination to aid policy development in this area.

It appears that the use of wide-base singles will grow, with the added concern that a new generation of wide-base singles may be developed that will be potentially more damaging to the pavement surfacing (Addis *et al.*, 1999).

2.2.4 Analytical consideration of dual and single tyres

The foregoing studies provided little information on the *relative* rutting of the surfacing layers of thick pavements, caused by dual and wide-base single tyres. To remedy this a parametric study was carried out using a finite element program. The objective was to determine whether or not the wide-base single tyre induced more damaging stresses or strains in the surface layers compared to a conventional dual wheel assembly for a pavement of 300mm total asphalt thickness.

In the analysis of a 3-dimensional stress system there are a number of indicators or criteria that can be used to indicate the physical cause of any distress. These criteria combine the individual stress components. Shear is generally considered to be an important indicator of deformation. In Figure 2.3, the contours of von Mises yield criterion, which is proportional to the shear strain energy, have been plotted to illustrate the regions of the pavement in which deformation is likely to originate. The von Mises yield criterion is defined as:

$$((s_1 - s_2)^2 + (s_2 - s_3)^2 + (s_3 - s_1)^2) / 6$$

Where, s_1, s_2 and s_3 are the principal stresses.

Figure 2.3 indicates that:

- For both wheel types, the zones of high shear strain energy are induced in the asphalt surfacing.
- The wide-base single wheel produces larger maximum shear strain energy than the dual tyres.

High shear strain energy values also occur close to the underside of the roadbase, but experience shows that this does not contribute significantly to asphalt rutting. Generally, mechanistic rut prediction models take these shear stresses in the lower roadbase into account and predict a distribution of rutting with depth that is not observed in practice.

(The analyses illustrated in Figure 2.3 were based on a pavement under hot summer conditions, 53^{O}C at the surface and 27^{O}C at the bottom of the asphalt. Similar analyses with a uniform asphalt temperature of 25^{O}C yielded very similar results.)

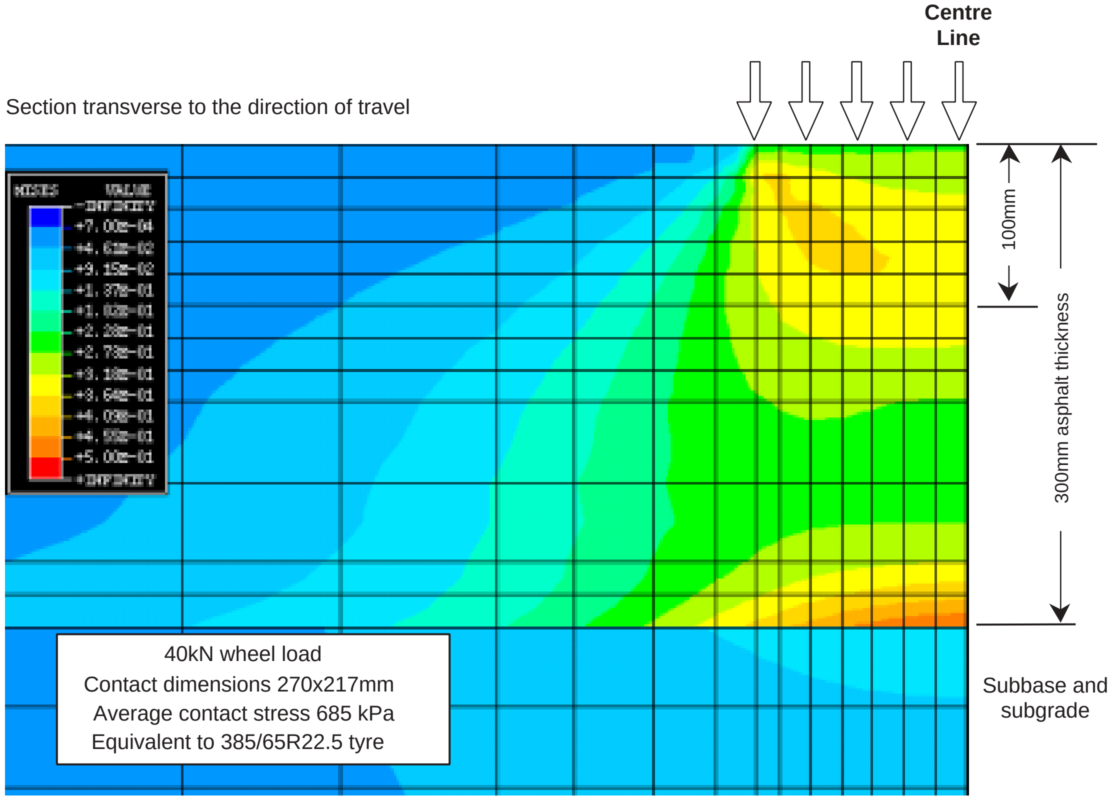
The accumulation of non-recoverable strains in the surfacing will not be governed by a 4th power damage law. The development of rutting in the asphalt is considered to be approximately related to the duration of loading of the wheel load and the value of whatever damage criterion is considered relevant. If the strain energy of deformation is considered to be the indicator of deformation then it is estimated to be 13 per cent higher for a wide-base single tyre than for a dual tyre assembly carrying the same load. However, the contact area of the wide-base single is greater than that of the individual tyres of the dual, which effectively increases the time the tyre is in contact with the road (duration of loading) by about 40%. Using these simplistic rules, about 50 per cent more rutting is estimated to develop under a wide-base single. However, there will be some lateral distribution of the wheel paths and consequent reduction of the effects of the peak strain energy. The lateral distribution of shear parameters is different for each wheel type and similar amounts of wander for each wheel type would result in relatively more reduction of stresses and strains for the wide-base single tyre. It is not known whether the typical wheel track wander of each tyre type is the same. There is a view that wide-base single tyres tend to be more rut-constrained than dual tyres and thus wander far less once a shallow rut has formed.

2.2.5 Reduced traffic speeds

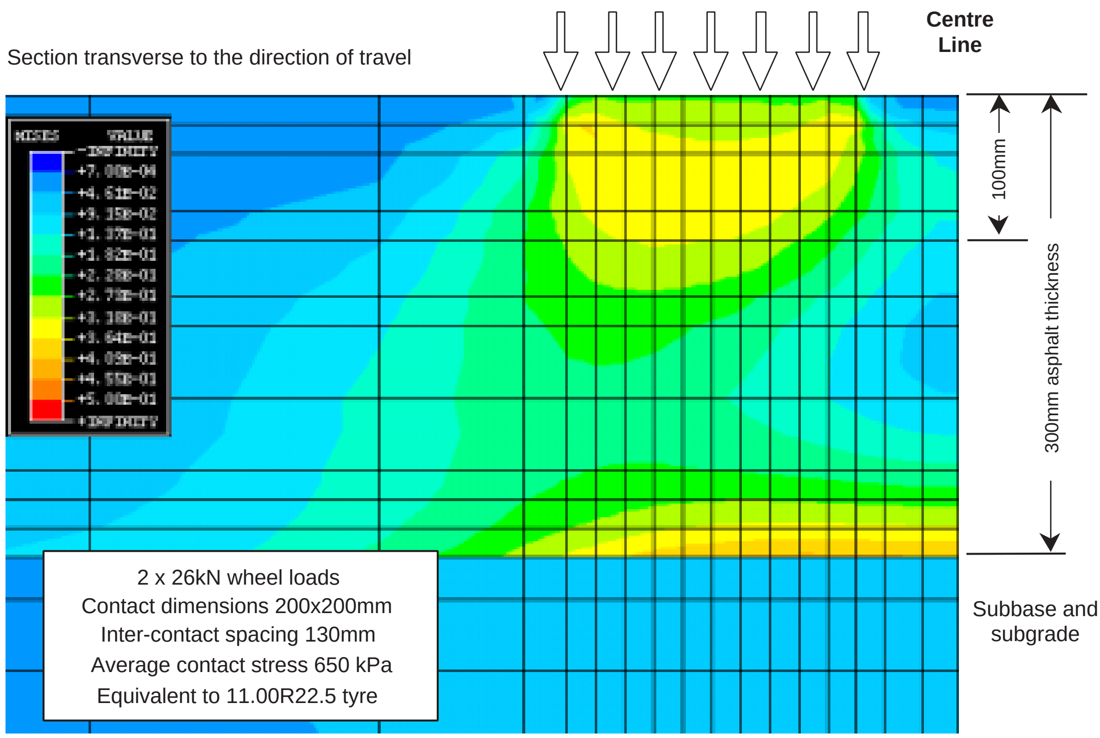
It is well known that permanent deformation in the asphalt layers is strongly influenced by the vehicle speed. Several researchers report that the deformation behaviour is, in fact, proportional to the effective duration of loading (Van de Loo, 1976; Nunn, 1985). The total duration of loading is related to the product of the number of wheel passes and the effective loading time of each, which increases as the speed decreases, rather than on just the total number of wheel passes.

Asphalt is a visco-elastic material and, as a result, the strain induced by a wheel load depends on the time of loading or vehicle speed. This aspect was examined on an instrumented pavement constructed on the TRL test track. The effect of vehicle speed on the measured longitudinal strain at the underside of the asphalt layer for a pavement consisting of 165 mm of asphalt resting on a typical foundation is illustrated in Figure 2.4.

This shows that as the vehicle speed decreases from 80 to 32 km/h, the asphalt strain can almost double. Sebaaly and Tabatabaee (1995) obtained similar results for an instrumented pavement in the Pennsylvania State test track. This implies that vehicle speed will be critical for the development of permanent deformation in the asphalt layers.



a Wide-base single tyre (half the contact shown)



b Dual tyres (only one wheel shown)

Figure 2.3 Contours of shear strain energy (von Mises) under a wide-base single and dual tyres

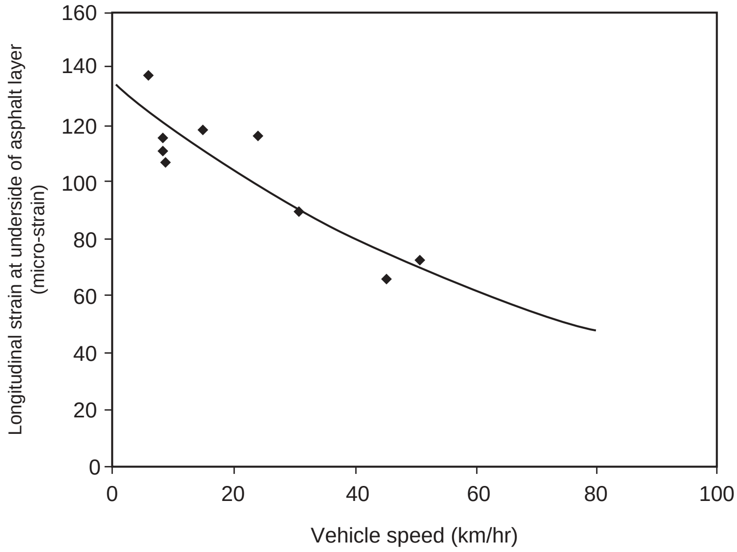


Figure 2.4 The effect of vehicle speed on asphalt strain

The monitoring of speeds of heavy goods vehicles on motorways, dual carriageways and single carriageway A roads has shown that the average speed has not changed significantly over the last 10 years (Government Statistical Service, 1998). However, incidences of severe rutting in newly laid surfacings have increased, especially when slow canalised traffic has resulted from traffic control measures that were in force for the rehabilitation of nearby stretches of the road, or in areas where congestion was a persistent problem.

2.2.6 Increased vehicle weights

For the period 1983 to 1995, average vehicle wear factors for all commercial vehicle classes have been calculated by Frith *et al.* (1997), using data from the Continuing Survey of Road Goods Transport (CSRGT). The wear factors have been derived from the static axle weights and the 4th power law. The wear factors for the three heaviest vehicle classes are reproduced in Table 2.2.

Table 2.2 Average vehicle wear factors for the heaviest classes based on 4th power law

	Average vehicle wear factor (80kN standard axles)				
Vehicle class	*1983*	*1986*	*1989*	*1992*	*1995*
4-axle rigid	2.58	2.55	2.49	2.45	2.40
5-axle articulated	2.69	2.70	2.60	2.47	2.50
6-axle articulated	1.26	1.50	1.48	1.36	1.36

For the first two vehicle classes, the data indicate that there has been a slight downward trend of vehicle weights in the period. The weights of the third vehicle class showed a marked increase between 1983 and 1986 but a decrease thereafter. Overall, in this period there has not been a significant change in the typical weights of the three heaviest goods vehicle classes.

However, from 1999 some increases in weight are likely as a result of EC directives relating to increased vehicle and axle weight limits. The vehicle weight limit was increased from 38 to 40 tonnes and the drive axle weight limit from 10.5 to 11.5 tonnes. The weight limit for non-drive axles was reduced marginally from 10.17 to 10.0 tonnes. Typical axle weights for 2 + 3 articulated lorries, the most common vehicle using wide-base single tyres, before and after this change have been estimated by the Department of Transport (1996) and are summarised in Table 2.3.

Table 2.3 Typical axle weights for a 2+3 axle articulated lorry

	Pre 1999 axle weights (tonnes)		*Post 1999 axle weights (tonnes)*	
Axles	*Limits*	*Typical (estimated)*	*Limits*	*Typical (estimated)*
Steering (single)	10.17	6.34	10.00	6.40
Drive (dual)	10.50	9.63	11.50	11.34
Trailer (triple axles – wide-base single)	8.00	7.34	8.00	7.42

The main effect of the change will be associated with the dual wheel drive axle on which the typical loading is expected to increase by 18 per cent from 9.63 to 11.34 tonnes. The typical loads on the wide-base single-wheeled trailer axles are expected to increase by only 1 per cent. The present limits for the 44 tonne ‘combined’ (road and rail transport, 3+3 axles) articulated lorries will continue. These are expected to carry the legal maximum of 8 tonnes on each wide-base single wheeled trailer axle as a normal load.

There are also proposals to allow the ‘combined’ (road and rail) transport weight limits to apply for general use within the UK and a consultation document (Department of Transport,1996) has been published. If this proposal is accepted, then typical wide-base single wheel axle loads would increase from 7.42 to 8.00 tonnes but the maximum drive axle load of the 3-axle tractor unit would be 8.56 tonnes compared to 9.63 and 11.34 tonnes for the 2-axle units of the current 38 tonnes and future 40 tonnes vehicles.

Overall it is expected that the changes in axle weight introduced in 1999 will cause slightly more surface rutting principally due to the increased dual-wheel drive axle weight.

2.2.7 Summary

i The principal factors responsible for increased rutting in the recent past, and which are likely to persist in the future appear to be:

- higher summer temperatures;
- reduced traffic speeds and canalised traffic resulting from localised congestion;
- the trend in the greater use of wide-base single tyres and, the possible development of a new generation of wide-base singles will potentially produce more damage to the pavement structure.

ii The increase in maximum vehicle weight, introduced in 1999, will have a slightly adverse effect owing to the increase in the allowed load on the drive axle (dual wheel).

iii The average axle weights have not increased significantly in the period 1982 to 1995.

2.3 The surfacing layers

The surfacing is the upper 100 mm of the total asphalt construction, consisting of a surface course and, generally, a binder course. Research, published in TRL Report 250, has demonstrated the importance of these layers in roads designed to have a very long structural life under heavy traffic (Nunn *et al.*, 1997). Deterioration in these *long-life* pavements will generally be confined to the surfacing in the form of asphalt deformation or cracking that initiates at the surface. The requirements for the surface course and the binder course are reviewed separately in this section and the necessity for a specifically dedicated binder course is considered.

2.3.1 Surface course

The functions of the surface course are more extensive than those of the other pavement layers, and there is also a much wider choice of materials. The surface course provides the running surface for traffic and it has a marked effect on the safety and comfort of the road user. Therefore it is necessary to consider carefully the role of surfacing materials for roads and the choices available to the highway engineer. Ideally, the *riding surface* should:

- offer good skid resistance;
- allow for rapid drainage of surface water;
- minimise traffic noise;
- resist cracking and rutting;
- withstand traffic turning and braking forces;
- protect the underlying road structure;
- require minimal maintenance;
- be capable of being re-cycled or overlaid;
- provide a structural contribution;
- be durable;
- give value for money.

Many treatments are available which provide some of these requirements but none offers them all. Therefore the selection of the surface course is a compromise and a matter of identifying the most appropriate material for each application.

Surface course materials range from thick conventional layers of HRA to thin veneer treatments. Table 2.4, reproduced from TRL Report 250 (Nunn *et al.*, 1997), provides an indication of the relative ability of the various types of surfacings to meet and maintain the desired properties. It is considered that the maintenance of texture, skidding resistance and surface profile are critical for the satisfactory performance of the surfacing layer. Of necessity, the ranking is subjective and many factors other than those associated with the surfacings themselves (for example, the condition and properties of the underlying layer) will affect performance. Therefore, Table 2.4 is only intended to be a preliminary guide to the type of material that will provide particular properties: a full understanding of each of the materials and of the appropriate circumstances for its use will be needed to optimise the selection of material type.

2.3.2 Binder course

The need to harmonise pavement terminology in Europe has led to the term binder course replacing the traditional UK term basecourse. The term *binder* appears to relate to the function of binding the surface course to the lower structural layers. In older, thin designs for low volumes of traffic, where the main structural layers were unbound, this function was probably very important. However, in modern asphalt pavements designed to carry heavy traffic there may be four or even five asphalt courses, which are all assumed to *bind* to each other. The property of *binding* is a feature of all asphalt layers not just the binder course.

The three editions of Road Note 29 (Ministry of Transport, 1960, 1965 and 1970) grouped the binder course and surface course together and designated them collectively as surfacing. The *surfacing* is required to:

- reduce the roadbase stresses to an acceptable level;
- keep water out of the material below;
- provide a satisfactory riding quality;
- provide satisfactory skid resistance.

The binder course would be expected to contribute to the first three functions. In the stress reducing role, it is not clear whether the binder course was primarily intended to act simply as an additional thickness of roadbase, reducing the tensile stresses (and strains) at the bottom of the roadbase, or whether the binder course was expected to resist the higher shear stresses near the road surface more effectively than roadbase material. Traditionally, the materials used in the binder course are generically similar to roadbase materials, but they usually employ a smaller nominal size aggregate and contain a higher binder content, rendering them less permeable than DBM roadbase. Providing an extra course of material also enables the surface tolerances to be more easily achieved.

Table 2.4 Effectiveness of different treatments in meeting desired properties

	Desired property (for fuller description, see below)										
Material#	*Suitability for re-profiling*	*Defor-mation resistance*	*Resis-tance to cracking*	*Spray reduc-ing*	*Noise reduc-ing*	*Skid resist-ance*	*Texture depth*	*Initial cost*	*Dura-bility*	*Speed of constr-uction*	*Quality of ride*
Thick surface course											
Rolled asphalt	✔✔✔✔	✔✔✔ (✔✔✔✔*)	✔✔✔✔	✔✔	✔✔	✔✔✔✔	✔✔✔✔	✔✔✔	✔✔✔✔✔	✔✔	✔✔✔✔
Porous asphalt	✔✔✔	✔✔✔✔✔	✔✔✔✔	✔✔✔✔✔	✔✔✔✔✔	✔✔✔✔	✔✔✔✔✔	✔✔	✔✔✔	✔✔✔	✔✔✔✔✔
Asphalt concrete / Dense bitumen macadam	✔✔✔✔	✔✔✔✔	✔✔✔	✔✔	✔✔✔	✔✔✔	✔✔	✔✔✔✔	✔✔✔	✔✔✔	✔✔✔✔
Mastic asphalt / gussasphalt	✔✔✔	✔✔	✔✔✔✔✔	✔	✔✔✔	✔	✔	✔	✔✔✔✔✔	✔✔	✔✔✔
Stone mastic asphalt	✔✔✔✔✔	✔✔✔✔✔	✔✔✔✔	✔✔✔✔	✔✔✔✔	✔✔✔✔	✔✔✔✔	✔✔✔	✔✔✔✔✔	✔✔✔	✔✔✔✔
Thin surface course											
26 – 39 mm thick	✔✔✔	✔✔✔✔✔	✔✔✔	✔✔✔✔	✔✔✔✔	✔✔✔✔	✔✔✔✔	✔✔✔✔	✔✔✔	✔✔✔	✔✔✔✔
18 – 25 mm thick	✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔✔	✔✔✔✔
< 18 mm thick	✔	✔✔✔	✔✔	✔✔	✔✔✔	✔✔✔✔	✔✔✔	✔✔✔	✔✔	✔✔✔✔	✔✔✔✔
Veneer treatment											
Surface dressing	n/a	n/a	✔✔✔	✔✔✔	✔	✔✔✔✔	✔✔✔✔✔	✔✔✔✔✔	✔✔	✔✔✔✔✔	†
High-friction systems	n/a	n/a	✔✔	✔✔	✔✔	✔✔✔✔✔	✔✔✔✔	✔	✔✔✔	✔	n/a
Slurry surfacing	✔✔‡	n/a	✔✔	✔✔	✔✔	✔✔✔	✔✔	✔✔✔✔✔	✔✔	✔✔✔	n/a

✔ = least advantageous to ✔✔✔✔✔ = most advantageous

 # Some of these materials will have a limited laying season.

** The deformation resistance of hot rolled asphalt can be enhanced by designing to conform to Clause 943 of the* Specification for Highway Works.

† The quality of ride for surface dressing will depend on the design of surface dressing, the aggregate size(s) employed and the evenness of the substrate.

‡ Slurry surfacing can give a useful improvement to the profile of the type of surface to which it is applied, for which this rating is appropriate - for other types of surfacing, it may not be appropriate.

In LR1132 (Powell *et al.*, 1984) the structural properties of a dense bitumen macadam binder course are assumed to be identical to those of the roadbase, provided that the same penetration grade binder is used for both layers. Subject to this condition, the binder course and roadbase are combined for pavement design calculations.

During the last several years, a purpose-laid binder course has often been dispensed with in a number of pavement construction contracts; roadbase macadam has been laid up to the surface course, although with some construction problems being experienced. This has led to a debate on whether it is essential to use a binder course. Therefore the role of the binder course was reviewed as part of this research programme. This review, described more fully in Appendix A, concluded that:

i There is little evidence that a separate binder course is an essential part of flexible pavement surfacing. The perception that it is appears to be a relic of past pavement practice where the surface course and binder course were the only asphalt layers in a flexible or flexible composite pavement.

ii A survey of Contractors' views on the usefulness of binder courses to achieve surface levels did not establish that it was essential. However, it is clear that the inclusion of a binder course or, alternatively, an upper roadbase layer of 60 to 80mm thickness, will assist in achieving surface levels.

iii Flexible pavement designs should assume that the total asphalt thickness will be sub-divided to provide a 60 to 80mm thick layer beneath the surface course. However, any proposal from the contractor to construct the pavement with fewer, thicker layers should also be considered.

iv The current standards for binder course material are not always adequate in providing deformation resistance under heavy traffic or impermeability under porous surfacing.

The review also indicated that the role of the various asphalt layers, including the binder course, should be restated in terms of our current knowledge of pavement design and performance.

2.3.3 Redefinition of asphalt courses

It is appropriate to periodically review the functions of the various pavement layers and to clarify or redefine their role after significant new knowledge of pavement design and performance has been attained.

In the absence of clear evidence of interaction between a surface course and a binder course it is now more logical to consider the latter as part of the roadbase or possibly as a separate zone within the pavement. This merely reflects present practice where the second pavement layer is either a binder course, but with properties similar to those of a roadbase, or is explicitly specified as roadbase.

A redefinition of the function of the binder course should recognise that its role will depend on the thickness and nature of the surface course and the intensity of traffic. For example, the evidence shows that the deformation within the asphalt layers occurs predominately in the top 100 mm of the pavement (COST Action 333, 1999). As a result, a heavily trafficked road with a thin surface course may require an 80 mm thick binder course that is resistant to deformation, whereas lower in the pavement, conventional roadbase macadam may be sufficient. Another example is when porous asphalt or other permeable surface courses are used. In this case the binder course must be impermeable as well as resistant to deformation.

The following definitions of functions of layers in fully flexible pavements are proposed:

Surfacing

Is the combined surface course and binder course, if present.

The surface course

Is the upper layer of the pavement, which includes the surface that is in contact with the traffic. Its primary function is to provide a surface with appropriate skid and rut resistance under all traffic conditions.

Note: It may also have significant load spreading properties by virtue of its thickness and stiffness. Usually the surface course will be impermeable and thus prevent moisture ingress to the underlying structure. When a permeable surface course is used, the binder course material must be impermeable.

The binder course

Is the layer on which the surface course is placed. In addition to spreading loads it must also possess adequate deformation resistance to withstand the high shear stresses near the pavement surface. Where permeable surface courses are used the binder course must also be impermeable.

Note: Depending on the thickness of the surface course, the binder course thickness will normally range from 50 to 100mm.

The roadbase

Is the main structural layer of a flexible pavement. It supports the surfacing and rests on the sub-base. Its primary function is to spread loads so that neither the roadbase nor the underlying foundation are overstressed.

Note: This is achieved by suitable selection of roadbase thickness and stiffness. The roadbase will be laid in several courses to facilitate compaction and level control.

2.3.4 Summary

i The choice of surface course for a particular situation depends on a number of factors, but there is a wide range of options available.

ii The specifications for binder course material prior to 1998 were not always adequate in providing deformation resistance under heavy traffic or impermeability under porous surfacing.

iii The 1998 changes in the specification in relation to air voids will have reduced the permeability of both binder course and roadbase materials.

iv It is recommended that the role of the various asphalt layers, including the binder course, should be restated in terms of our current knowledge of pavement design and performance.

2.4 Issues not addressed in current surfacing specifications

The review concluded that performance tests to assess the deformation resistance of the materials in the upper 100 mm of the asphalt pavement need to be identified and appropriate criteria specified to ensure that these materials have adequate resistance to deformation.

In the present specification, there are no special requirements to ensure that the binder course has adequate deformation resistance. Macadam binder course is specified in the same manner as the roadbase in that a minimum air voids content is required at the refusal density to ensure that an excess of binder does not result in an unstable mixture.

Many of the proprietary thin surfacings are permeable. Where such permeable materials are used, the binder course needs to be impermeable to protect the lower pavement layers from moisture damage.

If a regulating course is used under a thin surfacing, performance testing is required to ensure that the combination of thin surfacing and regulating course are deformation resistant.

Only proprietary thin surfacings that have been approved through the Highway Authorities Products Approval Scheme (HAPAS) are permitted on the trunk road network. Under this scheme these materials have been shown to be fit-for-purpose, therefore performance testing will not be required.

3 Research programme

The review of surfacing requirements described in the previous section identified the important characteristics that a surfacing system should possess in order to be suitable for use on heavily trafficked trunk roads in the UK. The next task was to:

- identify the means of ensuring good performance in the field by investigating the performance of a number of surfacing systems in a controlled environment;
- verify and refine the performance criteria by carrying out road trials as part of normal surfacing contracts using a draft surfacing specification.

The first task was achieved by trafficking, in the TRL Pavement Test Facility (PTF), trial pavements that were representative of current in-service construction. Particular emphasis has been placed on surface rutting. This section describes the format of that trial, detailing materials, construction, instrumentation, loading and all aspects of materials testing required to achieve the objectives.

3.2 Trafficking of trial pavements in the PTF

3.2.1 Objectives

The trial of the surfacing systems was required to provide the following:

- Information on surfacing performance to aid the development of a performance specification for asphalt surfacing.
- Identification of suitable performance tests by a correlation between performance in the trial and selected laboratory tests.
- Quantification of the relative performance of surfacing systems under simulated extreme traffic loading and high temperatures.

3.2.2 Experimental design

The trial was designed to investigate the behaviour of five representative asphalt constructions. These consisted of a control section constructed using traditional surfacing materials and four test sections that involved materials that have been introduced in recent years. The layout of the trial and construction details are shown in Figure 3.1.

The trafficking was carried out under severe conditions intended to resemble those found on a congested trunk road on a hot summer day (maximum air temperature of

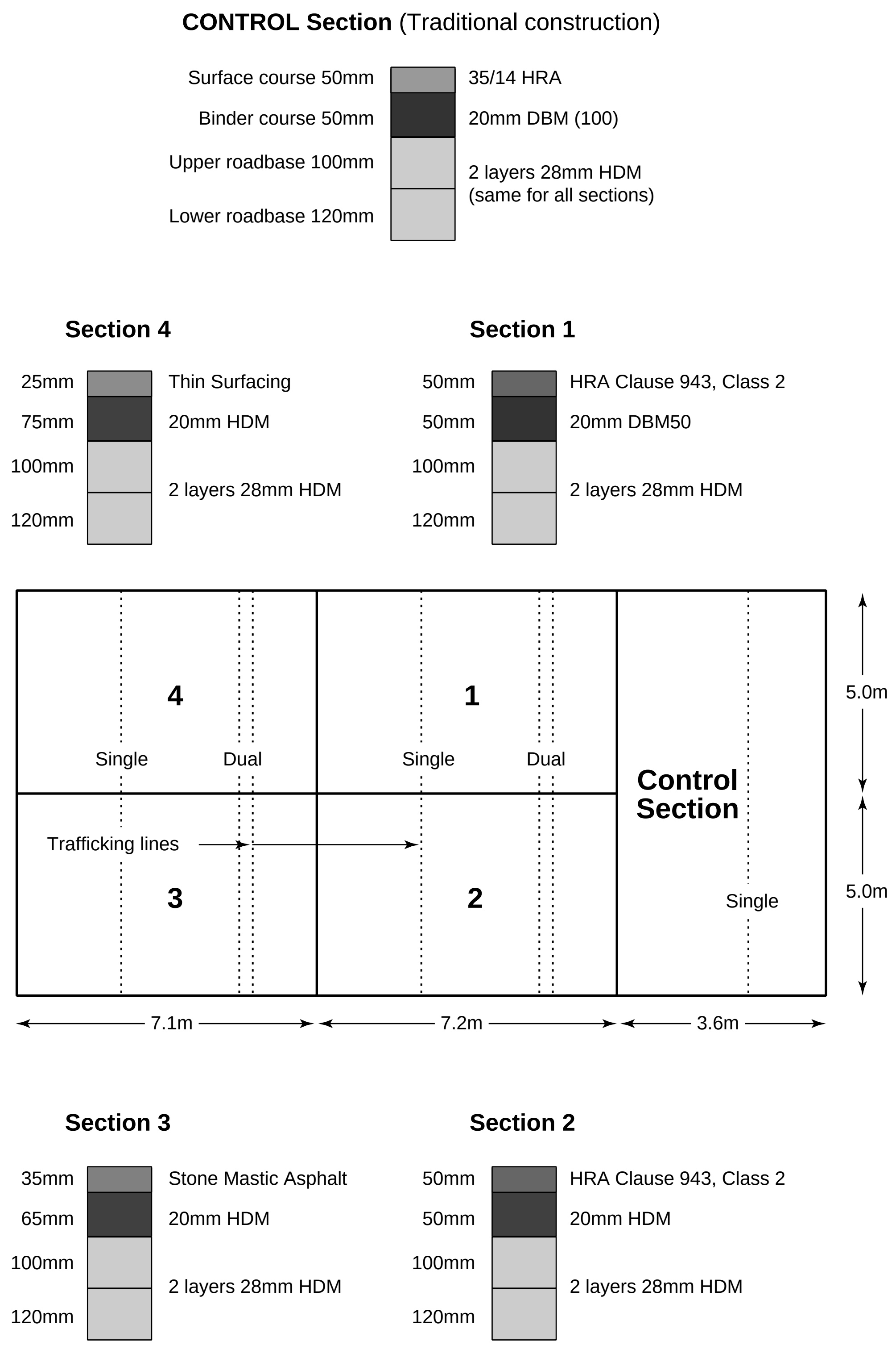


Figure 3.1 PTF trials: Layout and pavement types

around 30°C). This was to ensure that the design criteria developed would prevent serious rutting in most UK situations. For the main trial, a wide-base single tyre was used to simulate canalised traffic. This type of tyre was chosen because other researchers had reported it to be more damaging compared to traditional narrower tyres. This conclusion was also supported by the TRL finite element analysis described in Section 2.2.2. In four of the test sections there was space for a second trafficking line to enable the experiment to be repeated in the event of ruts developing at a much higher or lower rate than expected. In practice, satisfactory results were achieved within a reasonable time on the first trafficked line. A dual wheel assembly was used to traffic the second line. This enabled the effects of the wide-base single tyre to be compared directly with those of a dual wheel assembly.

Samples were cut from the trafficked areas and subjected to several different deformation tests. The results were then compared with the performance of the pavements in the PTF.

The trial is described in more detail in the following sections.

4 Surfacing trial in the TRL pavement testing facility

4.1 Trial materials and construction

The pavements for all the PTF test sections were long-life designs capable of carrying at least 80msa without structural deterioration (Nunn *et al.*, 1997). A two-layer HDM roadbase was adopted to achieve a total asphalt thickness of 320 mm.

The size of the available area of the PTF test pit and construction practicalities limited the trial to 5 test sections, each of different construction. These consisted of a control section, representing traditional surfacing materials, and 4 test sections, designated Section 1 to Section 4, representing recently adopted surfacing materials with good deformation resistance.

The *Control section* had an HRA surface course on a recipe mix DBM binder course with 100 penetration grade bitumen. Although not specified, it was expected that the HRA would have wheel tracking performance similar to the Clause 943, Class 1 (rut depth of < 4.0mm and a rate of rutting of < 2.0mm/hour at 45°C). The Control Section was expected to rut the most rapidly and provide a datum for comparison with the other sections. The Clause 943, Class 1 specification is believed to reflect the best deformation resistance that can be achieved by HRA surface course using standard 50 penetration grade bitumen.

Section 1 had a Clause 943, Class 2 specification HRA surface course on a 50 pen DBM binder course. The Class 2 specification for the HRA probably represented the best deformation resistance that could be achieved with this material and would require the use of a modified bitumen binder. It is a current solution to the potential problem of rutting in asphalt surfacings.

Section 2 also had a Clause 943, Class 2 specification HRA surface course but laid on HDM binder course. This would enable the effect of the change in binder course material to be quantified by direct comparison to the previous section.

Section 3 had a generic SMA surface course laid on HDM binder course and represented a surfacing system which is becoming quite common.

Finally, as the use of proprietary surface courses is increasing, it was considered necessary to include at least one proprietary material. *Section 4* had a proprietary thin surface course on the same HDM binder course as sections 2 and 3. This enabled the relative performance of this and the other surfacings to be examined.

The Control Section was expected to rut at a faster rate and was therefore constructed and trafficked on its own. The other four test sections were expected to have slower rut development and were expected to be trafficked in pairs. The layout of the five sections, shown in Figure 3.1, allowed for two lines of trafficking on Sections 1 to 4 but not on the Control Section. The figure also shows the types and thicknesses of the asphalt materials, the trial layout and the trafficking lines.

The constituent materials are summarised in Table 4.1.

Table 4.1 Material details for PTF surfacing trial

Surface course	*Binder course*	*Roadbase*
Control section		
HRA (35/14, Type F, Column 3/2, BS594: Part 1).	DBM (100pen bitumen) (20mm, Table 15, BS4987: Part 1)	HDM (28mm, Table 3 BS4987: Part 1)
Section 1		
HRA (Clause 943: Class 2)	DBM (50pen bitumen) (20mm, Table 15, BS4987: Part 1)	HDM (28mm, Table 3 BS4987: Part 1)
Section 2		
HRA (Clause 943: Class 2)	HDM (20mm, Table 15, BS4987: Part 1)	HDM (28mm, Table 3 BS4987: Part 1)
Section 3		
Stone Mastic Asphalt	HDM (20mm, Table 15, BS4987: Part 1)	HDM (28mm, Table 3 BS4987: Part 1)
Section 4		
Thin surfacing (Clause 942)	HDM (20mm, Table 15, BS4987: Part 1)	HDM (28mm, Table 3 BS4987: Part 1)

Preparation of the trial area began in mid-March 1998 with the excavation and disposal of the previous trial pavement. The subgrade of the previous trial was re-used. After excavation down to formation level, in-situ cone penetrometer tests were carried out and showed a very consistent subgrade CBR of 3 per cent over all test sections. A crushed rock Type 1 sub-base was laid and compacted in two layers to a total thickness of 280 mm. The construction of the asphalt layers was completed in May 1998.

Sensors to monitor temperature were installed at three depths (40 mm, 100 mm and 320 mm) from the pavement surface. The sensor at 40 mm was subsequently used to control the temperature of the pavement surface during trafficking and the other two provided a temperature profile through the materials.

4.2 Trafficking

The control section and the four test sections were all trafficked with a 40kN single wheel load using a 385/65R22.5 wide-base tyre with an inflation pressure of 850 kPa. This tyre, load and inflation pressure is typical of that found on a fully laden trailer with a tridem-axle in the UK. The additional trafficking line available on four of the test sections (control section excluded) was then tracked by a dual wheel with a load of 52kN using 11.00R20 tyres with an inflation pressure of 700kPa. Although the tyres used on the dual-wheel assembly were not typical of those currently used by heavy commercial traffic in the UK, they enabled a comparison to be made between different loading conditions. The wheel loads and tyre inflation pressures were those recommended by the manufacturer. The use of dual and wide-base single wheel loads enabled the effect of the increasing use of wide-base singles to be assessed. Trafficking commenced on the Control Section in early June 1998.

The pavement temperature at a depth of 40 mm was maintained at 42 to 43°C. This was slightly lower than the original target temperature of 45°C, which was closer to the temperature reached under hot summer conditions in the UK. However, unseasonally low ambient temperatures at the commencement of the trials meant that this higher temperature could not be achieved with the infra-red pavement-surface heating system. For consistency between test sections, the lower temperatures were maintained throughout the trial, even after the weather improved and higher temperatures were possible.

The heating applied to the surface of the trial pavements over a prolonged period resulted in producing moderately uniform pavement temperatures throughout the depth of asphalt. The mean temperature at a depth of 160 mm was 38°C, whereas in the field the temperature would be several degrees lower than this. Maintaining the temperature of the lower asphalt layers at a level higher than in-service pavements was expected to result in increased asphalt deformation deeper in the pavement.

At the start of the trial there was no clear information on the rate at which the various sections were likely to rut. For this reason, trafficking was initially applied without any lateral distribution or wander. However, an unexpectedly high rutting rate occurred in the first 150 passes and therefore the subsequent wheel passes were distributed up to 240mm each side of the centre line in 40mm increments. The numbers of wheel passes were in the following ratios:

Position	Centre line	±40 mm	±80 mm	±120 mm	±160 mm	±200 mm	±240 mm
Proportion	15	14	12	9	6	3	1

In order that valid comparisons could be made between all test sections, the subsequent sections were also initially trafficked with 150 non-distributed passes before proceeding with the distributed pattern.

After trafficking Sections 1, 2, 3 and 4 with the wide-base single tyre, these sections were subjected to trafficking by the dual-wheel, distributed laterally in the same manner as for the single wheel. These second trafficking lines were established well clear of the initial line.

4.3 Material testing

A summary of material sampling and laboratory testing for the surface course, binder course and roadbase materials is given in Appendix B. The main focus of the testing was to identify material performance tests that can be specified to prevent excessive rutting under severe traffic and climatic conditions.

The tests examined were the BS Wheel Tracking Test (BS 598: Part 110, 1996), the Repeated Load Axial Test with an effective confinement pressure (Nunn *et al.*, 1999) and a Triaxial Test originating in Holland. It has been demonstrated that the unconfined Repeated Load Axial Test (RLAT) can discriminate between asphalt mixtures of the same composition but with different binders; it cannot discriminate between mixtures with different aggregate gradations. However, if the test is carried out with an effective confinement pressure applied to the specimen by sealing the specimen with a membrane and applying a partial vacuum to the specimen (VRLAT), the results have been shown to correlate well with the BS Wheel Tracking Test (Nunn *et al.*, 2000). The triaxial tests were carried out partly to assist the Dutch developers of this test and also in the hope that it might provide a better indication of rutting under full size wheel loads than either the WTT or the VRLAT.

4.3.1 Conventional tests

Conventional testing of the asphalt materials laid in the PTF was carried out and this included grading, binder content, recovered binder properties, maximum density, air voids, percentage refusal density (PRD) and air voids at refusal. These tests confirmed that all the materials complied with either the standards specified in the Specification for Highway Works or those stated for the proprietary materials. Details of these results are given in Appendix B.

The PRD values of the macadams from all sections were good and the mean values ranged from 97 to 100 per cent.

Indirect tensile stiffness modulus (ITSM) tests were also carried out for general information and the results are presented in Appendix B. The stiffness values of the macadams are consistent with those measured on similar materials elsewhere. The stiffness of the Control Section, Class 1 HRA surface course, is similar to that of conventional 100 pen DBM binder course. The stiffnesses of the Class 2 HRA surface course in Test Sections 1 and 2 are slightly higher.

4.3.2 Deformation tests

The following three test methods were used to assess the deformation resistance of the asphalt material:

- BS Wheel Tracking Test (WTT) at 45°C and 60°C (BS 598: Part 110: 1998).
- Repeated Load Axial Test with Vacuum confinement (VRLAT) at 45°C (June 1998 version of BS DD 226:1996).
- Dutch Triaxial Test (DTT) at 50°C (Under development - no formal standard).

The wheel tracking testing of the surface course, binder course and roadbase was carried out on 50mm thick specimens. In the case of the SMA and the Thin Surfacing, some of the binder course material was included to achieve these thicknesses. The test specimens for the VRLAT were also 50mm thick except in the case of SMA where it was only possible to obtain specimens up to 30 mm thick. It was impractical to carry out the VRLAT on the Thin Surfacing as the material was only 25mm thick.

The test specimens for the DTT were approximately 120mm thick, built up from 30 to 50mm thick slices of 150mm diameter cores. The tests on the Control Section Class 1 HRA surface course could not be completed because the vertical strain exceeded the limit of the DTT test equipment.

Details of the test results are given in Appendix B and are summarised in Table 4.2.

Generally, the materials fell into three categories of deformation resistance:

- Low: Class 1 HRA.
- Medium: Class 2 HRA.
- High: SMA, all binder courses and roadbase.

The Thin Surfacing lay within either the medium or high deformation resistance category depending on whether total deformation or rate of deformation was considered.

4.3.3 Permeability

Traditional HRA surface course and DBM binder course are usually considered to be virtually impermeable due to their relatively high binder contents and consequent low air voids. Thin surfacings vary considerably but most would be expected to contain more air voids than HRA and have higher permeability. Deformation-resistant binder courses will generally have lower binder contents than the traditional recipe specifications, which could also result in higher permeability. In order to gain more information on this aspect of asphalt performance a limited number of permeability tests were carried out on the surface course and binder course materials of Test Sections 2 and 4.

The values of absolute permeability are plotted against air voids in Figure 4.1. The values of permeability are very sensitive to the air voids content. As expected, the HRA is practically impermeable. However, the Section 4 thin surfacing has a much higher permeability. The precise value of the air voids of this material is not known but is believed to be about 7 per cent. The permeability of other thin surfacings could be different to those shown, depending on air voids and binder content. The measurements were made using untrafficked material. In the initial years of service, the permeability of the surfacing materials would be expected to decrease with time as a result of traffic compaction.

The results for the binder course show a considerable difference in permeability between Sections 2 and 4 for nominally the same material, which is attributable to differences in air voids. This demonstrates that there will be large variations in permeability in typical macadam binder courses unless there is close control of air voids.

4.4 Rut development

4.4.1 Depth with time

Figure 4.2 shows the development of rut depth with traffic in the various test sections in the PTF under a wide-base single and dual wheel. Each data point represents the average of 7 wedge and straightedge measurements (14 in

Table 4.2 Summary of mean results from deformation tests (Results are generally the means of six separate tests)

			45 °C	*BS Wheel tracking*		*60 °C*	*VRLAT (45°C)*		*Dutch triaxial (50°C)*	
Test section	*Layer*	*Material*	*Rut rate (mm/hour)*	*Rut depth (mm)*	*Rut rate (mm/hour)*	*Rut depth (mm)*	*Strain rate (me/100c)*	*Strain (%)*	*Strain rate (me/cycle)*	*Strain (%)*
Control	SC	35/14 HRA	2.6*	**4.2***	13.3	**12.9**	125.8	**1.49**	30 **	**14 ****
1	SC	35/14 HRA (Class 2)	0.7	**3.1**	5.2 #	**8.1 #**	78.7	**1.19**	3.60	**6.03**
2	SC	35/14 HRA (Class 2)	1.2	**1.9**	4.0	**5.3**	42.0	**0.77**	–	–
3	SC	SMA	0.4	**2.0**	1.5	**3.3**	5.9	**0.26**	0.97	**3.06**
4	SC	Thin surfacing	0.9	**3.6**	1.7	**6.9**	–	–	–	–
Control	BC	20mm DBM (100pen)	0.2	**1.4**	0.9	**2.5**	15.5	**0.48**	0.13	**0.47**
1	BC	20mm DBM (50pen)	0.7	**1.9**	0.5	**2.6**	7.5	**0.18**	0.10	**0.39**
2	BC	20mm HDM	1.2	**3.2**	1.2	**3.6**	28.2	**0.43**	–	–
3	BC	20mm HDM	0.3	**1.6**	1.3	**3.5**	15.8	**0.28**	0.57	**1.71**
4	BC	20mm HDM	0.5	**1.7**	0.9	**3.1**	–	–	–	–
All	RB (U)	28mm HDM	0.5	**1.3**	0.5	**2.3**	–	–	0.53 +	**2.52 +**
Sections	RB (L)	28mm HDM	0.7	**1.8**	0.6	**2.4**	–	–	–	–

SC = Surface course
BC = Binder course
RB = Roadbase
U = Upper
L = Lower
** Almost meets Clause 943, Class 1 requirements # indicates marginal non-compliance.*
*** Denotes extrapolated values – refer to text.*
+ From Section 1 only.
All wheel tracking specimens were 50mm thick. SMA and Thin Surfacing test specimens include some binder course.

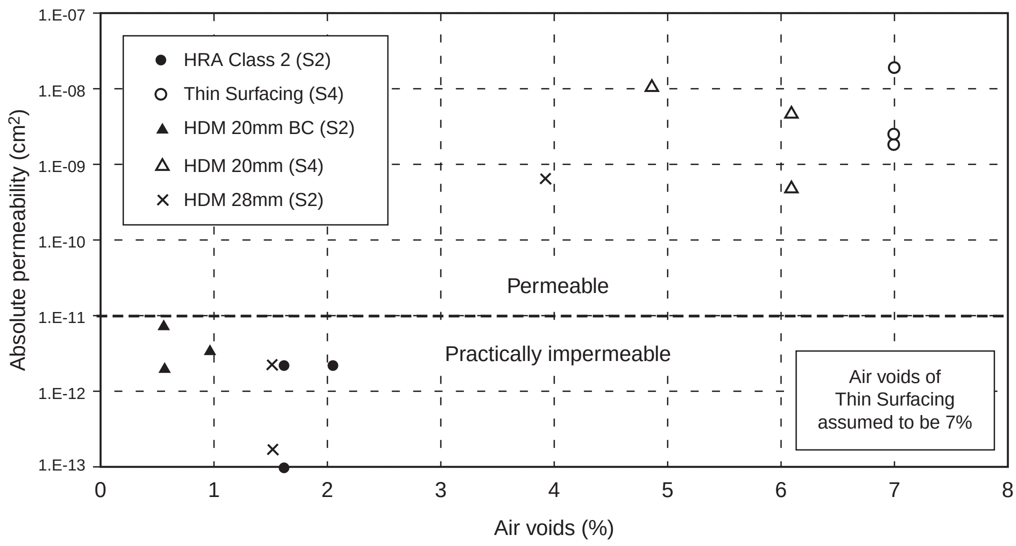


Figure 4.1 Permeability versus air voids

the case of the longer Control Section) at 0.5m intervals along the wheel track. The following features are evident:

- The rate of rutting of the wide-base single wheel is greater than that from the conventional dual wheel. In the cases of Test Sections 1 to 4, the formation of a 10mm rut requires an average of 18,000 passes of the dual wheels but only an average of 8,000 passes of the wide-base single wheels – an approximate doubling of the overall rutting rate.
- The wide-base single tyre rut depth curves of Sections 1 to 4 show greater diversity compared to the dual wheel curves, which are fairly similar to each other. This suggests that the susceptibility of a material to deformation is exaggerated by tracking with wide-base single tyres.
- The rate of rut development in the surface course of Section 1 was significantly greater than for Section 2, despite both sections having identical Class 2 HRA surface course and similar binder courses with similar deformation resistance (DBM50 and HDM).

4.4.2 Transverse profiles

A comparison of the average rut profiles at 13,170 wheel passes (measured by optical levelling) is given in Figures 4.3 and 4.4 for all sections for both dual and single wheels. The ridges at each side of the rut more or less coincide with the edges of the trafficked strip, including wander. In the case of the wide-base single tyres about one third of the total rut depth (measured from the top of the adjacent ridges) is attributable to uplift within the ridges. In the case of the dual tyres the uplift contributes about one quarter of the total rut depth.

4.5 Comparison of deformation tests with PTF performance

Comparisons of deformation in the PTF trial, described in this section of the report, have been made at 13,170 wheel passes, which is the point at which trafficking of the control section was terminated.

4.5.1 Change in layer thickness

After the completion of trafficking in the PTF, ten 1.2m × 0.5m slabs were cut from the traffic lines of all four test sections. The locations coincided with the positions at which the transverse profiles had been measured during the trafficking. The purpose of removing the slabs was to allow detailed measurement of the thicknesses of the pavement layers and, hence, determine the contribution of each to the surface rut. The contribution is the sum of the reduction in thickness of the layer beneath the rut and the increase in thicknesses of the layer underlying the shoulder of the rut. Examples of wide-base single wheel and dual wheel cross sections are given in Figures 4.5 and 4.6. The calculation of the contribution assumed that the thickness of each layer, before trafficking, was either constant or varied linearly across the section.

The thicknesses were measured at the end of the trial, after different amounts of trafficking of the various test sections. Consequently, the calculated rut contributions were adjusted to match the total rut depths at 13,170 passes by reducing the contributions in proportion to the total rut depths at 13,170 passes and the final number of passes (21,570 for Sections 1 and 2; 29,970 for Sections 3 and 4 and 44,145 for all dual wheel sections). The adjusted rut contributions at 13,170 wheel passes for the wide-base single wheels are presented in Tables 4.3 and 4.4. These tables give the deformation of each layer in millimetres and also as a percentage of the layer thickness. They also include a ranking based on these values. The percentages of deformation and the related rankings are considered to be the best basis for assessing performance.

The performance of the various layers of the different test sections (surface and binder courses and the roadbase) cannot be compared directly as they were subjected to different trafficking stresses due to their different thicknesses and depths within the test pavements.

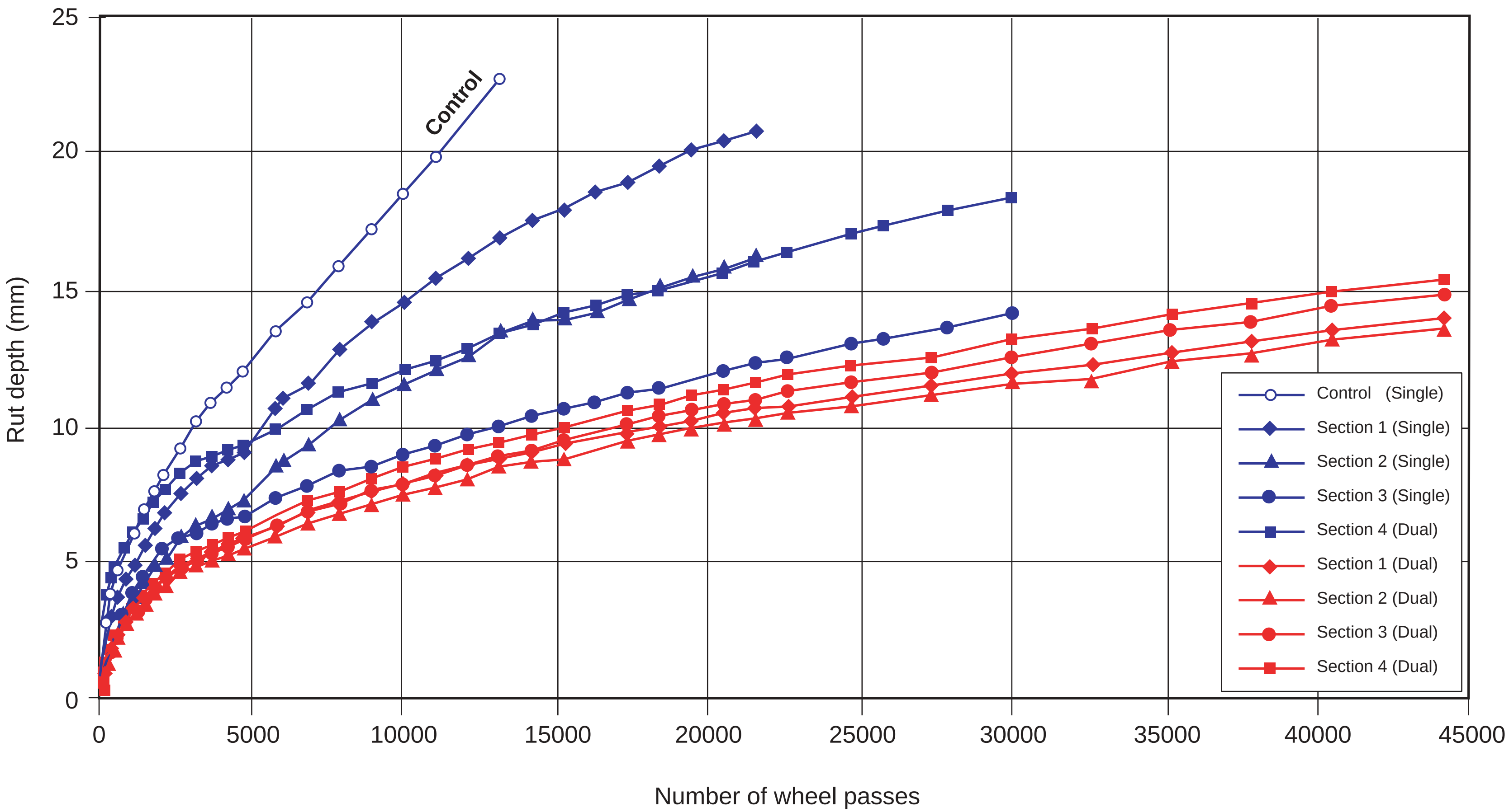


Figure 4.2 Rut depth versus wheel passes – single and dual wheels (wedge and straightedge measurements)

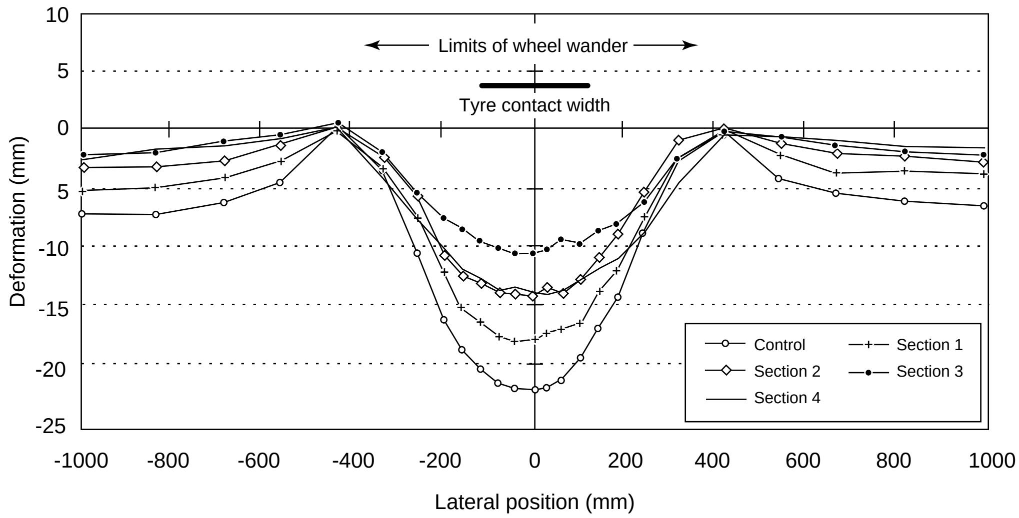


Figure 4.3 Rut profiles at 13170 passes: 40 kN wide base single wheel

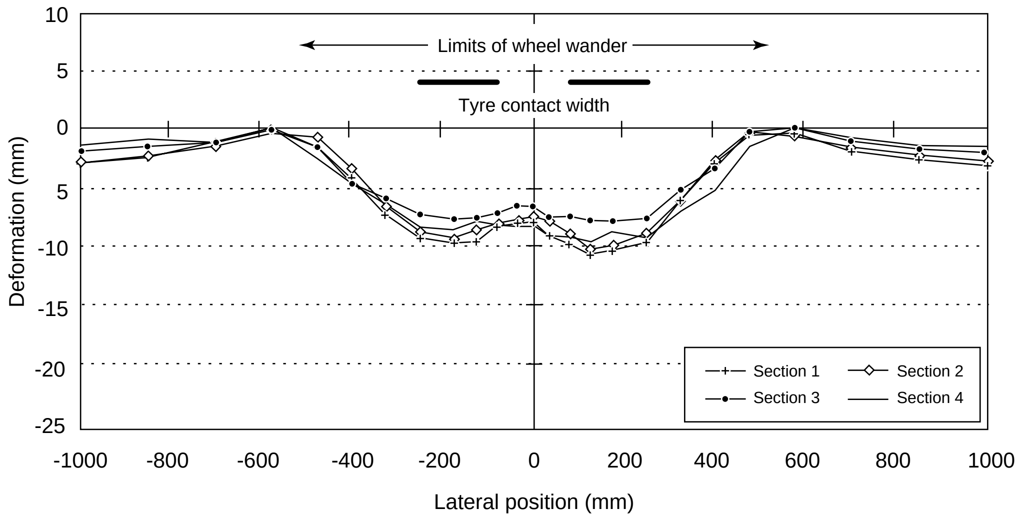


Figure 4.4 Rut profiles at 13170 passes: 52 kN dual wheels

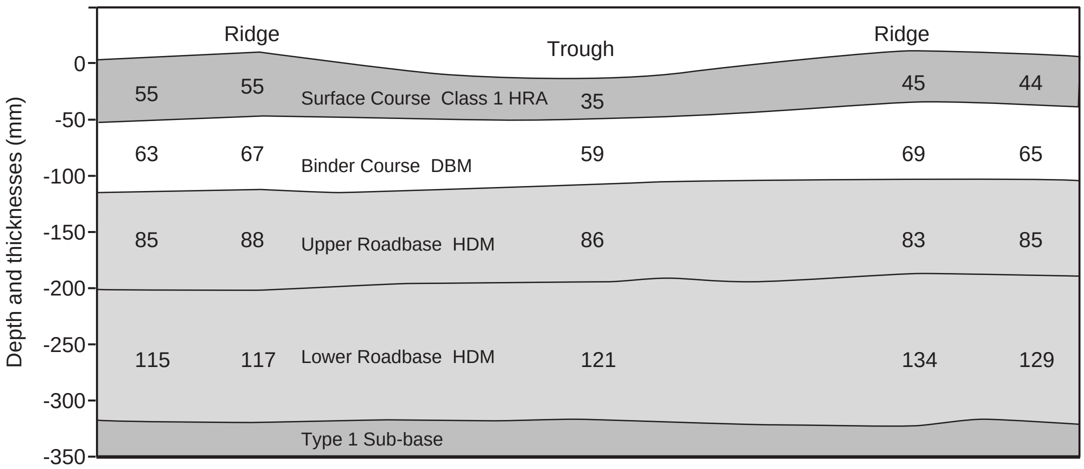


Figure 4.5 Control section: layer thicknesses after 13170 passes 4.0 tonnes, wide base, single wheel

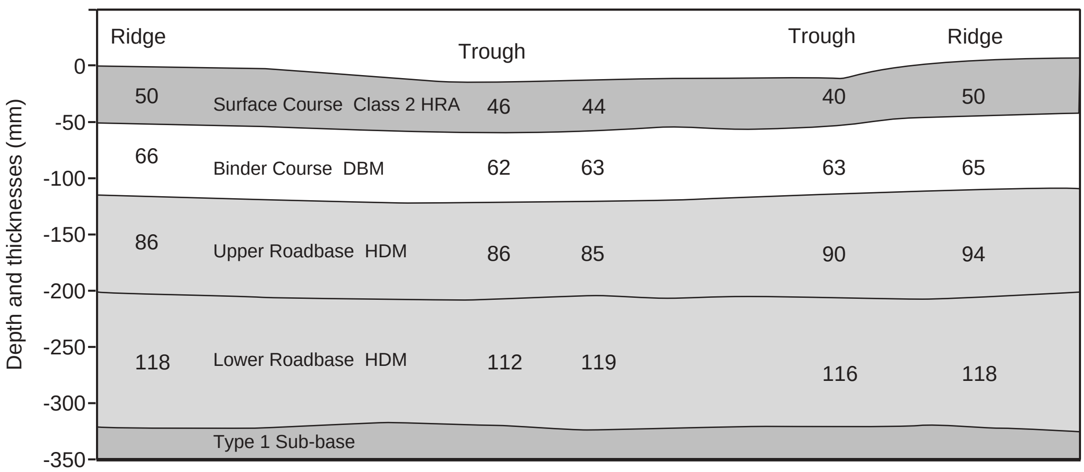


Figure 4.6 Section 1: layer thicknesses after 44145 passes 5.2 tonnes dual wheels

Table 4.3 Wide-base single wheel: summary of rut contributions of each layer

Layer		Contribution	Rank	Layer	Contribution	Rank
		To rut at 13,170 passes		*Thick-ness*	*As percen-tage of*	
Material	*Section*	*(mm)*	*(1= best)*	*(mm)*	*thickness*	*(1= best)*
Surface course						
HRA (Class 1)	Control	16.5	**4**	56	30	**4**
HRA (Class 1)	Control	15.0	**4**	48	31	**4**
HRA (Class 2)	1	10.0	**3**	48	20	**2**
HRA (Class 2)	2	2.0	**1**	45	5	**1**
SMA	3	4.0	**2**	21	19	**2**
Thin surfacing	4	4.0	**2**	21	18	**2**
Binder course						
DBM	Control	4.5	**1**	53	9	**2**
DBM	Control	9.0	**2**	66	14	**3**
DBM50	1	4.5	**1**	63	7	**1**
HDM	2	5.5	**1**	47	12	**3**
HDM	3	4.5	**1**	82	6	**1**
HDM	4	4.5	**1**	82	6	**1**
Road base (upper)						
HDM	Control	0	**1**	100	0	**1**
HDM	Control	0	**1**	100	0	**1**
HDM	1	3.0	**2**	100	3	**2**
HDM	2	3.0	**2**	100	3	**2**
HDM	3	0	**1**	100	0	**1**
HDM	4	4.0	**2**	100	4	**2**

Table 4.4 Dual wheels: summary of rut contributions of each layer

Layer		Contribution	Rank	Layer	Contribution	Rank
		To rut at 13,170 passes		*Thick-ness*	*As percen-tage of*	
Material	*Section*	*(mm)*	*(1= best)*	*(mm)*	*thickness*	*(1= best)*
Surface course						
HRA (Class 2)	1	2.5	**1**	48	5	**1**
HRA (Class 2)	2	3.5	**2**	45	8	**1**
SMA	3	4.5	**2**	21	21	**2**
Thin surfacing	4	4.0	**2**	21	18	**2**
Binder course						
DBM50	1	2.5	**1**	63	4	**1**
HDM	2	3.5	**2**	47	7	**1**
HDM	3	3.5	**2**	82	4	**1**
HDM	4	3.5	**2**	82	4	**1**
Road base (upper)						
HDM	1	0	–	100	0	–
HDM	2	0	–	100	0	–
HDM	3	0	–	100	0	–
HDM	4	0	–	100	0	–

The data in Tables 4.2 and 4.3 indicate:

Wide-base single wheel trafficking

- The surface course, binder course and the upper roadbase all contributed to the rutting of Test Sections 1, 2 and 4. In the other sections, only the surface course and the binder course had deformed.
- There was a major difference in performance between the conventional HRA, used in the Control Section, and the other three surface course materials used in Sections 1 to 4.
- The performances of the Clause 943, Class 2 HRA laid on Sections 1 and 2 were different by a larger margin than would have been expected from the modest differences measured in the laboratory wheel tracking test. The HRA in both these sections was nominally identical.

Dual-wheel trafficking

- The surface course and binder course both contributed to the rutting, with the surface course providing just over half the total deformation. The roadbase did not deform noticeably.

In the PTF Trial, the temperature for the full depth of the asphalt layers was close to 42^{o}C. The in-service situation is likely to place less demand on the asphalt layers deeper in the pavement structure as the pavement temperature will decrease with depth. On hot days, when surface temperatures are at their maximum, roadbase temperatures would be 5 to 10^{o}C lower and thus less susceptible to deformation.

Apart from the 100 pen macadam having marginally poorer performance than the 50 pen macadam, the three binder course materials are reasonably consistent. The higher binder content of the 100 pen material may also be a factor.

Deformation occurred in three of the four sections of the roadbase under the wide-base single tyre but none was detected under the dual wheel. Less deformation would be expected in this layer as the traffic induced shear stresses would be lower at this depth. It was assumed that all the deformation in the roadbase occurred in the top 100 mm (i.e., upper roadbase layer) and this thickness was used for the calculations given in Tables 4.2 and 4.3.

4.5.2 Deformation tests

Each laboratory test provided two methods of assessing the susceptibility of asphalt to deformation, namely total deformation and rate of deformation calculated at the end of the test.

Comparisons between the rutting in the PTF and the results from the laboratory tests are presented in Figures 4.7 (four different surface course materials) and Figure 4.8 (three binder course materials). The contribution to the PTF rut of each type of surfacing is indicated by the diamond symbol and the laboratory test results are shown as vertical bars. In the figures the materials have been arranged in order of PTF performance, with the material with the largest rut contribution on the left of the graph and the smallest on the right.

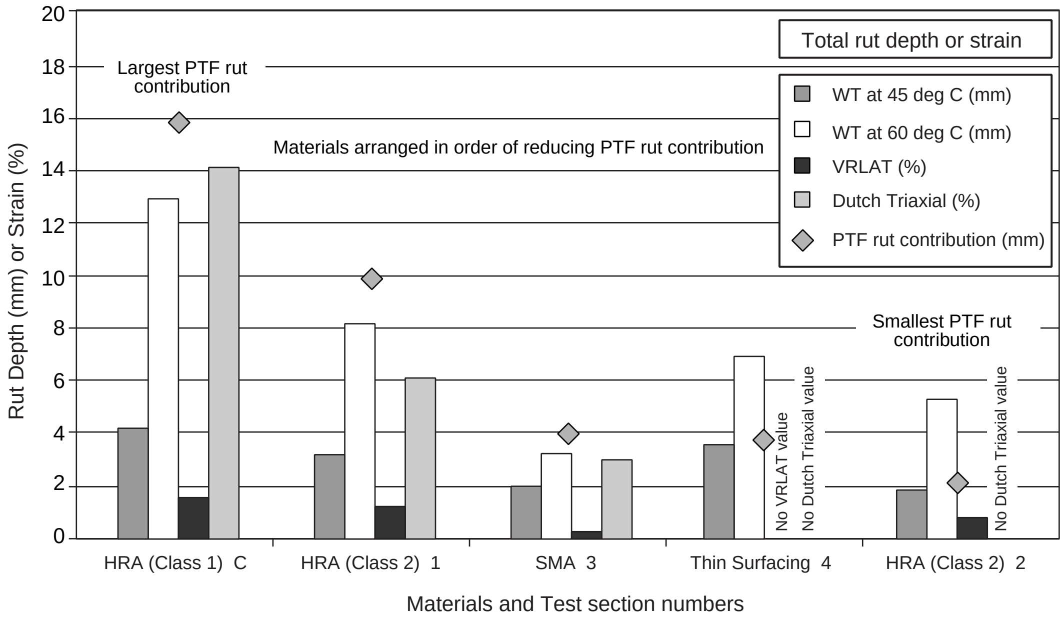


Figure 4.7a Surface course: PTF performance and deformation tests raw data (wide base single tyres)

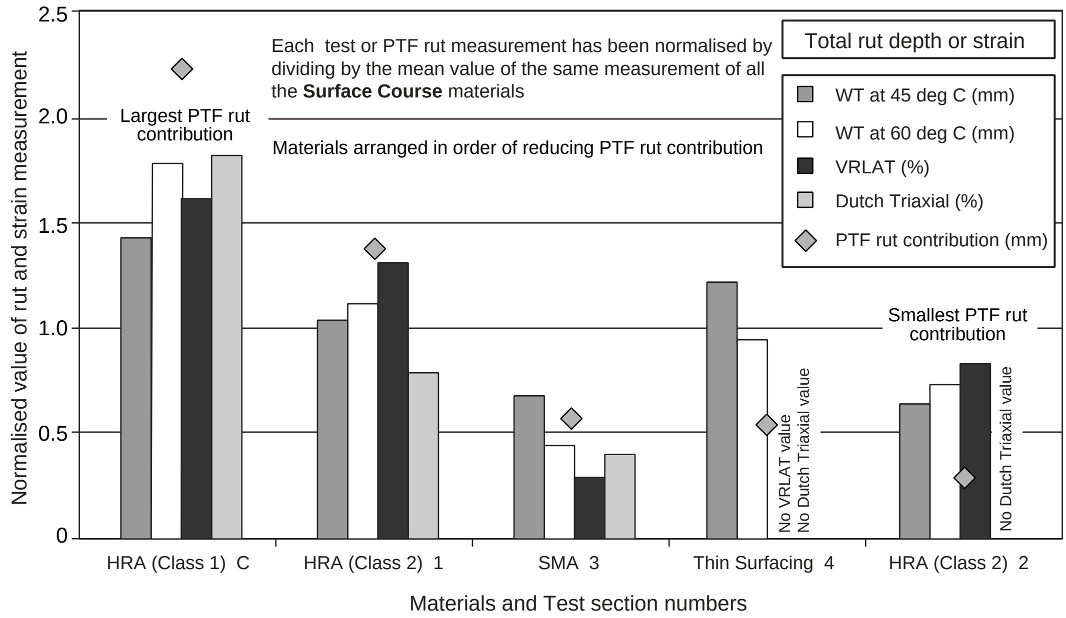


Figure 4.7b Surface course: PTF performance and deformation tests normalised data (wide base single tyres)

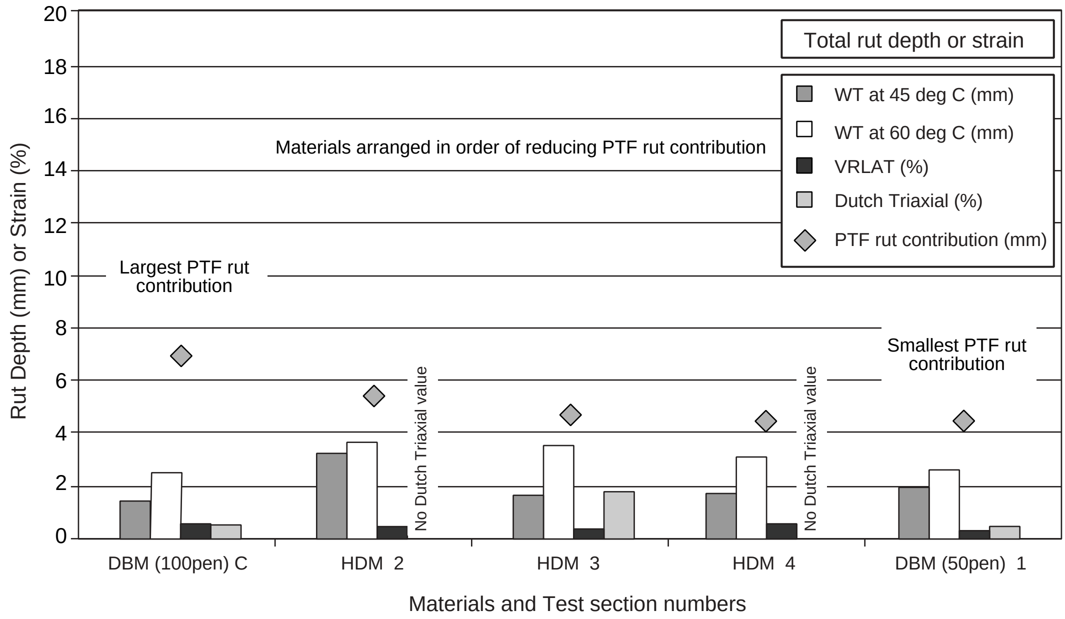


Figure 4.8a Binder course: PTF performance and deformation tests raw data (wide base single tyres)

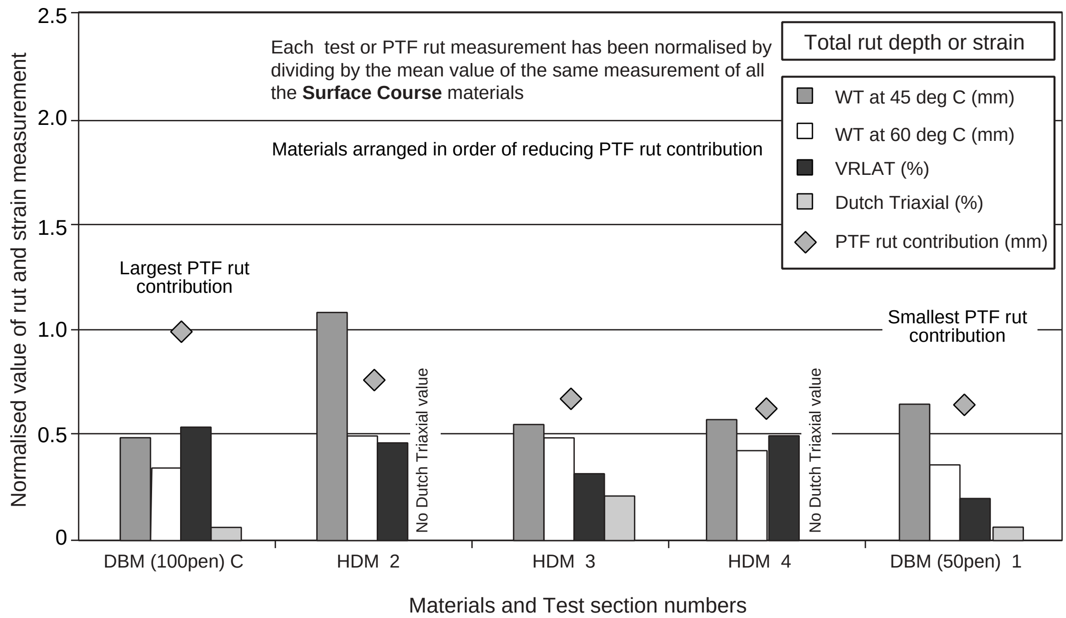


Figure 4.8b Binder course: PTF performance and deformation tests normalised data (wide base single tyres)

Each test method provides a different measure of deformation and therefore, in order to compare the results from the PTF and the laboratory tests more easily, the data for both the surface course and the binder course have been normalised. This has been done for each test method by calculating the ratio of the test result for each material with the mean value over all materials. These results are shown in Figures 4.7a and 4.8b.

The plot of a ‘good’ deformation prediction test would consist of a series of bars with relative values similar to the PTF performance, i.e. values decreasing to the right of the graph. In Figure 4.7b, the results of all four deformation tests do have this characteristic for the first three materials (Class 1 HRA, Class 2 HRA and SMA). However, this simple relationship is not sustained for Sections 4 and 2. Here, the deformation test results for the thin surfacing and the Class 2 HRA of Section 2 appear high in relation to the rut contributions measured in the PTF. The reason for the much lower rut contribution of the Class 2 HRA of Section 2 compared to the nominally identical material in Section 1 can only be attributed to variability within the batch.

For the binder course materials the performance measured in the PTF and the laboratory test values shown in Figure 4.8b generally showed less variation compared to the surface course materials, making it more difficult to judge the merit of the tests. However, the Dutch Triaxial Test was more erratic compared to the other tests, which gave reasonably consistent results for the similarly performing HDM and DBM50. None of the tests agreed very well with the performance of the Control DBM.

The general conclusions on the reliability of the deformation tests are:

- No one test was found to consistently correspond to the PTF performance.
- The wheel tracking test carried out at two temperatures and the VRLAT gave reasonable predictions for three of the surface course and two of the binder course materials. Overall the 60°C wheel tracking test corresponded best to the PTF performance but by a very small margin. Further comparisons would be necessary to demonstrate this conclusively.
- The Dutch Triaxial test in its current form does not appear capable of testing conventional HRA and it also under-predicts the deformation of the binder course.

4.5.3 Summary

i All the test sections with innovative surfacings performed substantially better than the Control Section with a traditional HRA surface course. The pavement with SMA produced the least rutting.

ii The performances of the three types of binder course (DBM, DBM50 and HDM) were similar except that half of the Control Section (DBM) deformed approximately twice as much as the other sections.

iii Under the trial conditions, in which the asphalt surfacing were maintained at a temperature close to 42°C and the mean temperature at a depth of 170 mm was 38°C, the binder course and also the upper roadbase contributed to the rutting when the wide-base single wheel was used. Under in-service conditions the roadbase would deform considerably less because much larger temperature gradients are present in pavements in service.

iv Although each separate material was from the same production run and was laid and compacted in an identical manner, there were a number of features of the results that could only be explained by random variation. For example, under the wide-base single wheel, the upper roadbase was at a similar depth in all the test sections; nevertheless whether it deformed or not appeared to be random. The different performance of the two HRA Class 2 test sections also appeared to be a random effect.

v On the four pavements with innovative surfacings (Sections 1 to 4) the 40kN wide-base single wheel trafficking produced 50 per cent greater rut depths compared to the 52 kN dual wheels.

vi The wide-base single wheel trafficking produced more diverse rutting performance compared to the dual wheels. This suggests that sensitivity of the material to deformation is exaggerated with wide single tyres

vii No one test was found to consistently correspond to the PTF performance. However, each of the laboratory tests could easily discriminate between the worst and best performing test sections. The wheel tracking test carried out at either 60°C and 45°C and the VRLAT gave a reasonable indication of PTF performance. The Dutch Triaxial Test in its present form was too aggressive to be able to test conventional HRA.

4.6 Equivalence of PTF trial with in-service performance

The trafficking applied to the PTF test sections was intended to simulate the extreme conditions which might be experienced on a UK trunk road. These are considered to be a newly constructed length of carriageway carrying substantial numbers of slow moving, heavy goods vehicles in high summer temperatures. Such a condition might be expected at roadworks or normal traffic operations adjacent to major towns. Although this condition was broadly met in the trial, there are some inevitable differences between the trial and in-service conditions. This means that a single pass of the PTF test wheel in the trial will not necessarily have the same rutting effect as trafficking by a similar wheel load under in-service conditions.

The main differences between the PTF and in-service conditions were:

- the vertical temperature profiles of the pavements and their daily variations;
- wheel speeds;
- proportion of total vehicles which are carried on wide-single wheels.

To obtain a rough estimate of the equivalence of the PTF performance of the Control Section to in-service performance, an analysis was carried out using the asphalt mix design software, PAMINA (Franken *et al.*, 1987) together with a multi-layer linear elastic program. First of all PAMINA was used to calculate the properties of the materials from mix design and pavement temperature data. These properties were used as input data to a multilayer elastic program to calculate the stresses in the pavement system. Finally, using these stresses together with traffic details and the deformation properties calculated by PAMINA, the permanent strain (the deformation) in the structure was calculated. Estimates were made of the rut depths that would develop in three situations namely, under the PTF conditions and under two in-service conditions, an extreme summer condition and a typical year-round condition.

A For the extreme summer conditions, the following was assumed:

Vehicle speed:	10 km/h.
HGVs per lane per hour:	450 – the calculated HGV capacity of a contraflow at the stated speed.
Pavement surface temperature:	40°C for 50% of the trafficking period and 30°C for the remainder.

B For the general, year-round, in-service conditions

Vehicle speed:	80 km/h.
HGVs per lane per day:	2975.
Pavement surface temperature:	40°C for 8%, 30°C for 23% and 20°C for 69% of the trafficking period. (Periods < 20°C were ignored).

The analysis predicted lower rut depths than observed in the PTF trial. In the discussion below the relative values between each of the three situations were used to make the comparisons.

The trafficking of the Control Section of the PTF produced a rut of 24mm depth after 13,170 passes of the wide-base single wheel. The analysis indicated that this corresponded to approximately one month of traffic under the extreme contraflow conditions, assuming that 10 per cent of HGVs are vehicles with wide base single-wheeled axles. If the traffic stream also includes cars and light vehicles, this equivalent time period will increase. Under normal trafficking conditions the PTF deformation behaviour was considered to be equivalent to approximately 15 years of trafficking.

For pavements currently being constructed using thin surfacings or performance-specified HRA (Clause 943, Class 2) substantially longer periods of service would be necessary to produce the same degree of rutting.

5 Full scale road trials

5.1 Objectives

- To obtain a wider range of laboratory deformation test results of surface course and binder course materials to enable realistic numerical deformation criteria to be determined.
- To assess the practicality and convenience of carrying out the deformation tests in a contractual environment.
- To obtain comments from the participants on the details and practicality of the proposed specification and testing regime.
- To provide sections of heavily trafficked pavements with surfacing of known laboratory deformation characteristics for future deformation monitoring.

5.2 Description of trials

It was intended to carry out trials in lane 1 of three separate heavily trafficked sites. Each trial would consist of four 200m sections of different construction. At each site, two types of surface course and two types of binder course would be assessed. Section 1 of each site would consist of the standard construction used on the scheme and this would be followed by three variants of surface and binder course. It was expected that proprietary thin surfacing and HDM binder course would be used in Section 1 at all sites and that performance specified Class 2 HRA and DBM would be selected as the alternative surface course and binder course materials.

Three sites were selected, all on pavement maintenance schemes, with the assistance of the Highways Agency. The first site was on the northbound carriageway of the M6 motorway between Junction 10 and 10A, just to the north-west of Birmingham. A 100mm deep inlay was being applied to correct rutting and other pavement surface faults. This site was the most heavily trafficked of the three. The estimated two-way traffic flows for the year 2000 are 115,000 Average Annual Daily Traffic (AADT), equivalent to approximately 5.6 million standard axles (msa) per year on lane 1. The main features of this, and the other two, trials are given in Table 5.1.

The second trial was also located on the northbound carriageway of the M6 between Junctions 1 and 2 just to the west of the M1. This section of the M6 carried less traffic, 69,000 AADT (two-way) equivalent to 4.8 msa per year on lane 1. The maintenance works consisted of a 100mm deep inlay to correct rutting and other surface faults and were similar to Trial 1. The pavement works were carried out with partial closure of the carriageway on a continuous basis.

The third trial was located on the A12 in Essex, just to the east of Chelmsford, adjacent to the village of Boreham. On this scheme the existing jointed, un-reinforced concrete pavement was being cracked and seated prior to being overlaid with 180mm total thickness of asphalt roadbase, binder course and surfacing. The estimated one-way traffic flow on the westbound carriageway was 67,000 AADT, equivalent to 2.2 msa per year on lane 1. (The low value of standard axles on the A12 compared to Trial 2 results from the lower proportion of heavy goods vehicles on this road (10 per cent) compared to the M6 sites (21 per cent)). Because of noise sensitivity at the A12 site it was not possible to include HRA surface course as a variant. Instead, an additional type of binder course, High Modulus Base (HMB) made with 25pen binder was included.

Table 5.1 Summary of surfacing trial sites (Section 1 of each trial is the standard construction for each scheme)

Trial No. and scheme	*Section No. and chainages*	*Surface course*	*Binder course*	*Comments*
1 M6: J10 to J10A	1: 2500 – 2780	Thin surfacing 'A' (30mm)	HDM (70mm)	Northbound Lane 1 Sections 1 & 4
	2: 2780 – 3100	HRA Cl.2 (50mm)	HDM (60mm)	100mm inlay Sections 2 & 3 110mm
	3: 3100 – 3400	HRA Cl.2 (50mm)	DBM (60mm)	inlay 26 Nov - 2 Dec 99
	4: 3400 – 3800	Thin surfacing 'A' (30mm)	DBM (70mm)	
2 M6: J1 to J2	1: 4000 – 4500	Thin surfacing 'B' (30mm)	HDM (70mm)	NW-bound Lane 1 100mm inlay
	2: 3500 – 4000	HRA Cl.2 (50mm)	DBM (70mm)	28 Jan - 2 Feb 00
	4: 3000 – 3500		DBM (50mm)	
	3: 2500 – 3000		HDM (50mm)	
3 A12: Boreham	1: 2300 – 2000	Thin surfacing 'C' (30mm)	HDM (70mm)	SW-bound Lane 1 Crack and seat
	2: 2000 – 1650		DBM (70mm)	scheme with 180mm asphalt overlay.
	3: 1650 – 1350		HMB (70mm) (25pen)	29 Feb – 10 Mar 00

At this trial site the maintenance agents had specified roadbase grading (28mm maximum particle size) rather than binder course (20mm maximum size) for the binder course. This coarser maximum size was also used for all three binder course materials in the trial sections. Consequently the trial consisted of only three sections with one thin surfacing and three binder course materials. The main features of this trial are summarised in Table 5.1.

The thin surfacings used in the three trials were three different Highways Agency approved proprietary materials.

5.3 Specification for the trials

The frequency or total number of test measurements of the surface course and the binder course for each section are indicated in Table 5.2. The normal Specification for Highway Works (1998) Series 900 requirements covering grading, binder content, air voids and air voids at refusal density were to apply to the surface course and binder course materials of the trial sections.

Table 5.2 Trial section testing

	Conventional tests				*Performance-based tests*		
	Grading	*Binder content*	*As laid air voids*	*Refu-sal air voids*	*Stiff-ness (ITSM)*	*Wheel tracking*	*Vac-uum RLAT*
Number of tests per section per material source	3	3	3 pairs	3 pairs	6	6	6
Thin surfacing Clause 942	0	0	0	0	0	x Class 2	x
HRA Clause 943	**X**	**X**	**X**	0	0	**X** Class 2	x
Binder course Clauses 933, 906 and 929	**X**	**X**	**X**	**X**	x Clause 944	x	x

X *Must meet stated criteria.*
x Information only.
0 No test required.
Shaded cells denote additional requirements.

In view of the limited quantities of variant materials, Job Mixture Approval Trials were generally not required. However, the suppliers were requested to provide test data from previous works or trials to demonstrate that the proposed material would comply with the conventional requirements.

Extra deformation and stiffness tests were carried out for the trial sections as indicated by the shaded cells of Table 5.2. The intention was to have all testing carried out by the laboratory being used for general testing on each contract. For this reason it was decided that the primary deformation test would be the Wheel Tracking test rather than the Vacuum RLAT. The procedure for the former test was well established whilst the procedure for the Vacuum RLAT was still under development at the time of setting up the trials. TRL carried out the Vacuum RLAT tests using the procedure current at January 2000.

The performance criteria which were to be achieved are detailed in Table 5.3. These deformation criteria should be met by the standard materials assuming that they are properly batched and laid. From the PTF trials the Clause 943, Class 2 Wheel Tracking specification seemed a reasonable target for all surface course and binder course materials. There was no equivalent Vacuum RLAT criterion but this would be determined from the data from the trials. The binder course stiffness values are taken from SPECLIB Clause 944 and the corresponding Notes for Guidance.

(SPECLIB is the collection of final draft specification clauses held by Highways Agency prior to their possible publication in the Specification for Highway Works.)

Contrary to the note in the Wheel Tracking test procedure (BS 594 Part 110: 1998) stating that specimen thickness in the range of 35 to 55mm has little effect on the results, TRL experience has been that different forms of deformation occur with the smaller thicknesses. In the interests of making robust comparisons between different materials of different thicknesses it was decided to carry out all Wheel Tracking testing on specimens nominally 50mm thick. In the case of thin surfacing, this results in some of the binder course being included with the surfacing. These composite specimens should be tested 'rightway up' so that the thin surfacing is in contact with the wheel.

Table 5.3 Deformation and stiffness values

Surface course (thin surfacing and HRA)
Wheel tracking criteria (Clause 943, Class 2)

Temperature (degrees C)	*Maximum rut rate (mm/hr)*	*Maximum rut depth (mm)*
60	5.0	7.0

Binder course (all types)
Stiffness requirements (SPECLIB Clause 944 Notes for Guidance)

	Stiffness (ITSM) (GPa)	
Material	*Minimum moving mean of 6 values*	*Minimum individual value*
DBM (100pen)	1.1	0.7
HDM (50pen)	3.5	2.0
HMB (25pen)	7.0	5.0

Vacuum RLAT testing was carried out by TRL on replicate cores to those used for the wheel tracking. The results of Vacuum RLAT testing are also dependant on specimen thickness so these too were standardised at 50 ± 5 mm.

5.4 Results

5.4.1 General

The test data for Trials 1, 2 and 3 are given in Appendices C, D and E, respectively.

5.4.2 Conventional Tests

The conventional test results were more or less as expected. The gradings all comply with their respective standards. The as-laid air voids and voids at refusal are all satisfactory and are summarised in Table 5.4.

Table 5.4 Voids

	Trial 1	*Trial 2*	*Trial 3*
In situ air voids (%)	4.4 to 5.1	5.7 to 5.8	3.7 to 3.9
Refusal air voids (%)	1.7 to 2.6	2.8	1.8 to 1.9

5.4.3 Deformation tests – all trial sites

Summaries of the Wheel Tracking rut depths and Vacuum RLAT total strain for the three road trials are presented in Figures 5.1 and 5.2, respectively, together with the equivalent data from the earlier PTF trials for comparison.. (Total strain rather than rate of strain is now the preferred parameter to characterise Vacuum RLAT behaviour.)

It was found that there were reasonably good correlations between rate of rutting and rut depth for the WTT and between rate of strain and total strain for the VRLAT with correlations lying in the range 0.73 to 0.93.

Wheel tracking tests

All the surface course materials of the three road trials meet the specified Wheel Tracking maximum rut depth requirement of 7mm. The rut depths of the three thin surfacings lie between 2 and 4mm except for Section 1 of Trial 3 where the mean value was 5.3mm.

The Class 2 HRA results show more variability and range from 1.4mm (Trial 1) to 5.8mm (Trial 2). The relative performance of thin surfacing versus Class 2 HRA in Trial 1 is reversed in the case of Trial 2. The HRA Class 2 results measured in the PTF were consistent with those of Trial 2 and showed more potential for deformation than Trial 1.

The binder course WTT results of nine of the eleven sections of the three road trials and the PTF trials are fairly consistent and the rut depths range from 1.5 to 3.6mm. The exception, the DBM of Section 3 of Trial 1, produced very diverse results (6.3 and 0.8mm) for the two sources, neither of which appears very credible. No explanation was found for this anomaly.

The effect of the stiffer binder on deformation resistance of binder course is evident in Table 5.5. All the materials easily meet the Clause 943 Class 2 requirement of 7mm.

Table 5.5 Wheel tracking rut depths of binder courses

Material	*Section averages (mm)*	*Mean of road trials (mm)*	*PTF section averages (mm)*
DBM*	3.5 2.3 3.2#	3.0	2.5 2.6
HDM	1.5 2.9 2.2 2.4 2.1#	2.3	3.6 3.5 3.1
HMB	1.5#	1.5	–

** Trial 1, Section 3 results not included.*
 # 28mm maximum aggregate size. All other materials 20mm.

Vacuum RLAT

The total strain of all the thin surfacings are very consistent and only vary from 0.21 to 0.30 per cent (see Figure 5.2). The Class 2 HRA strain values are substantially greater and range from 1.09 to 1.85 per cent. Contrary to the ranking indicated by the WTT, the Vacuum RLAT shows no great difference between the HRA of Trial 1 and that of Trial 2.

ITSM stiffness

The binder course stiffness values are shown in Figure 5.3. The values are close to or exceed the expected values except for Section 2 of Trial 1 and Section 3 of Trial 3.

5.5 Feedback of contractor and supervisors

Overall the comments were positive. The major problem encountered on all three trials, in varying degree, was the several weeks taken to obtain the deformation test results. As these tests were a departure from the established site practices there had been some uncertainties and consequent delays over the trial section test samples. In one case the deformation samples had been sent to a remote laboratory which had resulted in additional transport time. It was agreed that if the trial section requirements applied over the whole site these problems would be solved early in the contract and the turn-round time for the deformation tests for the bulk of the contract would be much shorter.

However, the contractors noted that many contracts, particularly those involving rehabilitation were carried out to very tight programmes. Often, overlying courses had to be laid or the road re-opened before the deformation tests could be available. Conventional composition and density test results, which can be available within 24 to 48 hours

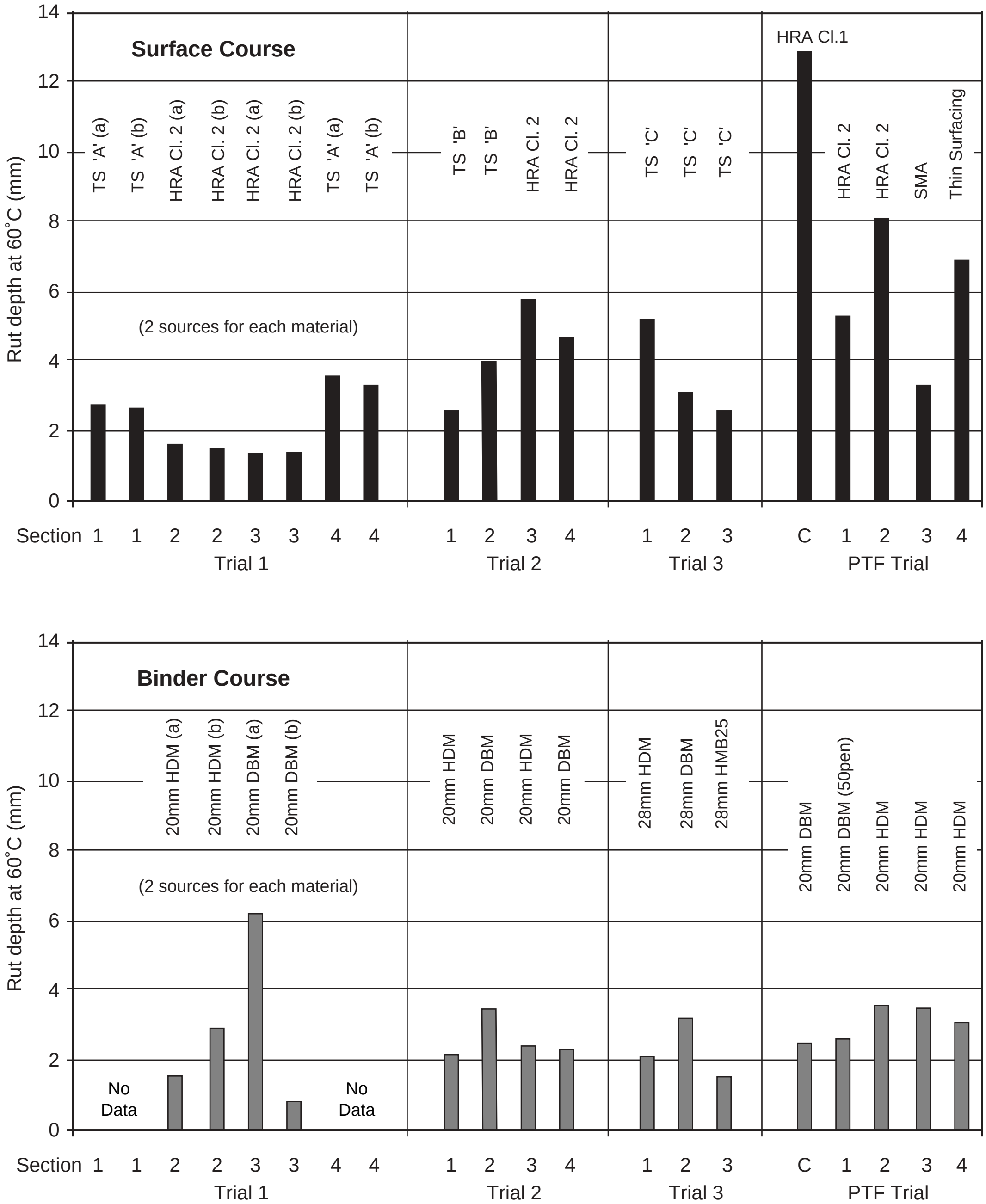


Figure 5.1 Wheel tracking rut depths for all trials
(Values are generally the means of 6 separate measurements)

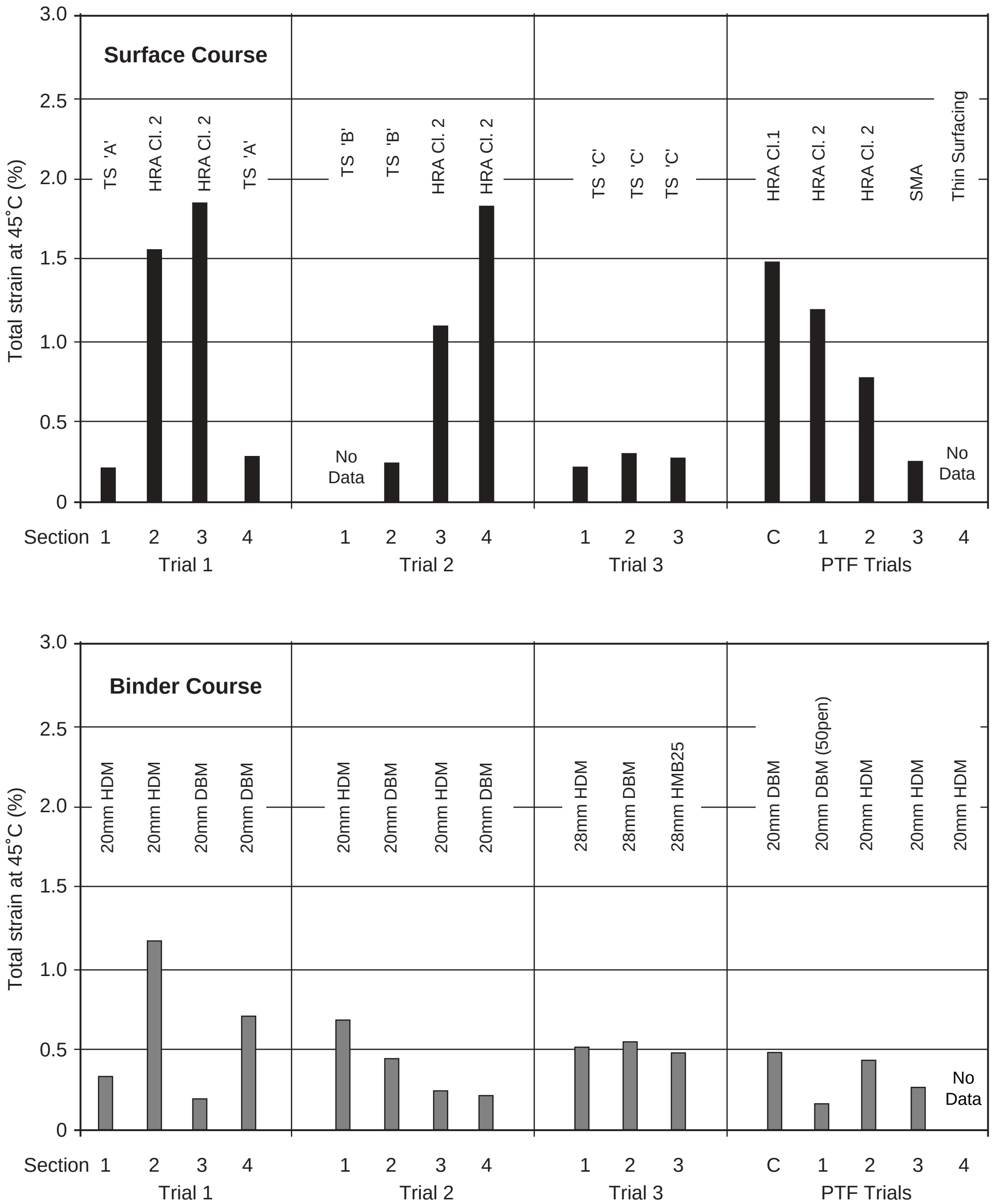


Figure 5.2 Vacuum RLAT total strain for all trials
(Values are generally the means of 6 separate measurements)

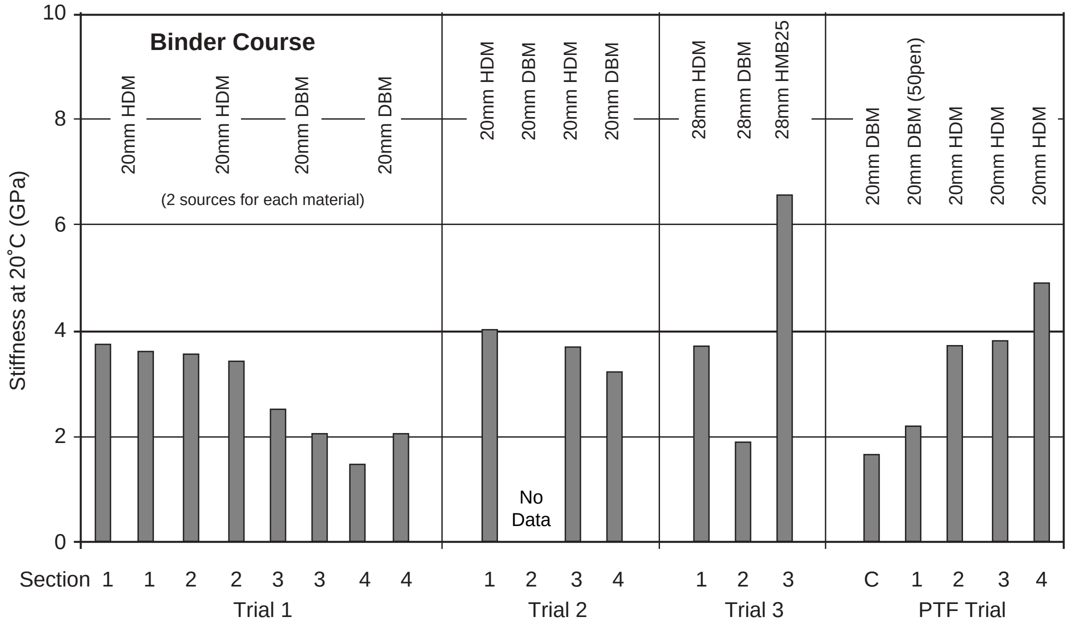


Figure 5.3 Binder course stiffness (ISTSM) for all trials
(Values are generally the means of 6 separate measurements)

of laying asphalt, would continue to be very important in such circumstances.

It was pointed out that regulating courses lying within 100mm of the final road surface should also be included in the surfacing specification.

5.6 Summary

- The practicality of the deformation tests was limited by longer turn-round time compared to conventional composition and density testing.
- The ranking of material deformation indicated by the Wheel Tracking and Vacuum RLA tests was not as consistent as that obtained in the TRL PTF Trial.
- The participants acknowledged that the proposed specification was practical and would assist in ensuring adequate deformation resistance of the surfacing.

6 Draft surfacing specification

6.1 Basis of specification

This is illustrated in Table 6.1. The three most likely materials to be used on heavily trafficked roads are indicated, all of which are already covered by existing specifications. The most popular surface courses are the proprietary thin surfacings which are covered by a detailed approvals system. Recipe specified or Marshall designed HRA is little used on heavily trafficked sites and the performance variant of this material is already subjected to wheel tracking testing under Clause 943. Consequently there is no justification in subjecting these surface course materials to further testing.

The binder course or other roadbase material lying within the top 100mm of the pavement is at some risk of deforming under heavy traffic, particularly in hot weather. It is proposed that either the Wheel Tracking Test or the Vacuum RLAT be carried out on 50mm thick test specimens. Where the surface course is relatively thick (40 to 50mm) a single specimen of 50mm nominal thickness taken from the binder course (or top of the roadbase if a binder course is not specified) will be sufficient. In cases of very thin surfacings (20 to 25mm) thickness a second test specimen immediately under the first will also be necessary.

It is anticipated that, in the near future, the Highways Agency will introduce SPECLIB Clause 944 which specifies roadbase in terms of stiffness, measured by the ITSM test. As the current pavement thickness design curves treat all bitumen bound layers as one, and attribute the same stiffness to both roadbase and binder course, it would be logical to apply the same stiffness testing regime to both. Accordingly, it is proposed that Clause 944, where adopted for the roadbase, should also apply to the binder course.

An upper limit on binder course permeability is already imposed by Clause 943 by reducing the maximum air voids of binder course, when placed under porous asphalt, to 7 and 8 per cent for mean and individual values. This is 1 per cent less than the value traditionally applied under HRA surface coures which is usually virtually impervious. Proprietary thin surfacings, in general, are considered semi-permeable but could be expected to exhibit a range of permeability from near impermeable to fairly impermeable. If the surfacing can no longer prevent water from penetrating the pavement then the binder course must take on this role.

The proposed surfacing specification is included in this report as Appendix F.

6.2 Criteria to be met

The deformation criteria to be met are set out in Table 6.2. For both tests the total rut depth or strain are considered the primary test parameters and are the simpler measurement. There can be difficulties in accurately

Table 6.1 Basis of surfacing specification

Pavement layer Material	*Thickness range (mm)*	*Deformation test sample*	*Notes*
Surface course			
Thin surfacing (Clause 942)	20 to 50	None	Must satisfy the relevant HA/HAPAS or relevant SHW Clause requirements.
Porous asphalt (Clause 938)			No further testing required.
HRA (Clause 943, Class 2)			
Binder course (or upper roadbase)			
DBM	40 to 120	50mm thick	All binder course or roadbase material within 100mm of the pavement surface must satisfy either WTT or VRLAT requirements; and
HDM			
HMB 25		50mm thick	Binder course or upper roadbase subject to reduced air voids limits; and
SMA (Draft clause)			Binder course subject to same stiffness criteria as the roadbase (Clause 944)
Roadbase			
DBM HDM HMB 25	100+	No requirement	A second deformation measurement specimen may be required if the first does not extend to 100mm depth

Table 6.2 Binder course deformation criteria (These criteria apply to means of 6 values, individual values may be 50% greater). All test specimens 50 mm thick

Wheel tracking test (BS 598: Part 110)

Test temperature (°C)*	*Max. rut rate (mm/hr)*	*Max. rut depth (mm)*	*Comments*
60	5.0	7.0	Same as Clause 943, Class 2 All trial samples comply

Vacuum RLAT (BS DD 226 and TRL PA3287/97)

Test temperature (°C)*	*Max. strain rate (micro-strain/hr)*	*Max. strain (%)*	*Comments*
45	100	1.5	All trial samples comply

* *The test temperatures do not necessarily relate to in-service pavement surface values. They are the standard values adopted by the test methods drafting committees.*

measuring the small rates of rutting or strain with deformation resistant materials.

The Wheel Tracking criteria are the same as those specified in Clause 943 for performance specified HRA surfacing and are easily met by all the binder course materials used in the trials including the high value (rut depth of 6.3mm) recorded in Road Trial 1. The Vacuum RLAT criteria were determined from the trials and, again, all the measured results comply (highest value 1.18mm).

The Highways Agency has plans to introduce Stone Mastic Asphalt as a binder course material and a draft clause has already been prepared, based on the Wheel Tracking Test.

The maximum air voids of binder course, except when placed under HRA, shall be less than 7 and 8 per cent, respectively for mean (6 results) and individual values. Under HRA, the normal air voids values of 8 and 9 per cent shall apply.

6.3 Application of proposed specification

The proposed surfacing specification is only intended to be applied to roads which are exposed to a reasonably high risk of surface rutting. The criteria established for use with the HRA performance specification Clause 943 are a reasonable basis for deciding to which pavements the specification should apply. The trials have shown that the standard macadam binder course materials can easily reach a high level of deformation resistance, superior to Class 2, Clause 943 HRA surface course. This is without the assistance of any special binders or types of aggregates. When properly formulated and laid, conventional macadam materials provide satisfactory binder course performance, therefore it is not appropriate to change standards from current levels. A lowering of specification criteria will not result in any cost savings and the need to raise them has yet to be demonstrated. For the present, a single standard of deformation performance is proposed, as detailed in Table 6.2.

Table 6.3 indicates the traffic levels and other circumstances controlling whether or not the specification should apply. In circumstances where the specification does not apply, the nominal properties of the binder course are deemed to be sufficient.

7 Benefits

There are benefits in specifying asphalt by performance criteria for all parties who are involved with the UK highway network, from the infrastructure owner, to the

Table 6.3 Sites where surfacing specification should apply (based on TABLE NG 9/33 from Volume 2 of the SHW)

		Traffic at design life (commercial vehicles per lane per day)				
Site category	*Site definition*	*Up to 250*	*251 - 500*	*501 – 1000*	*1001 - 1500*	*> 1500*
I & II						
A	Motorway (main line)					
B	Dual carriageway (all purpose) non-event sections					
D	Dual carriageway (all purpose) minor junctions					
C	Single carriageway non-event sections					
E	Single carriageway minor junctions					
IA & IIA						
As I and II, above, but with contraflow anticipated during summer months						
III						
F	Approaches to and across major junctions (all limbs)					
G1	Gradient 3 per cent to 10 per cent, longer than 50 m:	Clause 929 only			Clause 929 and Wheel tracking or Vacuum RLAT	
L	Dual (uphill and downhill)					
	Single (uphill and downhill)					
	Roundabout					
IIIA						
As III, above, but with contraflow anticipated during summer months or in a south-facing cutting uphill						
IV						
G2	Gradient steeper than 10 per cent, longer than 50 m:					
	Dual (uphill and downhill)					
	Single (uphill and downhill)					
IVA						
As IV, above, but with contraflow anticipated during summer months or in a south-facing cutting uphill						
V						
J/K	Approach to roundabout, traffic signals, pedestrian crossings, railway level crossings and similar					

construction industry and, ultimately, to the road user.

The development of CEN Standards, which will be implemented in 2003, has involved the harmonisation of national standards for a wide range of materials. The first phase has been the harmonisation of essentially recipe-based standards and it is expected that some measure of performance will be introduced in the next phase. As well as generic standards for materials, European Technical Approvals (ETA) for proprietary materials will be developed, which will be similar to the HAPAS developments in the UK.

The potential benefits of a performance-based system are manifest in various ways, and consideration of the relevant values of each of the parties can be split into:

- Ensuring quality.
- Obtaining best value.
- Reduction in roadworks.
- Encouragement of innovation.

These benefits, distributed between the infrastructure owner, the construction industry, and the road user, are shown in summary in Table 7.1.

Such potential benefits have already been partially realised for roadbase materials (Nunn and Mercer, 1996) with the introduction of performance-based specifications, firstly on a trial basis and then more widely with the introduction of stiffness testing in Clause 944 of the Specification for Highway Works in 2001.

7.1 Ensuring quality

When describing the performance required of any construction material, and using a test method that directly relates to that performance, the Infrastructure Owner/Manager is provided with a quality benchmark. This gives a direct assurance that the quality of materials and associated workmanship are likely to achieve the performance required. This has a number of secondary benefits to the clients, suppliers and users of the infrastructure.

Objective measurement of performance

Current recipe specifications can lead to a conflict between Client and Contractor during construction when materials fail to comply with recipe requirements but at the same time appear ‘fit for purpose’. The availability of suitable performance test methods has provided an objective measure of material performance and thus should reduce the number of ‘acceptability’ disputes during the construction process.

Table 7.1 Summary of potential benefits

Quality	*Economy*	*Innovation*	*Environment*
Road user			
Reduced delays and accidents. Smoother and more consistent ride. Improved reliability of journey time.	Better use of available road funds.	The road user will benefit from the new solutions that this form of specification encourages.	Less congestion at roadworks resulting in reduced traffic emissions. Encourages sustainable development.
Infrastructure owner			
Improved performance of surfacing designs. High consistency of surfacing. Reduces contractural risk. Improved public image.	Ensures value for money Performance criteria can be changed to match circumstances. Less maintenance. Easier to compare technical merits of competing bids.	Encourages innovation.	Road management can be carried out in a manner that is less harmful to the environment.
Construction industry			
Reduces contracual risk. Provides an objective measurement of performance. Improved public image.	Clear basis for alternative bids. Reduces risk of defects. Potential to reduce material production costs.	Rewards innovation and encourages industrial research initiatives.	Removes barriers to the introduction of 'alternative' materials. Encourages sustainable solutions. Reduced material haulage.

Improved performance of surfacing designs

Results from the PTF trial demonstrate that the performance criteria recommended will produce a marked increase in the service life of the surface courses over the traditional recipe mix designs. This is an obvious benefit to the infrastructure owner if it can be shown to be cost effective, see Section 7.2.

Improved consistency of performance

The design of materials using performance-based criteria should improve the consistency of material and lower the risk of early-life defects occurring. Any problems with materials are likely to be identified and rectified before the construction has been completed. This will result in saving on early-life maintenance.

7.2 Obtaining best value

There is increasing emphasis on the Infrastructure Owner providing a ‘best value’ solution. This is considered in ‘whole-life’ terms rather than just the initial capital costs of carrying out the works. The future is likely to see other, non-financial indicators, such as environmental and sustainability factors used to help indicate the best value solution. The definition of materials by their performance will help to consider projects in this way.

Developing optimum solutions

Although this work has focused on providing high performance materials for some of the UK’s most heavily trafficked roads, the principles of the performance specification can obviously be extended to all road types. In future, the use of a performance-based system with less severe and more focussed acceptance criteria could be used on roads with lower traffic levels. This would ensure that the design of all surface courses is appropriate to their design traffic levels, thus guarding against ‘over-design’.

Transfer of risk

Various developments in highway construction contracts during the last five years have transferred the risks of highway construction and maintenance away from Central Government to Partnerships, Design and Build (DB) and Design Build Finance and Operate (DBFO) projects. A performance-based specification provides another tool with which to transfer this risk, initially to the Contractor and ultimately to the Material Supplier. Thus suppliers who can best quantify this risk by detailed knowledge of material behaviour are in a position to profit from taking this risk.

Allows development of sustainable solutions

Increasing focus on the need to provide ‘best value’ solutions in terms other than financial has already been identified for the Construction Industry and the need to provide ‘sustainable’ solutions is often raised. The introduction of a performance-based specification will encourage sustainable solutions to be developed, through recycling and a reduction in the amount of virgin material required during the life of the road, while ensuring there is no loss in performance.

Encourages maximum utilisation of constituents

The greater freedom available in mix design based on performance will allow the Industry to develop materials that, whilst achieving the required performance, produce the minimum amount of waste.

Potential decrease in Whole Life Costs

Longer lasting surfacings will incur reduced maintenance and consequent traffic delays at roadworks will help to reduce the whole life cost of asphalt roads.

7.3 Reduction of roadworks

For the Road User, the key aspect of performance is network availability. The performance-based specification developed has the potential to increase the life of surfacing materials beyond that expected of traditional recipe mixes. This has the effect of reducing the amount of maintenance work required during the life of the road.

Reduced traffic delay and congestion

An obvious advantage of a reduction in roadworks during the life of the road is the resulting reduction in traffic delays for the road user and associated traffic congestion during the works.

Reduced fuel consumption and reliable journey times

The reduced occurrence of roadworks means that, on average, each journey will require less fuel to complete, thus reducing energy consumption and pollution. The road user would also have the benefit of a more reliable journey time from this more consistent level of service.

Reduced accidents

The presence of roadworks has been shown to increase the risk of accidents occurring. There are a large number of factors involved in assessing the risk; road type, traffic level, weather, time and length of closure etc. Previous work, reported in TRL Project Report 37 (Hayes and Taylor, 1993), showed the increases in personal injury accident rates for motorways, dual and single carriageways to be 57%, 14.5% and 170% respectively, when roadworks were present. A performance specification that leads to an extended life of surfacing materials will reduce the amount of roadworks required during the life of the road and, in turn, reduce the risk of accidents throughout the life of the road.

Since 1993, the valuation of road traffic accidents has been based on a consistent ‘willingness to pay’ approach, this is described in detail in TRL Report 163 (Hopkin and Simpson, 1995). DETR have used this methodology to develop values per accident (DETR, 1998) and an average value was found to be £61,710 for all classes of road (based on 1997 data and 1997 prices). This average is very close to the value reported for Motorways alone of £65,820 per accident. The reduced need for resurfacing will result in shorter total duration of roadworks in a given period and a consequent reduction in the numbers and costs of accidents.

7.4 Encouraging innovation

A performance-based specification is a key step to giving greater freedom to the Construction Industry in the design of materials. Its introduction will assure the Infrastructure Owner that the required performance will be achieved without constraining the industry to use specific materials defined by narrow restrictive specification clauses.

Rewards innovation

Providing a ‘benchmark’ of performance provides an incentive for the Construction Industry to develop materials that either out-perform that benchmark or offer other advantages whilst achieving the benchmark. Materials and construction techniques that offer reduced noise generation, improved ride quality or high long-term skid resistance, whilst conforming to the specification developed in this work, will provide the Infrastructure Owner with a premium product at an appropriate market rate.

Opportunity to reduce costs

Knowledge of the performance to be achieved give the Construction Industry, and more specifically the material supplier, the opportunity to rationalise the way in which the materials are produced from any particular source. Establishing the performance of ‘non-standard’ mixes may allow optimisation of production to reduce the amount of material processed and the consequent waste generated.

Promotes alternative solutions

The performance specification is a vital tool in the development of alternative solutions. For example, the use of non-standard materials which fall outside current specifications, will be encouraged if it can be shown that they comply with or exceed the performance criteria. This allows the Industry to suggest design alternatives, supported by objective measurements of material performance, and thus gives greater confidence that these alternatives will be acceptable to the Infrastructure Owner.

8 Implementation

There are no overriding difficulties for the implementation of a performance-based surfacing specification. The controls for the surface course are now largely in place. The introduction of Clause 943 Class 2 HRA has ensured that premature rutting resulting from traditional HRA under adverse high temperature and traffic will not occur in the future. Also type approval of proprietary thin surfacings through HAPAS is resulting in a new generation of rut resistant surfacings.

The outstanding requirement is now to ensure that the deformation resistance and the permeability of the binder course is adequately specified. There is no reason why the proposed elements of the specification described in this report cannot be introduced almost immediately.

The Wheel Tracking Test (BS 598, Part 110), can now be implemented for the binder course while the Vacuum RLAT may have to await a final version of the draft standard. If this version of the test is significantly different to that used in the trials the deformation criteria may need to be reviewed.

In view of the significant periods between laying material and obtaining test results, and the difficulties this creates for quality assurance, it may be preferable to commence the implementation process by applying the specification only to the approval of the job mixture. Testing of laid material might be reserved only for situations where there was substantial deviation from the approved job mixture.

9 Conclusions

1 The investigations have shown that:

- rutting of fully flexible pavements is generally confined to the top 100 mm of the pavement. Even under the more demanding conditions of current traffic, the asphalt layers deeper in the pavement are not at high risk of rutting;
- improved material specifications are required for the surfacing to reduce the risk of future rutting that could result from the increased use of wide-base single tyres, slower vehicle speeds and a possible trend towards warmer summers. This is especially the case for the binder course in which higher traffic induced shear stresses will result from thin surface courses now being widely used.

2 The trial of rut-resistant pavement design solutions in the TRL accelerated pavement test facility (PTF) showed that:

- the wide-base single tyre produced substantially more rutting compared with dual tyres and that material sensitivity to deformation is exaggerated with wide-base single tyre. On the four pavements with innovative surfacing, the wide-base single produced ruts 50% deeper than those produced by the dual wheels;
- excluding the control section (traditional HRA surface course), the binder course contributed an average of approximately 40 per cent of the surface rut depth for both types of tyre.
- no single laboratory deformation test was found to correspond consistently with the material behaviour in the PTF. However, the wheel tracking test and the repeated load asphalt test with vacuum confinement both gave a reasonable indication of performance.

3 The full-scale road trials demonstrated that:

- The views of the Contractor and Supervisor of the draft performance-based specification were generally positive. The participants acknowledged the practicability of the proposed specification and that it would assist in ensuring adequate deformation resistance of the surfacing. A long turn-round time for the test results was experienced with these trials. This problem would normally be solved at the beginning of a contract.
- The ranking of the deformation of the materials indicated that the wheel tracking test and the repeated load asphalt test with vacuum confinement was not as consistent as that obtained in the TRL Pavement Test Facility trial.

4 The main features of the performance-based specification for the surfacing layers are:

- appropriate criteria are included to prevent unacceptable deformation occurring in the surface course and binder course as a result of aggressive traffic and high pavement temperatures;
- deformation control is best implemented by testing zones in the road. These zones are the top 50 mm of the pavement and the depth between 50 and 100 mm. This is a practical solution for dealing with surface courses of varying thickness;
- the wheel tracking test and the repeated load asphalt test with vacuum confinement are both suitable for inclusion in the performance-based specification. However as the wheel tracking test is currently used in Clause 943 of the Specification for Highway Works and it is recommended that this test with suitable criteria is adopted in the by the performance-based specification;
- porous asphalt and some thin surfacings are permeable. The impermeability of the pavement is assured by imposing a maximum air voids content requirement on the layer beneath the surface course.

5 The introduction of a performance-based specification for the surfacing will ensure that the roads built to withstand the more demanding conditions likely to be encountered in the future will have good rut resistance. It will also provide a framework in which the criteria can be adjusted to suit specific conditions or additional criteria can be added, for example, for the reduction of tyre-generated noise.

10 Acknowledgements

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11 References

Addis R R (1992). *Vehicle wheel loads and road pavement wear.* Heavy vehicles and roads: technololgy, safety and policy. London: Thomas Telford.

Addis R, Vos E, Hahn W and Glaeser K-P (1999). *COST334: Effects of wide single and dual tyres.* Brussels: 2nd European Road Research Conference: COST 334 Workshop. June 1999.

Bonaquist R (1992). *An assessment of the increased damage potential of wide-based single tires.* Nottingham: Proceedings of the 7th International Conference on Asphalt Pavements.

Booth R E (1961). *Monthly and annual maps of mean daily temperatures.* Climatological Memorandum No. 43. Bracknell: The Metereological Office.

Child S M (1997). *Rolled asphalt surface courses*. Asphalt Surfacings (Editor J C Nicholls), Chapter 5. London: F & N Spon.

Corté J-F, Brousseaud Y, Simoncelli J-P and Caroff G (1994). *Investigation of rutting of asphalt surfacing layers: Influence of binder and axle loading configuration.* Transportation Research Record No. 1436. Washington DC: National Academy Press.

COST Action 333 (1999). *Development of a new bituminous pavement design method.* Brussels: European Commission, Directorate General Transport.

Curtis C R (1997). *The impact of performance specifications on British practice.* Leeds: Proceedings of the second European symposium on the performance and durability of bituminous materials, (Ed. J G Cabrera)

Department of the Environment, Transport and the Regions (1998). *1997 Valuation of the benefits of prevention of road accidents and casualties*. Highway Economics Note No.1. London: Department of the Environment, Transport and the Regions.

Department of Transport, Scottish Office Industry Department, The Welsh Office and the Department of the Environment for Northern Ireland (1994). *Design Manual for Roads and Bridges. Volume 7 Pavement Design and Maintenance, Section 3 Pavement Maintenance Assessment, Part 3 Structural Assessment Procedure HD30/94.* London: The Stationery Office.

Department of Transport (1996). *Lorry weights - a consultation document.* London.

ESSO (1983). *ESSO road design technology*. London: ESSO Petroleum Company Ltd.

Forsgate J A (1971). *Tables of temperature frequency distributions in flexible road pavements.* Technical Note TN608. Crowthorne: TRL Limited.

Franken L and C Claauwaert (1987). *The characterisation and structural assessment of bound materials for flexible road structures.* Washington: Proceedings 6th International Conference on the Structural Design of Asphalt Pavements.

Frith B A, Haliday A and Smith R (1997). *Heavy goods vehicle effects including lane distribution: Final report and recommendations.* Project Report PR/TT/138/97. Crowthorne: TRL Limited. *(Unpublished report available on direct personal application only)*

Government Statistical Service (1998). *Vehicle speeds in Great Britain.* Department of the Environment, Transport and the Regions, Statistics Bulletin (99)17.

Hayes M R and Taylor P J (1993). *A review of the accident risks associated with major road works on all-purpose dual carriageway roads*. Project Report PR37. Crowthorne: TRL Limited.

Highways Agency, Scottish Office Development Department, The Welsh Office and the Department of the Environment for Northern Ireland (1998). *Manual of Contract Documents for Highway Works. Volume 1, Specification for Highway Works.* London: The Stationery Office.

Hopkin J M and Simpson HF (1995). *Valuation of road accidents.* TRL Report TRL163, Crowthorne: TRL Limited.

Hopman P, Nilsson R and Pronk A (1997). *Theory, validation and application of the visco-elastic multilayer program VEROAD.* Seattle: 8th ICAP, Vol I.

Huhtala M, Pihlajamaki J and Miettinen V (1992). *The effect of wide-based tyres on pavements.* Heavy vehicles and roads: technology, safety and policy. London: Thomas Telford.

Highways Agency (1995). *Rolled Asphalt Wearing Course (Performance-Related Design Mix).* Draft Specification Clause 943. London: Highways Agency.

Jordan P G and Still P B (1982). *Measurement of rut depths in road surfaces by the TRRL high-speed profilometer.* Laboratory Report LR1037. Crowthorne: TRL Limited.

Leech D and Nunn M E (1997). *Deterioration mechanisms in flexible roads*. Proceedings 2nd European Conference on Performance and Durability of Bituminous Materials. Leeds: University of Leeds.

Mercer J and Nicholls J C (1997). *Binder Requirements for Performance-Related Specification of Rolled Asphalt.* 2nd European Symposium on Performance and Durability of Bituminous Materials, University of Leeds (Editor J G Cabrera). Zurich: Aedificatio Publishers.

Ministry of Transport (1960, 1965 and 1970). *Road Note 29: A guide to the structural design of flexible and rigid pavements for new roads, 1st, 2nd and 3rd editions*. London: The Stationery Office.

Nishizawa T, Shimeno S and Sekiguchi M (1997). *Fatigue analysis of asphalt pavements with thick asphalt mixture layer.* Seattle: 8th ICAP, Vol II.

Nunn M E (1994). *A question of fatigue?* First European symposium on performance and durability of bituminous materials. Leeds: University of Leeds.

Nunn M E (1985). *Prediction of permanent deformation in bituminous pavement layers.* 3rd Eurobitume Conference. The Hague.

Nunn M E, Brown A J, Weston D J and Nicholls J C (1997). *Design of long-life roads for heavy traffic.* TRL Report TRL250. Crowthorne: TRL Limited.

Nunn M E, Brown A J, Lawrence D J (1999). *Assessment of practical tests to measure deformation resistance of asphalt.* 2nd European Symposium on Performance and Durability of Bituminous Materials, University of Leeds (Editor J G Cabrera). Zurich: Aedificatio Publishers.

Nunn M E, Lawrence D J and Brown A J (2000). *Development of a practical test to assess the deformation resistance of aspha*lt. Barcelona: 2nd Eurasphalt and Eurobitume Congress.

Nunn ME and Mercer J (1996). *Experience of a performance specification in motorway strengthening.* Euraspahlt and Eurobitume Congress 1996.

Nunn M E and Merrill D (1997). *Review of flexible and composite pavement design methods.* Published Article PA328. Crowthorne: TRL Limited.

Owen D R J and Hinton E (1980). *Finite elements in plasticity: theory and practice.* Swansea: Pineridge Press, Swansea.

Powell W D, Mayhew H C, Potter J F and M E Nunn (1984). *Design of bituminous pavements.* Laboratory Report LR1132. Crowthorne: TRL Limited.

Rowe G M and Brown S F (1997). *Fatigue life prediction using visco-elastic analysis*. Seattle: 8th International conference on Asphalt Pavements.

Sebaaly P E (1992). *Pavement damage as related to tires, pressures, axle loads and configurations.* Vehicle, Tire, Pavement Interface, ASTM STP 1164 (Henry and Wambold, Eds). Philadelphia: American Society for Testing and Materials.

Sebaaly P E and Tabatabaee N (1995). *Influence of vehicle speed on dynamic loads and pavement response.* Transportation Research Record TRR 1410. Washington: Transportation Research Board.

Schmorak, N and van Dommelen A (1995). *Analysis of the structural behaviour of asphalt concrete pavements in SHRP-NL test sections.* Prague: International Conference*: SHRP and Traffic Safety*.

Shell International Petroleum Company (1978). *Shell pavement design manual*. London: Shell International Petroleum Company Ltd.

Society of Motor Manufacturers and Traders (1995). *The UK commercial vehicle market review, 1994.* London: Society of Motor Manufacturers and Traders Ltd.

Thrower E N, Dougill J and Mortazavi S (1986). *Methods for predicting permanent deformation for flexible pavements.* Contractors Report CR38. Crowthorne: TRL Limited.

Van der Loo (1976). *A practical approach to the prediction of rutting in asphalt pavements.* Symposium on predicting rutting in asphalt concrete pavements. Washington DC: Annual meeting of the Transportation Research Board. January 1976.

Weissman S L and Sousa J B (1996). *An elastic constitutive law for asphalt-aggregate mixtures*. Flexible Pavements (Editor: Gomes Correia*).* Rotterdam: Balkema.

Witzak M W, Quintus A B and Schwartz C W (1997). *Superpave support and performance models management: Evaluation of the SHRP performance models system.* Seattle: 8th International Conference on Asphalt Pavements.

Wu F (1992). *Assessment of residual life of bituminous layers for the design of pavement strengthening*. Ph D Thesis, Wales: The Polytechnic of Wales.

Appendix A: The role of binder course

A1 Introduction

There is now a fairly clear understanding of the performance requirements of asphalt surface courses and roadbases and there are practical tests to measure key properties. However, the purpose of the binder course and its performance requirements are not well defined. It appears to be perceived as superior roadbase but strongly associated with the surface course. In many instances, the binder course as well as the surface course has been found to have deformed and contributed to rutting.

Currently, Section HD 26/94 of the Design Manual for Roads and Bridges (DMRB) (Department of Transport *et al.*, 1994) only requires a binder course in pavements where porous asphalt is used as the surfacing. In all other fully flexible pavements, the inclusion of a binder course is optional but the basis of deciding whether or not to use it is not clear.

This appendix presents an extensive review and assessment of the requirements for binder courses. A summary of French and German binder course practices, and a comparison of these with UK practice is also presented.

In order to obtain an indication of recent binder course practice, a questionnaire was sent out to a number of asphalt construction companies asking for information on the types and thicknesses of recently laid surfacing (surface course and binder course). The views of the contractors on the ease of laying of the various systems were also requested.

The term *binder course* was once used in the UK for the layer beneath the surface course, and is still so used in the USA and by other authorities when translating their documents into English. (The German term for this layer is Binderschicht.) However, since the 1950s and until recently, the most usual UK term has been *basecourse*. In the USA, the use of the term binder course is understandable as the roadbase is called *base course*. The term *binder* appears to relate to the function of binding the surface course to the lower structural layers. In old or very thin construction, where the structural layers were unbound, this function was probably very important. However, in modern asphalt pavements, designed to carry heavy traffic, there may be four or even five courses all of which are assumed to *bind* to each other. The property of binding is a feature of all asphalt layers, not just the binder course or baescourse.

A2 Development of binder course

A2.1 The 'dawn' of modern practice

An early publication on general British roadworks practice (Spielmann and Elford, 1934) describes a number of typical pavement constructions including 'asphalt (single-coat)' and 'asphalt (double-coat)'. The five, two-coat constructions cited comprise top courses of 25 mm placed on a *bottom (binder) course* of 50 to 75 mm. The *bottom (binder) course* appears to be the equivalent of binder course, at least in the context of wet-mix macadam roadbase pavement. The term basecourse was not in use at this time.

The top coats consisted of more or less obsolete materials such as mastic asphalt, clinker asphalt and stone filled asphalt. The bottom (binder) courses consisted of asphalt macadam or clinker asphalt. All five of the asphalt (double-coat) constructions were intended to be used to upgrade existing unbound macadam pavements and were placed directly on them after re-shaping and rolling. In this context, the term *binder course* seems justified as it is binding the new surfacing to the old, re-shaped construction. No explicit comment was made on the role of the *binder course*. However, the authors mention that there was debate over the roles of the components of the pavement structure including whether the top course should merely provided a suitable running surface, supported by the foundation (equivalent to modern roadbase) or should also contribute to the load spreading capacity of the road structure.

As the pavement structures of this period are so different from those of today, it cannot be assumed that the 'bottom (binder) course' was the forerunner of modern binder course rather than additional roadbase (or foundation in 1930s terminology).

A2.2 Pre-motorway period

Twenty-eight years later the Road Research Laboratory publication Bituminous Materials in Road Construction (Road Research Laboratory, 1962), defined binder course as *a layer in the surfacing of a road pavement immediately below the surface course*. Slightly different statements of binder course function were made in respect of coated macadam and rolled asphalt binder courses. For coated macadam the purpose was stated as:

- The binder course plays a major part in distributing traffic stresses before they reach the road base;
- It often performs the additional function of a regulating course to enable a better riding quality to be achieved on the final surface.

When using rolled asphalt binder courses the purpose was:

- The binder course provides a regular, tightly-bound and mechanically stable surface over the foundation of the road on which the surface course may be laid and compacted without difficulty.

Both open- and close-textured (dense) macadams were in use but the close-textured material was preferred for its superior load spreading ability and was recommended in cases where the binder course was laid on granular material. The close-textured material was not much used until the publication of the first edition of Road Note 29 (Road Research Laboratory, 1960) with the general introduction of dense bitumen macadam.

The following conclusions are drawn:

- Considering the wide variety of dense- and open-textured, crushed rock and flint gravel, bitumen and tar bound materials used, binder course properties must have been very variable.
- The stated functions of the binder courses of this period would be achieved by almost any modern DBM or HRA binder course or roadbase.

A2.3 Road Note 29 period

The three editions of Road Note 29 spanning 1960 to 1970 (Road Research Laboratory, 1960, 1965 and 1970) and the Transport Research Laboratory (Croney, 1977) grouped the binder course and surface course together and designated them collectively as *surfacing*. Possibly this is a relic of the 1930s when these two courses were the only asphalt courses or it implies some mutual interaction. Croney defines the functions of surfacings as:

i to reduce roadbase stresses to an acceptable level;

ii to keep water out of the materials below;

iii to provide satisfactory riding quality;

iv to provide satisfactory skid resistance.

The binder course would be expected to contribute to the first three functions. In the stress reducing role, it is not clear whether the binder course was intended primarily, to act simply as an additional thickness of roadbase, reducing the tensile stresses (and strains) at the bottom of the roadbase or, that the binder course was expected to resist the higher shear stresses near the road surface more effectively than roadbase material. The rich DBM or HRA binder courses then in use would be less permeable than DBM roadbase. Providing an extra course of material will enable the small surface tolerances to be more easily achieved.

Croney cites the results of trials involving different surfacings and HRA and dense coated macadam and concludes that there was a slight advantage in using HRA binder course but the advantage reduced on stronger subgrades. However, these trials involved only 38 mm of surface course on 42 mm of binder course on unbound wet-mix roadbases, subjected to only a maximum of 3.3 million standard axles. The performance of such light construction would depend markedly on limiting stresses in the unbound roadbase and preventing moisture ingress. Modern DBM roadbases are far more robust, impermeable and less moisture susceptible.

The binder course materials in use in the late 1960s and early 1970s included rolled asphalt, dense bitumen or tar macadam and open-textured coated macadam. The latter material was intended for low trafficked roads only, and was specified by recipe and compaction method. The gradings and nominal binder contents are almost identical with current BS4987 specifications (British Standards Institution, 1993) summarised in the next section. The binder content was rich, when compared to similar material used as roadbase, and would have assisted compaction and resulted in an almost impermeable binder course. However, Croney states that 40 mm maximum size material would be used in 65 to 75 mm thick courses and 28 mm in 50 to 65 mm courses which would be considered very oversized for the course thickness, by current standards.

A2.4 Period following the introduction of LR1132 (1984 onwards)

This period extends from 1984 when LR1132 (Powell *et al.*, 1984) was published up to the present time. In LR1132 binder course and surface course are combined and referred to as surfacing. In the flexible pavement design chart, surfacing and roadbase thicknesses are combined but kept separate from the roadbase in the flexible composite or granular roadbase designs. There is no comment on the function of binder course.

In the second and third editions of the Design and Performance of Road Pavements (Croney and Croney, 1991 and 1998) the definitions of binder course functions stated in the first edition (Croney, 1977) no longer appear and the binder course is simply noted as being the lower course of surfacing.

The binder course materials are little changed from the previous period and are described more fully in the next section.

A2.5 Comments on binder course development

- Current pavement types, materials and traffic conditions are very different to those existing when the concept of binder course or base course were introduced.
- Considering the wide range of asphalt materials which have been used as binder course, performance must have been very variable. The only consistent and definite effect of this layer is to separate the surface course from the roadbase.
- No clear reason has been found for the perception that the binder course is an essential component of the surfacing. The term *surfacing* may once have referred to all the asphalt layers laid on the unbound roadbase. An effective surfacing can be achieved with a rolled asphalt surface course laid directly on reasonably even roadbase.
- The requirement for the binder course to contribute structurally and be able to resist deformation is largely unrecognised.

A3 Current binder course practice

A3.1 Definitions

The current British Standard Glossary of building and civil engineering terms (British Standards Institution, 1992a) perpetuates the Road Note 29 practice in the following definitions for binder course and related courses:

Surfacing	That part of the pavement above the roadbase. *(Note. It normally consists of a surface course and binder course or a surface course only.)*
Surface course	Part of the surfacing, the surface of which is in contact with the traffic.
Binder course	Course forming part of the surfacing immediately below the surface course.
Roadbase	One or more layers of material placed above the sub-base that constitute the main structural element of a flexible or a composite pavement.

These definitions state little more than the order in which these courses are placed and, with the exception of the roadbase entry, avoid attempts to define the function or nature of the layers.

For comparison, the Draft CEN TC227 equivalent terminology (Personal communication) is as follows:

Surface course	The upper layer of the pavement which is in contact with the traffic.
Binder course	The part of the pavement between the surface course and the base. *(A binder course is not always used.)*
Base	The main structural element of a pavement.

The CEN view is that the binder course (binder course) is not an integral part of the surfacing, but a separate, optional layer. However there is no indication of its function or the circumstances when it is required.

A3.2 Mix requirements

The mixes are specified in BS594:Part 1, BS4987:Part 1 (British Standards Institution, 1992b and 1993) and Clauses 905 and 906 of the Specification for Highway Works (Highways Agency *et al.*,1998). The British Standards materials include rolled asphalt, dense bitumen macadam and open graded macadam. However the last material is not included in the Specification for Highway Works. The constituent materials, grading envelopes and nominal binder contents are specified on a recipe basis in BS594 and BS 4987 and are summarised in Table A1.

The rolled asphalt binder course mixes are also specified for use as regulating courses and roadbase. Similarly, the 28 and 40 mm dense binder course (DBM) gradings are identical to the 28 and 40 mm DBM roadbase mixes which are also specified in BS 4987. The only differences are the binder course binder contents which are 1.0 and 0.7 per cent greater than for the 40 and 28 mm roadbase mixes, respectively. This is presumably to achieve greater impermeability in the binder course.

For Highways Agency works, the DBM binder course mix is also controlled by Clause 929 of the Specification for Highway Works (SHW) which requires that the minimum air voids in the material compacted to refusal is greater or equal to 1.0 per cent. This requirement dates only from 1993 and also applies to the roadbase. Prior to this only the BS4987 requirements applied to both materials.

The Clause 929 voids requirement will usually require a reduction in binder content from the BS4987 recipe values, which may increase permeability. Despite the clear intention of BS4987 to provide richer and impermeable DBM binder course mixes the effect of Clause 929 results in binder course and roadbase mixes of very similar properties.

A3.3 Compaction and level tolerances

The compaction requirements for all rolled asphalt courses are defined in BS594:Part 2 and Clause 901.13 to 901.18 of the SHW and are method-based. Due to the high fines and binder content the material is easily compacted to produce low voids and low permeability.

The compaction requirements for all macadam courses are defined in BS4987: Part 2 and in Clause 929 of the SHW and are end-result based. Prior to 1998 the compaction standard for binder courses was that the average Percentage Refusal Density (PRD) of sets of six measurements should not be less than 93 per cent. The air voids in the compacted material could occasionally be

Table A1 Summary of binder course specifications

Mix designation	*Maximum aggregate (mm)*	*Bitumen content[1] (%)*	*Constituent materials*
Rolled asphalt (BS 594: Part 1, 1992) Group 1 - roadbase, binder course and regulating course[2]			
50/14[3] (Col.2/2)	**14**	**6.5**	35, 50, 70 or 100 pen bitumen
50/20 (Col.2/3)	20	6.5	35, 50 or 70 pen lake asphalt-bitumen
60/20 (Col.2/4)	20	5.7	Crushed rock, slag or gravel
Coated macadam – dense binder course (BS 4987: Part 1, 1993)			
Tables 11/12	40	4.5	50, 100 or 200 pen bitumen
Tables 13/14	28	4.7	C50 or C54 tar
Tables 15/16[4]	**20**	**4.7**	Crushed rock, slag or gravel
Coated macadam - 20mm open graded binder course (BS 4987: Part 1, 1993)			
Tables 5/6/7	20	4.0 C[6]	100 or 200 pen bitumen
		3.8 L[6]	C34, C38 or C42 tar
			Crushed rock, slag or gravel
Coated macadam – 40mm single course[5] (BS 4987: Part 1, 1993)			
Tables 8/9/10	40	3.9 C[6]	100 or 200 pen bitumen
		3.6 L[6]	C34, C38, C42 or C46 tar
			Crushed rock, slag or gravel

[1] Binder content for crushed rock. Other aggregate types require different amounts.
[2] Only the mixes appropriate for a 60mm thick course are shown.
[3] Preferred mix.
[4] Preferred mix and the most common mix in practice.
[5] The single course may be used as a combined surface course and binder course or just as binder course.
[6] C = Crushed rock, excluding limestone.
L = crushed limestone

quite high. For example, if the refusal air voids were 3 per cent and an individual PRD value was 92 per cent, the voids in the laid material would be 11 per cent. However, generally macadams are less porous than this as mean values are around 96 to 97 per cent and individual PRD values seldom fall below 93 per cent.

In 1998 the Clause 929 compaction standard was revised and is now based on the air voids of the laid material. The average air voids of consecutive sets of 6 nuclear density gauge measurements must not exceed 8.0 per cent and the average air voids of a pair of cores at the same location must not exceed 9.0 per cent. This represents a significant improvement in the control of air voids and indirectly, permeability. Clause 929 also specifies that, when placed under porous asphalt, the macadam binder course the air voids criteria are one per cent lower at 7.0 and 8.0 per cent.

The level tolerances and permitted surface irregularities of the various pavement layers are detailed in Clause 702.2 of the Specification for Highway Works (Highways Agency *et al.*, 1998). Level tolerances for pavements with and without binder course are as follows:

	With binder course	*Without binder course*
Road surfaces	±6 mm	±6 mm
Binder course	±6 mm	–
Roadbase	±15 mm	±8 mm
Sub-base	+10 mm –30 mm	+10 mm -30 mm

The numbers of permitted surface irregularities for Category A roads, as measured by the TRRL rolling straightedge, are as follows:

Irregularity	*4 mm*		*7 mm*	
Length	*300 m*	*75 m*	*300 m*	*75 m*
Number of irregularities				
Road surface	20	9	2	1
Binder course or top of road base when base course is absent	40	18	4	2

There are no irregularity limits for the top of roadbases in pavements with binder courses. For lengths less than 75m there are 3m straightedge requirements compatible with the table above.

Assuming that the level tolerances are *just* achieved at all levels, the contractor must apply his main effort to control levels, at or below the binder course, in both situations. In the *with binder course* situation, the final surface has only to maintain the tolerance already achieved on the binder course and in the *without binder course* situation only a slight improvement of 2 mm must be achieved. In the *with binder course* situation, a major improvement must be made during the laying of the binder course, possibly more than could reasonably be expected without wire guidance. In both cases, the effort to achieve the surface course or binder course tolerances must commence in the first course of the roadbase and be sustained through each subsequent course.

For surface irregularities the situation is different. If the number of surface irregularities are *just* achieved it is evident that a significant improvement is required when laying the surface course in either binder course situation. When a binder course is not used, it may be more difficult to achieve the standard for the upper roadbase if this is substantially thicker than normal binder course (60 mm). Even if the pre-rolled surface is near-perfect, subsequent rolling will compress the layer thickness by a fixed proportion of its thickness, and result in a profile reflecting the irregularities of the layer below but with reduced amplitude.

Achieving the irregularity standards should not be too difficult provided that non-complying irregularities at the top of the third layer are not excessive. McLellan (1982) reports that irregularities can be reduced by approximately half for each course laid, with level control by means of an averaging beam.

A3.4 Application of binder courses

HD 26/94 (DMRB 7) (DoT, 1994) which deals with new pavement design, states that the inclusion of a binder course is optional under HRA surface course but is mandatory under porous asphalt surface course. The 1996 revision of this standard also requires that a binder course, either HRA or macadam, is required under porous asphalt surface course. No statement is made on the need for a binder course with other, thinner types of surfacing which are increasingly being used.

HD 27/94 (DMRB 7) (DoT, 1994) requires that porous asphalt is laid on an *impermeable* binder course or existing surface course, presumably to prevent water within the porous asphalt from penetrating any deeper. However, as discussed above, macadam binder courses compliant with SHW Clause 929 and BS4987 may not always be impermeable.

HD 26/94 also requires that binder course used over HDM or DBM 50 roadbase shall be formed from the same material. This is a consequence of the standard pavement thickness design chart being based on total asphalt thickness. Such binder courses should be more deformation resistant than 100 pen materials, as well as being stiffer.

A3.5 Comments on current binder course practice

- Current macadam binder course materials are similar to those used in roadbases, except that, because of the reduced course thickness, the maximum particle size of the binder course is reduced. In addition the binder contents are higher.
- The standard definitions of flexible pavement courses require clarification.
- The introduction of voids controls in 1993 should have considerably improved binder course deformation resistance.
- The change to density control based on air voids in 1998 should have reduced binder course permeability.
- The evidence from most surface rutting investigations is that a significant proportion of the deformation arises in the binder course. In heavily trafficked situations the

existing mix specifications may not be adequate; limitations on what material or grade of binder is permissible may need to be revised.

- In situations where thin surfacings are being considered, more deformation resistant binder course material may be needed as it will be subjected to higher shear stresses and temperatures than with traditional construction.
- Some thin surfacings are not impermeable and may need to be laid on low permeability binder courses to prevent moisture penetrating the pavement.

A4 European and USA practice

A4.1 General

As the origins of British binder course practice and the purpose of this layer were not very clear, European and USA binder course practice was briefly examined to see if this would assist in achieving a better understanding. The CEN TC227 terminology, mentioned in Section A3.1, recognises binder course, but not as part of the surfacing. Establishing the degree of similarity of practice in other countries with that of Britain was also thought to be useful. Germany, France and USA were chosen because of their general climatic similarity and because it was known that binder courses are used to some extent and that the design documents were readily available.

A4.2 France

The French design guide for road pavements (LCPC and SETRA, 1997) states that the pavement surfacing consists of a surface course and possibly a binder course (couche de liaison). However, the purpose of the binder course is not defined but there is considerable discussion of the four objectives for selecting the surface course in terms of evenness, skid resistance, drainability, impermeability, noise and future maintenance. It is mentioned that the binder course may complete or provide impermeability, particularly in cases where permeable surface courses are used. Total thicknesses of surfacing (surface and binder courses) are reported as ranging from 60 to 140 mm depending on traffic and type of construction. Typical binder course thicknesses are reported as 50 to 70 mm but greater thicknesses may be chosen in order to achieve satisfactory rutting resistance, particularly if the surface course is very thin. The most frequently used binder course materials are high modulus asphalt (béton bitumineux à module élevé - BBME, NF P 98-141) and thick asphalt (béton bitumineux semi-grenus - BBSG, NF P 98-130). The BBME and BBSG are also used as surface courses and are specified in detail by the French Standards Association (AFNOR, 1995). The standards include wide-ranging criteria covering aggregate grading and type, mix strength and stiffness, wheel-tracking, fatigue and complex modulus. The same criteria apply to both surface course and binder course for each material. BBME is specified in three grades and has the most demanding requirements. The voids in the compacted material range from 4 to 9 per cent.

The requirement for the binder course to have the same standard of performance as the surface course recognises that these courses may be subject to the same aggressive forces. However, setting the same numerical criteria may be conservative as, generally, the binder course is subject to lower temperatures and shearing stresses than the surface course. However, when thin or very thin surface courses are used, surface course standards for the binder course may be justified as this will be stressed almost as intensively as the surface course.

The same suite of aggregate and asphalt tests are used to specify the two principal French roadbase materials, high modulus asphalt (enrobé à module élevée - EME) and roadbase asphalt (grave bitume - GB), but with different numerical criteria. The EME roadbase stiffness criteria are at least as onerous as those for the BBME surfacing but, for the GB, the wheel-tracking requirements are less demanding than for either surfacing material. The maximum voids in the laid material range from 6 per cent for the Grade 2 EME to 13 per cent for the weakest grade of GB. The GB roadbase is similar to DBM made with 50 pen binder but with a smaller maximum aggregate size of 20 or 14 mm. It is unlikely that DBM would meet the French binder course requirements unless made from 35 pen binder, or harder.

French practice may be summarised as follows:

- Binder courses are generally used on the more heavily trafficked roads and where thin and very thin surface courses are used.
- The principal materials used in binder courses are two surface course materials, high modulus asphalt and thick asphalt (BBME and BBSG). The same structural, deformation and volumetric criteria apply to surface courses and binder courses.
- The binder course deformation criterion for the most deformation resistant binder course, BBME/C3, is much more onerous than those for GB roadbase and slightly more than for EME roadbase.
- There is no specific mention of binder course being required to achieve surface levels on the pavement surface. However, the wider use of high compaction effort pavers in France may make this less of a problem than in the UK.

A4.3 Germany

The German pavement design manual, RStO 86 (Road and Traffic Research Association, 1989), includes a binder course (Binderschicht) for all its asphalt surfaced pavements for medium to heavy trafficked sites (Classes SV and I to III). No specific reasons are given for the inclusion of binder course or its purpose. The standard thickness of this course is 80 mm except for the lightest traffic class for which 40 mm is specified. The normal thickness of the surface course is stated as 40 mm. However, where this is only 30 or 35 mm thick, for example, where stone mastic asphalt is used, the binder course should be thickened to provide a total surfacing thickness of 120 mm. The specification for binder course asphalt (Asphaltbinder) (Der Bundesminister für Verkehr, 1984) includes three similarly graded materials with 11, 16 and 22 mm maximum sizes. The coarsest of these has a grading similar to BS4987 20 mm DBM binder course except that the German grading contains a greater proportion of coarse aggregate. At least half of the sand fraction must be crushed material.

Binder course asphalt is specified by grading envelope, binder grade and range of binder content and Marshall voids. The bitumen grade is either 65 or 80 pen, although 45 pen may be used in special cases. The binder content ranges from 3.8 to 5.5 per cent and the precise value is determined on the basis of Marshall air voids. The limits for these are approximately 3 to 7 per cent, depending on the grading selected. The compacted density must be at least 97 per cent of the Marshall density. The voids in the compacted material would probably be 3 to 10 per cent. There are no requirements for strength, stiffness or deformation resistance.

The requirements for the binder course asphalt mixes are more demanding than the best of the asphalt roadbase mixes (Der Bundesminister für Verkehr, 1986) in having narrower grading envelopes and a smaller range of Marshall voids. However, a moderate level of Marshall stability (8 kN) and flow are specified for roadbase. The same bitumen grades (80, 65 and 45 pen), as used in the binder course, are also used in the roadbase.

There appear to be more similarities between German and British binder course material specifications than between French and British practice. The voids in the compacted material will probably be quite similar at approximately 7 per cent. Given the higher summer temperatures which occur over much of Germany, the use of relatively soft 80 and 65 pen binder is surprising. The more gap-graded German aggregate and the requirement for at least half the sand to be crushed may produce better deformation resistance than obtained with British binder course material. However, the adequacy of the German specification has been questioned. Tappert (1996) reported a motorway rutting failure caused by deformation within the binder course. It was claimed that 45 pen binder and 100 per cent crushed fines would have greatly reduced the problem. There does appear to be a case for either tightening the recipe component of the specification, with consequential cost increases, or of introducing a test to assess deformation resistance which may not necessarily lead to higher cost materials but to an adjustment of mix proportions.

German practice may be summarised as follows:

- The specification is essentially based on recipe. The criteria for selecting the grade of binder, which controls performance, are not evident.
- The binder course properties are probably less variable, including lower permeability than those of the roadbase because of the tighter grading envelope and the lower voids limit.
- The absence of a wheel-tracking, or similar, requirement results in uncertain deformation resistance of the binder course, particularly as the bitumen grade is not prescribed.

A4.4 USA

The Asphalt Institute (1995) describes the upper asphalt courses of a flexible pavement as follows:

- Surface course mixes must be designed to have sufficient stability and durability to both carry the anticipated traffic loads and to withstand the detrimental effects of air, water and temperature change.
- Binder course mixes are often used as an intermediate layer between the surface course and the underlying asphalt or granular base. (The USA term for roadbase is base.) Binder courses typically have a larger maximum size of aggregate of 19 to 38 mm and are often used interchangeably with base. Where heavy wheel loads are involved, binder course mixes can also be used as surfacing if a coarse surface texture is not of concern.

Asphalt mixes are specified in ASTM D3515 (American Society for Testing Materials, 1998). Aggregate grading envelopes and nominal binder contents are given for ‘dense’ mixtures and ‘open’ mixtures. The application of the first class is not stated but the second class is subdivided into two groups - base courses and binder courses, and surfacing and levelling courses. (In the USA ‘base course’ refers to roadbase.) The binder contents are purely nominal and the precise amount must be determined by appropriate testing or precedent. No test criteria are specified. Test procedures and criteria may have been established by some highway authorities, otherwise the Marshall or Hveem method of mix design described in MS-2 (Asphalt Institute, 1995) can be used.

The Asphalt Institute (1995) gives test criteria for both the Marshall and Hveem methods of design. For the Marshall method there are preliminary mix design criteria for stability, flow, air voids, voids in the mixed aggregate and voids filled with bitumen. The applicability of these to the binder course is unclear because despite the heading of the criteria table mentioning both surfacing and base courses, a footnote restricts the criteria to layers more than 100 mm from the road surface. For the Hveem method, the stabilometer value and swell are specified without any distinction between layers.

Separate from the mix design, the Asphalt Institute (1995) also gives some advice on the types of suitable binder for three different temperature ranges. The suggested binders range from 130 pen to 45 pen for the coldest to hottest climates but again there is no differentiation between layers. It is expected that many of the state or larger municipal highway authorities will have more specific requirements for binder and mix design requirements.

The Strategic Highway Research Program (SHRP) has produced a new improved method of mix design entitled SUPERPAVE (Kennedy *et al.*, 1994). This involves bitumen selection on the basis of local climate (performance graded binders) and assessment of mix compactability and voids at full compaction using a gyratory compactor. However, in common with the Asphalt Institute, the SUPERPAVE system does not make a distinction between the various pavement courses.

USA practice may be summarised as follows:

- Although the second layer of an asphalt pavement may be called a binder course, no particular functions are attributed to this layer, not even surface level regulation.

- Binder course material appears to be very similar to USA base course (UK roadbase) except possibly being of a smaller maximum size aggregate.
- The national specification appears to lack criteria to ensure that the risk of deformation of the binder course is minimised. Local specifications may be more demanding.

A4.5 Comments on French, German and USA Practices

- Both the French and German binder course specifications detail materials which are distinct from their roadbases and thus infer a different purpose for this layer within the pavement.
- The USA binder course specification is very similar to that of the USA base course (roadbase). American use of the term binder course for the second layer may simply be an attempt to harmonise with continental European practice.
- The French binder course materials are almost identical to surface course material and are comprehensively specified with demanding stiffness and rut resistance criteria.
- The German mix specification, based on recipe, is similar to the British but has a more limited range of material with smaller maximum sizes. The basis for the choice of binder grade is not evident.
- In some heavily traffic situations, the performance of the German binder course may be inadequate as a result of the relatively soft, binder grades (65 and 80 pen) and the lack of any performance requirement such as wheel-tracking.
- None of the specifications of the three countries mention any benefits in meeting surface levels by using a binder course.

A5 Binder course questionnaire

A5.1 Questionnaire

A questionnaire on current UK binder course practice has been sent to a number of asphalt construction companies and is summarised as follows:

Question 1: The first question asked for information on the upper courses of up to six recent schemes carried out by the company. The remaining questions asked for opinions relating to the necessity of binder courses.

Question 2: In pavements where a binder course is not included, do you find difficulty in meeting the level and regularity tolerances for the top of the roadbase?

Question 3: In pavements where a binder course is not included, do you find difficulty in meeting the regularity tolerances for the road surface?

Question 4: Do you consider that pavements without binder courses are as easy to construct as those with?

Question 5: Do you consider that the elimination of binder courses would assist construction, eg by reducing the number of types of asphalt required on a specific site?

Question 6: Any further comments?

A5.2 Responses

The thirteen responses received are summarised in Table A2. Each responding company is identified by a number. A suffix letter has been used where more than one response was received from one company. The main findings are as follows:

- About two thirds (29 out of 45) of the paving schemes detailed, included conventional binder courses. (Question 1)
- Continuously graded material (DBM or HDM) was the most common binder course material accounting for 27 out of 29 cases, the other two being HRA. (Question 1).
- Of the continuously graded binder course, 50 pen binder was used in 16 out of 27 cases, the remainder being 100 pen. With one exception, the binder course binder grade matched that of the roadbase. In the one exception, 50 pen binder course was used over 100 pen roadbase. (Question 1)
- Approximately three quarters of the 45 schemes were surfaced with HRA and the rest with a stone mastic (SMA) material. There was one instance of porous asphalt. (Question 1)
- A majority of the respondents (8 of 13) considered that without a binder course there were problems in achieving the surface levels of either the roadbase (± 8 mm) or the surface course (± 6 mm). (Questions 2 and 3)
- However only 5 out of 13 considered that the overall construction was made more difficult by the exclusion of a binder course. (Questions 4 and 5)

The three respondents who considered that there were problems in achieving surface levels without a binder course but felt that a binder course was unnecessary had only experienced problems in achieving the tighter top of roadbase levels and not those of the surface course. They and others believed that levels could be improved by limiting the maximum thickness of upper roadbase to 100 mm, and in one case, 80 mm.

For schemes where no roadbase was included, the thicknesses of the upper roadbase (forming a binder course by default), varied considerably from 75 to 140 mm. However, not all the responders reported this thickness. It is possible that some of the positive or negative views on the need for a binder course were a reflection of experience with thick and thin roadbase.

A6 Redefinition of binder course

The functions of the courses or zones of flexible pavements should be redefined in terms of current knowledge of pavement design and performance. In the absence of clear evidence of interaction between surface

Table A2 Summary of responses to binder course questionnaire

Responder	*Schemes with BC Q1*	*Type* of scheme Q1*	*Surface course (SC) material Q1*	*BC material Q1*	*Non-BC pavements: Achieving levels difficult on RB? Q2*	*Non-BC pavements: Achieving levels difficult on SC? Q3*	*Ease of construction with and without binder course Q4 / Q5*	*Responder's comments Q6*
1A	0 of 5	NT (5)	SMA (3) HRA (2)	–	No	No	Same	1. Including BC can be helpful in dividing up total roadbase into optimum thickness courses.
1B	3 of 4	NT (1) NM (3)	SMA (1) HRA (2) Unknown (1)	20 mm DBM 100pen (3)	No See comment	No	Same	1. Where there is no binder course, top layer of roadbase should be 80 mm thick, 28 mm aggregate.
2	1 of 1	NC (1)	HRA (1)	20 mm HDM (1)	Yes	Yes	More difficult without BC	1. Binder course important in achieving surface levels.
3A	Details not supplied				Yes	Yes	More difficult without BC	1. BC should be retained to ensure correct levels before WC. 2. More regular compaction on BC compared with RB.
3B	2 of 4	RT (3) NC (1)	HRA (4)	20 mm DBM 50pen (2)	No	No	Same	1. Assists construction by reducing the number of materials. 2. Where there is no binder course, top layer of roadbase should be 80 mm thick, 28 mm aggregate. 3. All major pavements should consist of HMB/DBM50/HDM roadbase with either Clause 943 HRA or thin surfacing.
3C	4 of 4	NT (1) NC (1) RT (2)	HRA (3) HRA/PA (1)	20 mm DBM 100pen (4)	No See comment	No	Same	1. Where there is no binder course, top layer of roadbase should be 80 mm thick, 28 mm aggregate. 2. Elimination of binder course does not assist construction. 3. Binder course provides a regular, impervious WC substrate which minimises wastage of high cost surfacing.
3D	Part of 1 of 2	NT (2)	HRA (2)	20mm DBM 100pen (1)	Yes See comment	No	Same	1. When no BC is used it is difficult to achieve levels at top of roadbase when upper roadbase is 100 mm or thicker.
3E	0 of 4	NT (4)	HRA (4)	–	Yes See comment	No	More difficult without BC	1. When BC is not used, achieving the top of roadbase levels requires a reduced thickness of upper roadbase and 28 mm rather than 40 mm aggregate . 2. Specs and designs for no-BC pavements may not reflect practical course thicknesses and aggregate sizes. 3. Binder courses favoured by all those involved in the practical aspects of pavement construction. 4. DBM rather than HDM binder course preferred to meet Cl. 702 as it is more 'forgiving' when laying cooler material.

Continued ....

Table A2 (Continued) Summary of responses to binder course questionnaire

Responder	*Schemes with BC Q1*	*Type* of scheme Q1*	*Surface course (SC) material Q1*	*BC material Q1*	*Non-BC pavements: Achieving levels difficult on RB? Q2*	*SC? Q3*	*Ease of construction with and without binder course Q4 / Q5*	*Responder's comments Q6*
4	5 of 5	RT (2) NT (1) RM (1) RT/NT (1)	HRA (4) SMA (1)	20mm HDM (4) 20mm DBM (1)	Yes See comment	No	Same Assists construction	1. Problems when top roadbase is thick or varies in thickness. 2. Top roadbase thickness should not vary or be greater than 100mm. 3. Modern electronic surfacing equipment should eliminate tolerance difficulties and allow abandonment of binder courses.
5A	3 of 3	RT (2) NC (1)	SMA (2) HRA (1)	20/28mm DBM (2) 20mm HDM (1)	No See comment	No	Same Assists construction	1. Less transport required without binder course. Time factor?
5B	2 of 2	RT (2)	HRA (2)	28mm HD DBM (1) 14mm HRA (1)	No See comment	Yes	More difficult without BC	1. More difficult to achieve FRL tolerances. 2. Deletion of BC speeds up construc tion but makes achieving levels more difficult.
5C	5 of 7	NT (3) NC (2) NM (1) RT (1)	HRA (5) SMA (2)	HDM and DBM50 (4) HRA (1)	Yes See comment	No	Same Does not assist construction	1. Use of high compaction screeds would assist in tolerance compliance. 2. Where traffic uses pavement prior to surfacing a binder course resists wear better than roadbase.
5D	4 of 4	NT (4)	HRA (3)	20mm HDM	Yes See comment	Yes	More difficult without BC	1. Fewer level and irregularity problems encountered when binder course is used. 2. Incompatibilities in level tolerances and thicknesses.
Summaries	29 of 45 schemes have BC	NT 22 NC 6 NM 4 RT 22 RM 1	HRA 33 SMA 11 PA 1	DBM (11) DBM 50pen or HDM (16) HRA (2)	7 of 13: RB level problems 4 of 13: WC level problems		5 of 13 responders: 'More difficult without BC'	–

**Scheme type codes:*				
	New	*Trunk roads = NT*	*County roads = NC*	*Municipal roads = NM*
	Rehabilitation	*Trunk roads = RT*	*County roads = RC*	*Municipal roads = RM*

course and binder course it is now more logical to consider the latter as part of the roadbase or possibly as a separate zone within the pavement. This merely reflects present practice where the second pavement layer is either a binder course, but with properties similar to those of a roadbase, or is explicitly specified as roadbase. It should be borne in mind that the full thickness of both binder course and HRA surfacing is included in pavement design, in Volume 7 of the Design Manual for Roads and Bridges (DoT, 1994).

A redefinition of the function of the binder course should recognise that this will vary depending on the thickness and nature of the surface course and the traffic intensity. The need for a binder course material differing from the rest of the roadbase will vary depending on circumstances. For example, for a pavement consisting of HRA surface course on HDM roadbase carrying moderate traffic, normal roadbase could be used as binder course. On the other hand a thin surfacing on standard DBM roadbase carrying heavy traffic might require 80 mm or more of HDM binder course of adequate rut resistance. Where porous asphalt or other permeable surface course are used, the binder course must be impermeable.

The following definitions of functions of layers in fully flexible pavements are suggested:

Surface course

The upper layer of the pavement, the surface of which is in contact with the traffic. Its primary function is to provide a surface with appropriate skid and rut resistance.

Note: It may also have significant load spreading properties by virtue of its thickness and stiffness. Usually the surface course will be impermeable and thus prevent moisture ingress to the underlying structure. When a permeable surface course is used, the binder course material must be impermeable.

Binder course

The upper layer of the roadbase on which the surface course is placed. In addition to spreading loads it must also possess adequate deformation resistance to withstand the high shear stresses near the pavement surface. Where permeable surface courses are used the binder course must be impermeable.

Note: Depending on the thickness of the surface course the binder course thickness will normally range from 60 to 100 mm.

Roadbase

The main structural element of a flexible pavement, which supports the surface course and rests on the sub-base. Its primary function is to spread loads so that neither the roadbase or the underlying foundation are overstressed.

Note: This is achieved by suitable selection of roadbase thickness and stiffness. The roadbase will be laid in several courses to facilitate compaction and level control, and includes the binder course.

Surfacing

This term shall apply to the combined surface course and binder course.

The second layer term *binder course* shall replace the term *basecourse*, that has been used traditionally for more than 60 years. This will be consistent with European terminology and a new term will help to focus attention on its new deformation resistance function. This choice is not in recognition of any binding action.

A7 Conclusions

i There is little evidence for the concept that a binder course is an essential part of flexible pavement surfacing. This perception appears to be a relic of past pavement practice where the surface course and binder course were the only asphalt layers in a flexible or flexible composite pavement.

ii The survey of Contractors' views on the usefulness of binder courses to achieve surface levels did not establish that it was essential to provide a binder course. However, it is clear that inclusion of a binder course or, alternatively, a top road base layer of 60 to 80 mm thickness, will assist in achieving surface levels.

iii Flexible pavement designs should assume that the total asphalt thickness will be sub-divided to provide a second course of 60 to 80 mm thickness but also allow contractors the option of dividing the total thickness into thicker layers.

vi The current standards for binder course material are not always adequate in providing deformation resistance under heavy traffic or impermeability under porous surfacing.

A8 References

American Society for Testing Materials (ASTM) (1998). *Annual book of ASTM Standards*, Vol. 04.03. USA: Conshohocken.

Asphalt Institute (1995). *Mix design methods for asphalt concrete and other hot-mix types.* MS-2, 6th edition. USA: Lexington.

Association Francais de Normalisation (AFNOR) (1995). *Enrobés hydrocarbonés, recueil de normes Francaise*. Paris.

British Standards Institution (1990). *Sampling and examination of bituminous mixtures for roads and other paved areas; Part 107, Method of test for the determination of the composition of design surface course rolled asphalt.* BS 598: Part 107: 1990. London: British Standards Institution.

British Standards Institution (1992a). *Glossary of building and civil engineering terms.* Highway engineering. BS 6100: Subsection 2.4.1: 1992. London: British Standards Institution.

British Standards Institution (1992b). *Hot rolled asphalt for roads and other paved areas; Part 1, Specification for constituent materials and asphalt mixtures; Part 2, Specification for transport, laying and compaction.* BS 594: Parts 1 and 2: 1992. London: British Standards Institution.

British Standards Institution (1993). *Coated Macadam for Roads and Other Paved Areas; Part 1, Specification for Constituent Materials and for Mixtures; Part 2, Specification for transport, laying and compaction.* BS 4987: Parts 1 and 2: 1993. London: British Standards Institution.

British Standards Institution (1996a). *Sampling and examination of bituminous mixtures for roads and other paved areas; Part 110, methods of test for the determination of the wheel-tracking rate of cores of bituminous surface courses.* BS 598: Part 110: 1996. London: British Standards Institution.

British Standards Institution (1996b). *Method for determining resistance to permanent deformation of bituminous mixtures subject to unconfined dynamic loading.* BS DD 226: 1996. London: British Standards Institution.

Der Bundesminister fur Verkehr (1984). *Zusätzliche technische vertragsbedingungen und rechtlinien für den bau von fahrbahndecken aus asphalt ZTV bit - StB 84.* (Additional technical contract conditions and guidelines for the construction of asphalt road surfacing.) Bonn.

Der Bundesminister fur Verkehr (1986). *Zusätzliche technische vertragsbedingungen und rechtlinien für den bau von tragschichten im strassenbau ZTVT - StB 86.* (Additional technical contract conditions and guidelines for roadbases in road construction.) Bonn.

Croney D (1977). *The design and performance of road pavements.* London: The Stationery Office.

Croney D and Croney P (1991). *The design and performance of road pavements.* London: McGraw Hill Book Company.

Croney P and Croney D (1998). *The design and performance of road pavements*. London: McGraw Hill Book Company.

Department of the Environment (1970). *Road Note 29: A guide to the structural design of pavements for new roads, 3rd edition.* London: The Stationery Office.

Department of Transport (1998). *Manual of Contract Documents for Highway Works.* Volume 1: Specification for Highway Works (MCHW 1). London: The Stationery Office.

Department of Transport (1994). *Design Manual for Roads and Bridges.* Volume 7, Pavement Design and Maintenance. London: The Stationery Office.

Highways Agency, Scottish Office Development Department, The Welsh Office and the Department of the Environment for Northern Ireland (1998). *Manual of Contract Documents for Highway Works. Volume 1, Specification for Highway Works.* London: The Stationery Office.

Kennedy T W, G A Huber, E T Harrigan, Cominsky R J, Hughes C S, von Quintus H and Moulthrop J S (1994). *Superior performing asphalt pavements (Superpave): The product of the SHRP asphalt research program.* Report SHRP-A-410. Washington: National research Council.

Laboratoire Central des Ponts et Chaussee et Service d'Etudes Techniques des Routes et Autoroutes (1997). *French design manual for pavement structures (English translation of the 1994 design manual).* Paris.

Manual for Contract Documents for Highway Works (1998). London: The Stationery Office.

Volume 1: Specification for Highway Works (MCHW 1)

Volume 2: Notes for Guidance on the Specification for Highway Works (MCHW 2)

McLellan J C (1982). *Pavement thickness, surface evenness and construction practice.* Supplementary Report SR706. Crowthorne: TRL Limited.

Powell W D, Potter J F, Mayhew H C and Nunn M E (1984). *The structural design of bituminous roads.* Laboratory Report LR1132. Crowthorne: TRL Limited.

Road Research Laboratory (1960, 1965 and 1970). *Road Note 29: A guide to the structural design of flexible and rigid pavements for new roads, 1st, 2nd and 3rd editions*. London: The Stationery Office.

Road Research Laboratory (1962). *Bituminous materials in road construction.* London: The Stationery Office.

Roads and Traffic Research Association (1989). *Guidelines for the standardisation of the upper structure of traffic bearing surfaces*. RStO 86. (In German). Cologne.

Spielman P E and Elford E J (1934). *Road making and administration.* Volume 1 of The Road Makers' Library. London: Edward Arnold.

Tappert A (1996). *Asphalt für schwerste Beansprungen - Schlussfolgeren aus praktischen Erfahrungen (Asphalt for the heaviest stresses - conclusions derived from practical experience).* Strasse und Autobahn, Part 11/96. Bonn: Kirschbaum Verlag.

Appendix B: Trial in the TRL pavement test facility

B1 Pavement layer test results

B1.1 Conventional tests

Conventional testing of the trial pavement layers was carried out and included grading, binder content, recovered binder properties, maximum density, air voids, percentage refusal density (PRD) and air voids at refusal. These tests showed that all the materials complied with either the standards specified in the Specification for Highway Works or the stated parameters of the proprietary materials and that the intended grades of bitumen had been used.

The binder contents were as expected and complied with the normal standards. The binder content (5.0 per cent) of the binder course in the control section was intentionally higher than that of the other binder courses to reflect the traditional richer binder courses.

The PRD values of the macadams from all sections were good and the mean values ranged from 97 to 100 per cent.

A summary of the binder and volumetric tests is given in Table B1.

Indirect tensile stiffness modulus (ITSM) tests were also carried out for general information and the results are presented in Figure B1. The stiffness values of the macadams are consistent with those measured on similar materials elsewhere. The stiffness of the Control Section HRA surface course is similar to that of conventional 100pen DBM binder course. The stiffnesses of the HRA surface course in Test Sections 1 and 2 are slightly higher.

B1.2 Deformation tests

Three different types of test to assess deformation resistance were carried out. These were:

- BS Wheel-Tracking Test (WTT) at 45°C and 60°C (BS 598: Part 110: 1998).
- Repeated Load Axial Test with Vacuum confinement (VRLAT) at 45°C (June 1998 version of BS DD 226:1996).
- A Dutch Triaxial Test (DTT) at 50°C (No formal standard).

The VRLAT test was carried out with a confining pressure of 50 kPa and an applied axial stress of 100kPa. For the HRA surfacing, binder course and roadbase material 50mm thick by 150mm diameter specimens were tested. The test specimens of SMA were about 30mm thick, the maximum which could be obtained. It was impractical to test the Thin Surfacing as the material was only 25mm thick.

The Dutch Triaxial Testing was carried out at the Delft University of Technology. The test method is still under development and there is no formal Standard as yet. The test is similar to the VRLAT and was carried out using the pneumatic Universal Testing Machine, from Australia. The test conditions were as follows:

- Nominally square waveform load application of 0 to 600 kPa.

Table B1 Summary of compaction and binder properties

Section	*Layer*	*Material*	*Density Mg/m³*	*Maximum density Mg/m³*	*Air voids %*	*PRD %*	*Refusal density Mg/m³*	*Air voids at refusal %*	*Binder %*	*Recovered properties*	
										Pen 0.1mm	*SP °C*
Control	SC	35/14 HRA (1)	2.318	2.377	2.5	–	–	–	6.9	37	57.0
	BC	20mm DBM 100	2.486	2.579	3.6	98.8	2.515	2.5	5.0	70	47.2
	RB (U)	28mm HDM	2.450	2.524	2.9	96.8	2.531	-0.3	4.3	39	55.6
	RB (L)	28mm HDM	2.480	2.533	2.1	98.8	2.511	0.9	4.5	38	57.2
1	SC	35/14 HRA (2)	2.340	2.377	1.6	99.4	2.355	0.9	–	40	61.4
	BC	20mm DBM 50	2.466	2.528	2.4	97.9	2.518	0.4	4.4	43	53.9
	RB (U)	28mm HDM	2.470	–	–	96.9	2.550	-1.0	–	–	–
	RB (L)	28mm HDM	2.509	–	–	99.2	2.530	0.1	–	–	–
2	SC	35/14 HRA (2)	2.318	2.387	2.9	–	–	–	6.7	37	65.0
	BC	20mm HDM	2.485	2.537	2.0	98.7	2.519	0.7	4.4	44	54.4
	RB (U)	28mm HDM	2.454	–	–	98.4	2.493	2.0	–	–	–
	RB (L)	28mm HDM	2.509	–	–	100.6	2.493	2.0	–	–	–
3	SC	SMA	2.318	–	–	–	–	–	5.4	–	–
	BC	20mm HDM	2.388	–	–	97.9	2.438	4.3	4.4	40	55.7
	RB (U)	28mm HDM	2.444	–	–	–	–	–	–	–	–
	RB (L)	28mm HDM	2.456	–	–	–	–	–	–	–	–
4	SC	Thin surfacing	–	–	–	–	–	–	4.2	–	–
	BC	20mm HDM	2.359	2.523	6.5	96.9	2.434	3.5	4.4	43	56.1
	RB (U)	28mm HDM	2.451	2.536	3.3	98.7	2.483	2.1	–	42	55.4
	RB (L)	28mm HDM	2.419	2.582	6.3	97.1	2.492	3.5	–	37	58.1

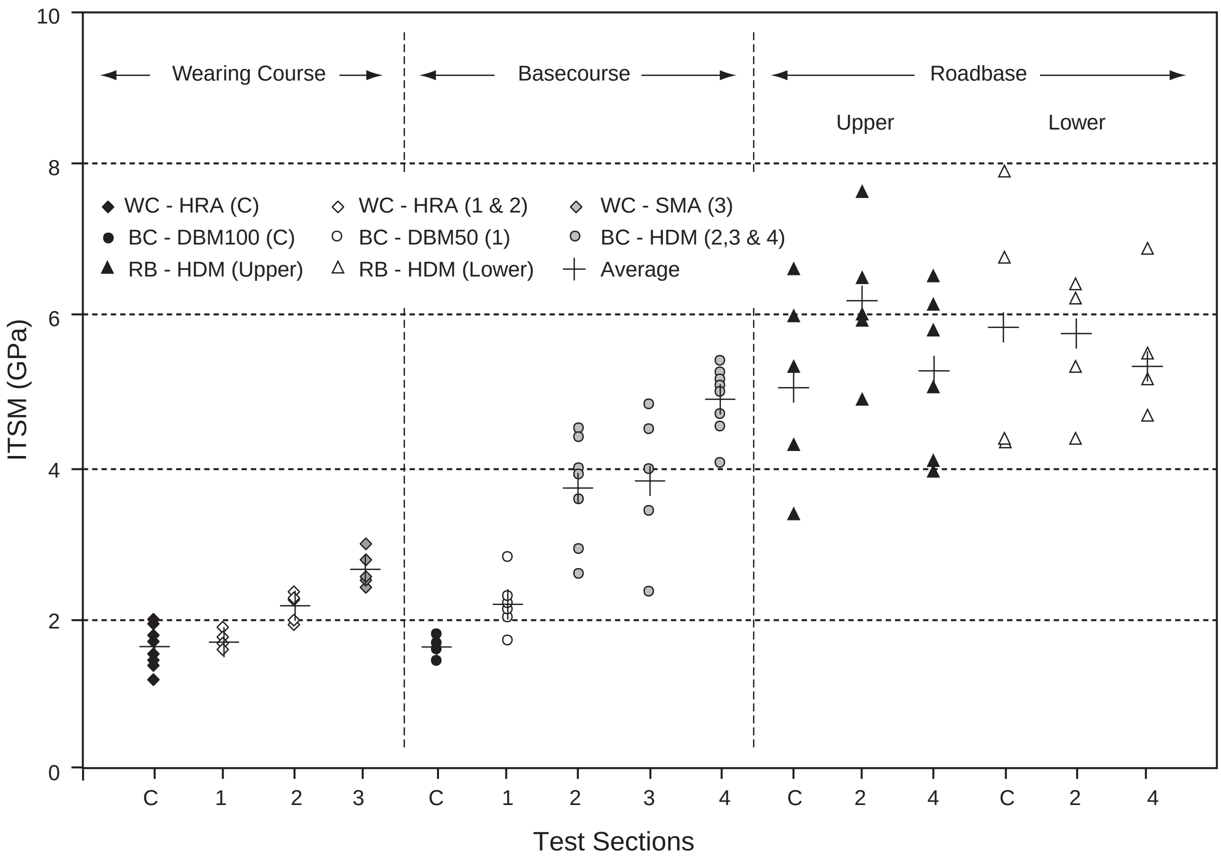

Figure B1 ITSM results

- Load pulse duration 0.2 seconds, rest period duration 0.8 second.
- 7500 load pulses are applied.
- Confining pressure of 100 kPa.
- Test temperature 50°C.
- Test specimens approximately 120mm thick built up from slabs of 150mm diameter cores.

The outputs from the test are the axial strain rate between 3000 and 6000 load pulses and the total axial strain after 7500 load pulses.

The main differences between this test and the VRLAT are the specimen dimension ratio, the higher frequency of load pulses, the greater proportion of rest time, and the much higher axial stress. All the materials except the thin surfacing were tested.

The Dutch Triaxial tests on the Control section HRA surface course could not be completed because the vertical strain in the compound specimen had reached 8.5 per cent, the limit of the apparatus, after only 2000 load repetitions and the test was terminated. The strain and strain rate values in the table have had to be extrapolated to 7500 repetitions and could therefore contain considerable errors.

The mean values of the deformation test results for each layer of each section are given in Table B2. Both the total deformation and rate of deformation are given although current expert opinion favours the former as the more reliable measure of in-situ deformation performance

From Table B2 it is evident that:

- The range of Rut depths for the WTT at 60°C is greater than that at 45°C for both total rut depth and rutting rate which suggests that the former are more discriminating.
- The DTT results covered an even larger range of values but this may have been affected by the estimated test values for the Control Section HRA.
- The DTT procedure is too aggressive for UK surface course materials as it does not allow the testing of conventional HRA. HRA is likely to be used and tested for some time.
- The 60°C WT and VRLAT data for the two sections of Class 2 HRA surface course show marked differences whilst those of the HDM binder course sections are reasonably similar.

The wheel-tracking results of the Control Section HRA, made with conventional 50 penetration grade bitumen, were close to the Clause 943 Class 1 requirements, as expected. Also, the Clause 943 Class 2 HRA in Section 1 does not quite meet the specified requirements, but that in Section 2 does.

B2 Rut development

B2.1 Depth with time

Figure B2 shows the average rut depth for all the trial sections and for the single and dual wheel tracks. Each data point represents the average of 7 wedge and

Table B2 Summary of deformation test results

			45 °C	BS Wheel tracking		60 °C	VRLAT (45°C)		Dutch triaxial (50°C)	
Test section	*Layer*	*Material*	*Rut rate (mm/hour)*	*Rut depth (mm)*	*Rut rate (mm/hour)*	*Rut depth (mm)*	*Strain rate (με/100c)*	*Strain (%)*	*Strain rate (με/cycle)*	*Strain (%)*
Control	SC	35/14 HRA	2.6*	**4.2***	13.3	**12.9**	125.8	**1.49**	30 *	**14 ***
1	SC	35/14 HRA (Class 2)	0.7	**3.1**	5.2 #	**8.1 #**	78.7	**1.19**	3.60	**6.03**
2	SC	35/14 HRA (Class 2)	1.2	**1.9**	4.0	**5.3**	42.0	**0.77**	–	–
3	SC	SMA	0.4	**2.0**	1.5	**3.3**	5.9	**0.26**	0.97	**3.06**
4	SC	Thin surfacing	0.9	**3.6**	1.7	**6.9**	–	–	–	–
Control	BC	20mm DBM (100pen)	0.2	**1.4**	0.9	**2.5**	15.5	**0.48**	0.13	**0.47**
1	BC	20mm DBM (50pen)	0.7	**1.9**	0.5	**2.6**	7.5	**0.18**	0.10	**0.39**
2	BC	20mm HDM	1.2	**3.2**	1.2	**3.6**	28.2	**0.43**	–	–
3	BC	20mm HDM	0.3	**1.6**	1.3	**3.5**	15.8	**0.28**	0.57	**1.71**
4	BC	20mm HDM	0.5	**1.7**	0.9	**3.1**	–	–	–	–
All	RB (U)	28mm HDM	0.5	**1.3**	0.5	**2.3**	83.5	**1.18**	0.53 +	**2.52 +**
Sections	RB (L)	28mm HDM	0.7	**1.8**	0.6	**2.4**	94.7	**1.48**	–	–

SC = Surface course
BC = Binder course
RB = Roadbase
U = Upper
L = Lower
** Almost meets Clause 943, Class 1 requirements # indicates marginal non-compliance.*
*** Denotes extrapolated values – refer to text.*
+ From Section 1 only.
All wheel tracking specimens were 50mm thick. SMA and Thin Surfacing test specimens include some binder course.

straightedge measurements (14 in the case of the longer Control Section) at 0.5m intervals along the wheel track. A number of features are evident:

- The rate of rutting of the wide base single wheel is greater than that from the conventional dual wheel. In the cases of Test Sections 1 to 4, the formation of a 10mm rut requires an average of 18,000 passes of the dual wheels but only an average of 8,000 passes of the wide base single wheels – an approximate doubling of the overall rutting rate.
- In all cases, with the exception of the Control Section, there is an initial high rate of rutting followed by a substantially lower rate. In the Control Section, the secondary rate continued to decrease throughout the remaining trafficking.
- The rut depth curves resulting from wide single tyres of Sections 1 to 4 show greater diversity than the dual wheel curves, which are fairly similar for Sections 1 to 4. This suggests that any material sensitivity to deformation is exaggerated with wide single tyres. This was also the conclusion of Corte at al (1995) after carrying out trafficking trials in the circular test track at LCPC.

Although 44,145 passes of the dual wheel were needed to produce a rut depth of only 10mm in all test sections, the single wheel-trafficking of the control section produced a rut depth of 24mm after only 13,170 passes and was terminated at this point. Consequently deformation comparisons between all the materials have been made at 13,170 wheel passes.

B2.2 Transverse profiles

A comparison of the average rut profiles at 13,170 wheel passes for each of the test sections is given in Figures 4.2 and 4.3 of the main report. The profiles from which these were derived are given in Figures B3a and B3a to B7a and B7b.

B2.3 Change in layer thickness

After the completion of trafficking in the PTF, 10 slabs, 1.2m x 0.5m were cut from the traffic lines of all four test sections. The locations coincided with the transverse profiles which had been monitored during the trafficking. The purpose of removing the slabs was to allow detailed measurement of the thicknesses of the pavement layers and, hence, determine the contribution of each to the surface rut. This was achieved by determining the difference between the reduced thickness of the layer, at the bottom of the rut, with the thicknesses at the ends of the slabs. As the thicknesses were measured at the end of the trial, after different amounts of trafficking, they were reduced to standard values at 13,170 passes in proportion to the total rut depths at this number of passes and the final value.

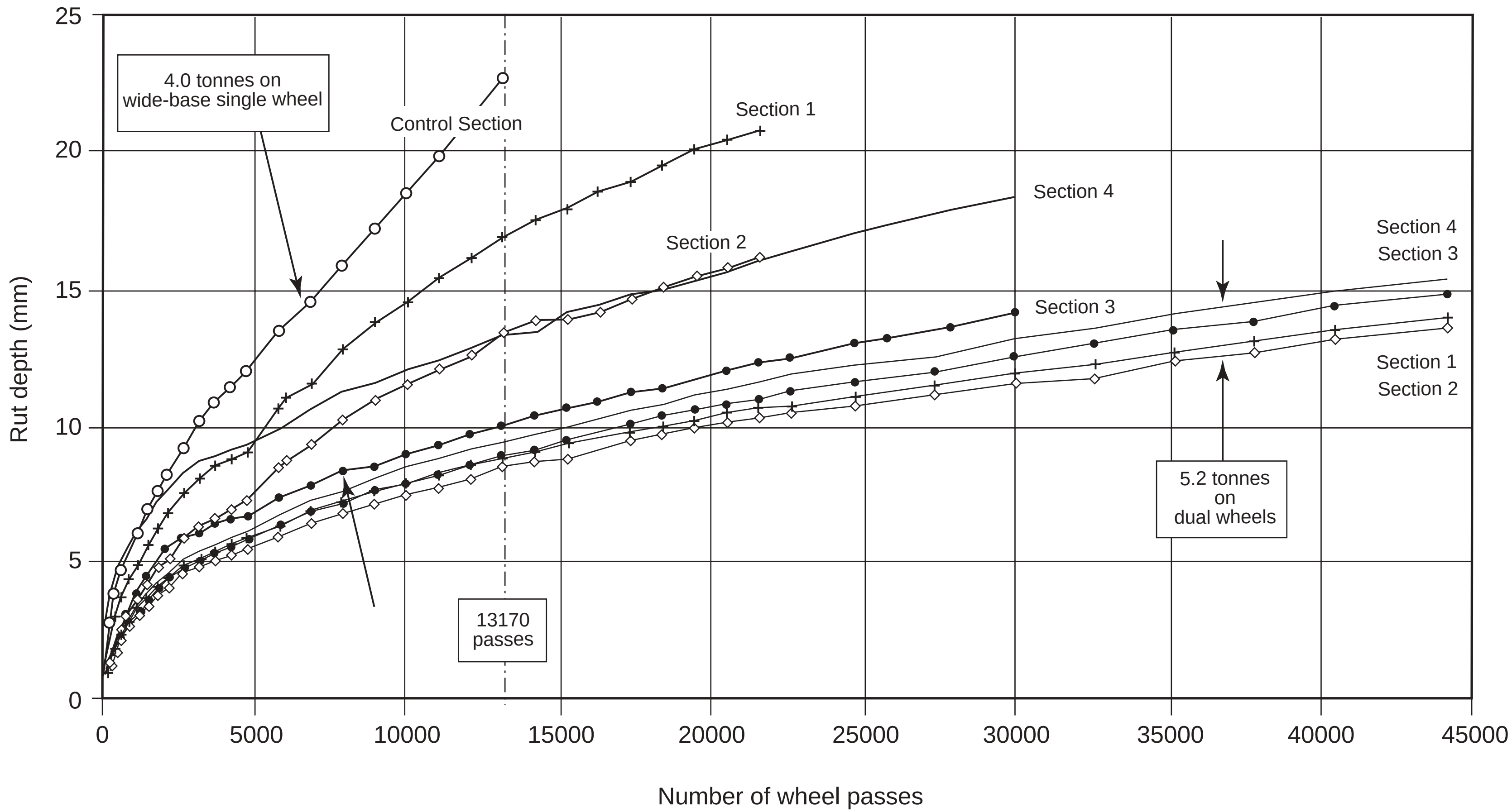

Figure B2 Rut depth versus wheel passes – single and dual wheels (wedge and straightedge measurements)

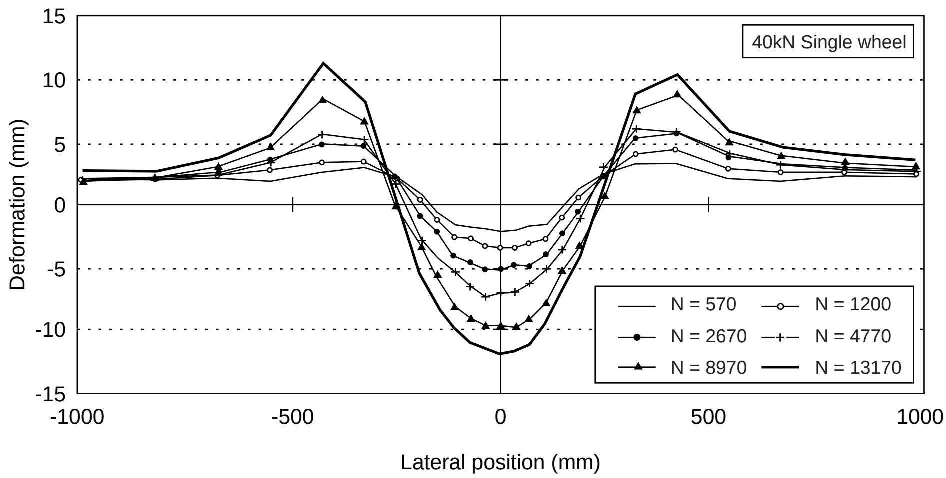

Figure B3a Control section (0-5m): Rut development

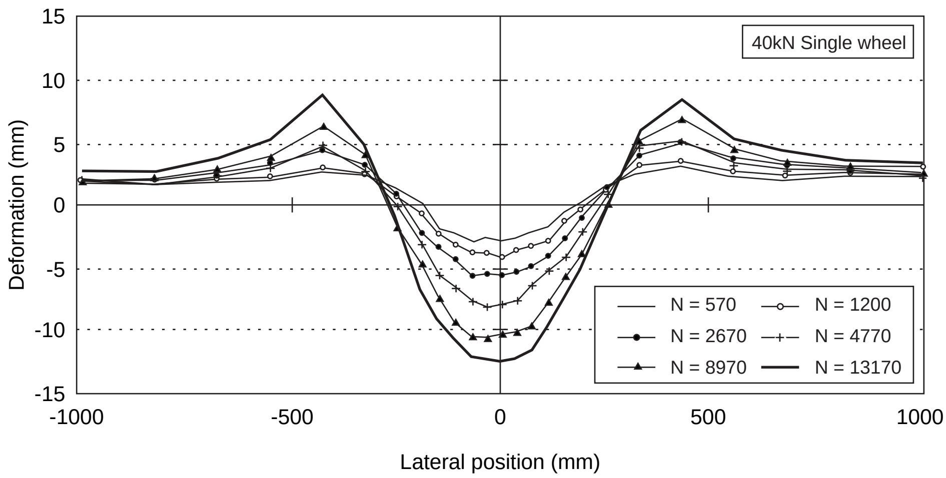

Figure B3b Control section (5-10m): Rut development

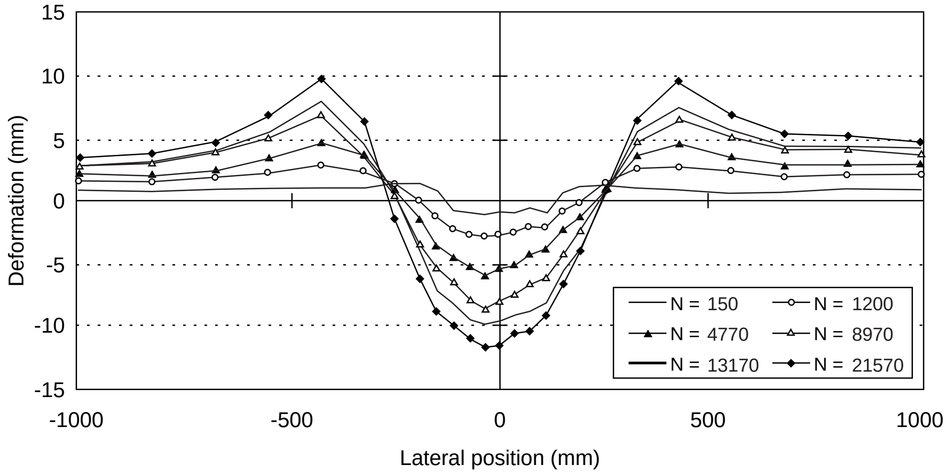

Figure B4a Section 1: Rut development – 40 kN single wheel

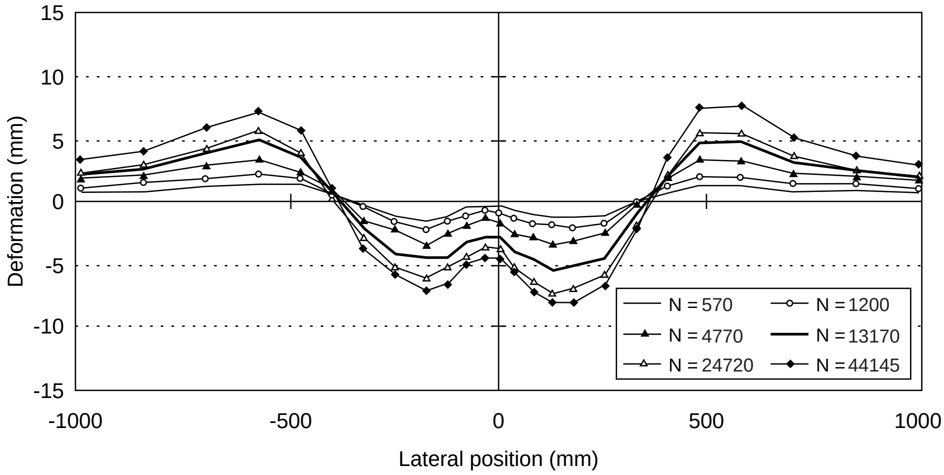

Figure B4b Section 1: Rut development – 52 kN dual wheel

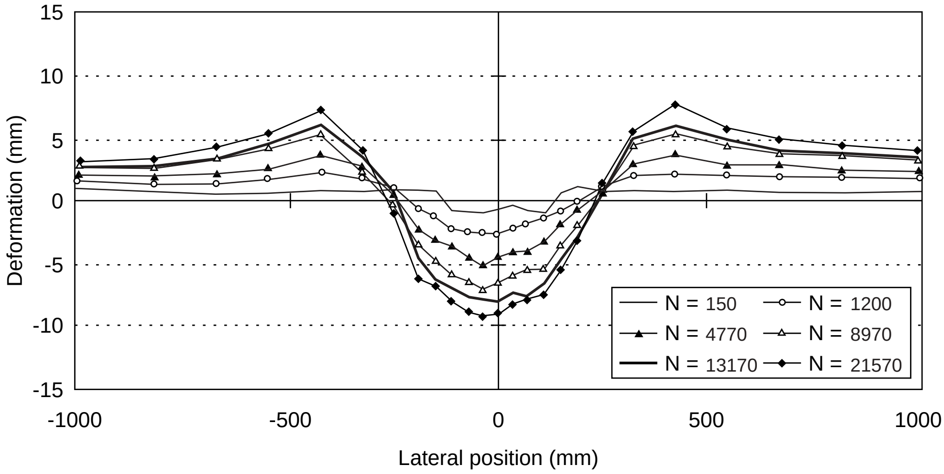

Figure 5a Section 2: Rut development – 40 kN single wheel

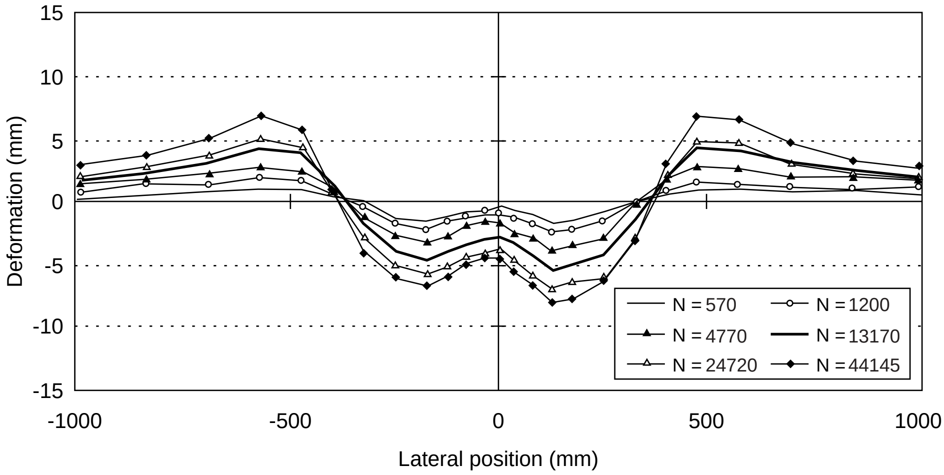

Figure B5b Section 2: Rut development – 52 kN dual wheel

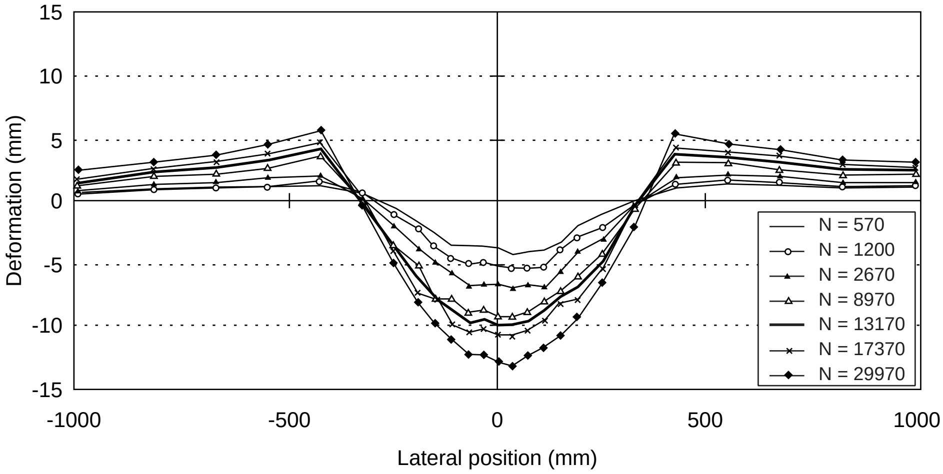

Figure B6a Section 3: Rut development – 40 kN single wheel

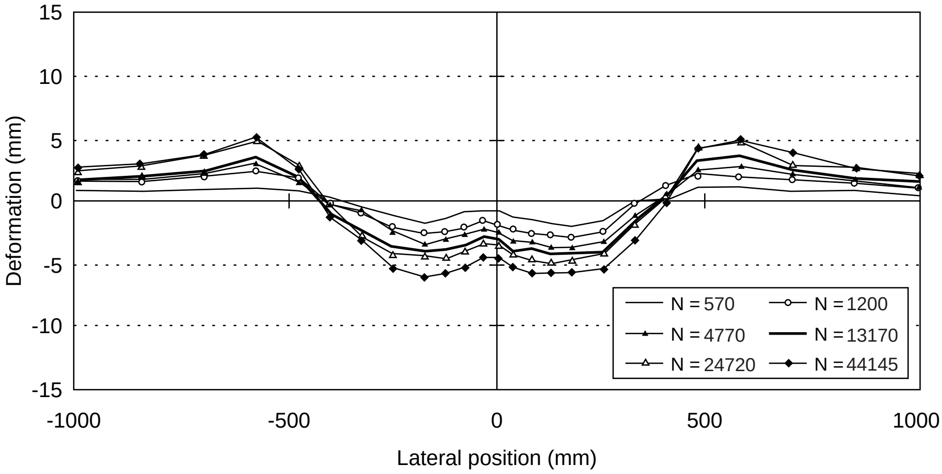

Figure B6b Section 3: Rut development – 52 kN dual wheels

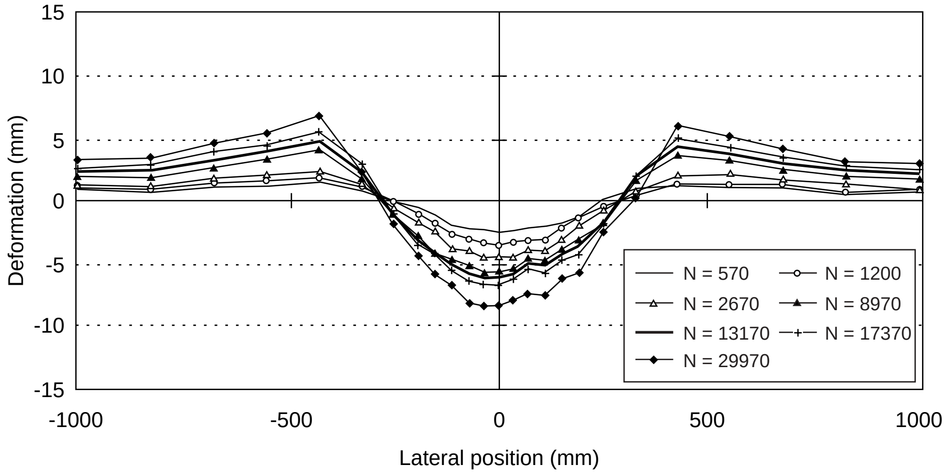

Figure B7a Section 4: Rut development – 40 kN single wheel

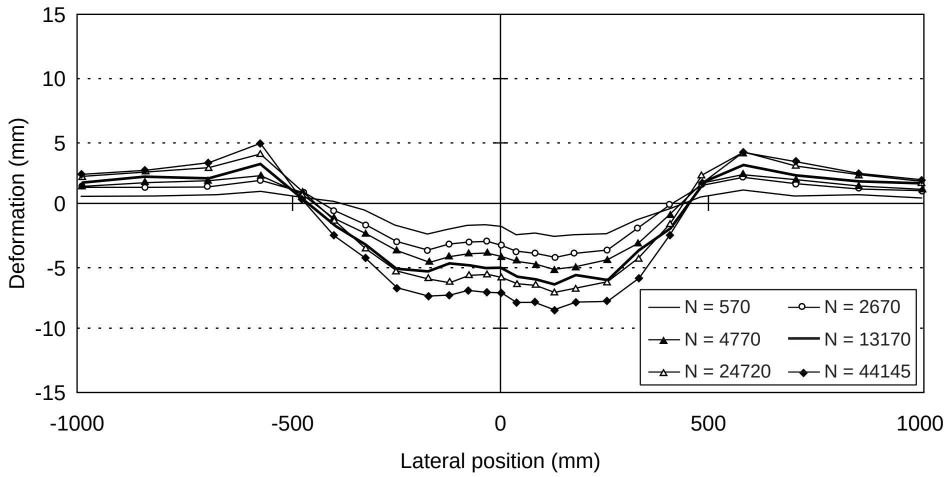

Figure B7b Section 4: Rut development – 52 kN dual wheels

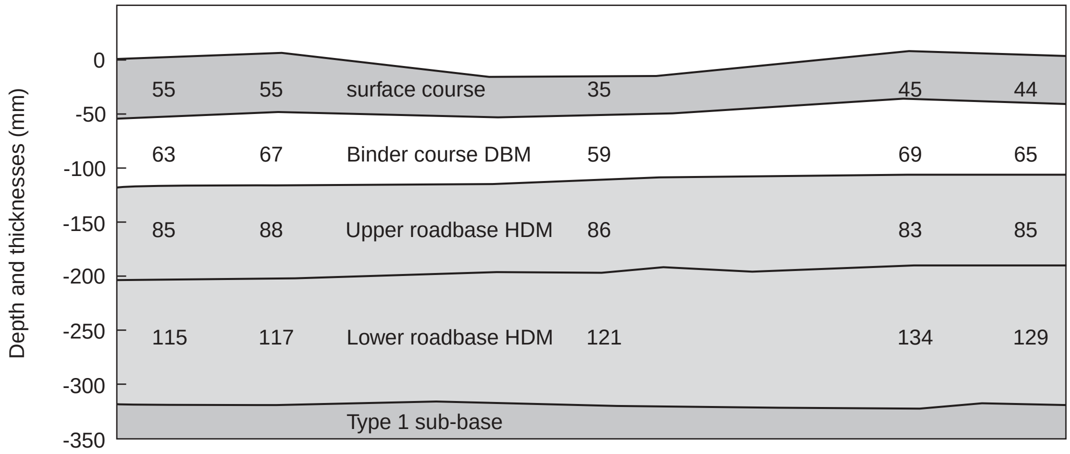

Figure B8 Control section: Layer thicknesses after 13170 passes – 40 kN single wheel

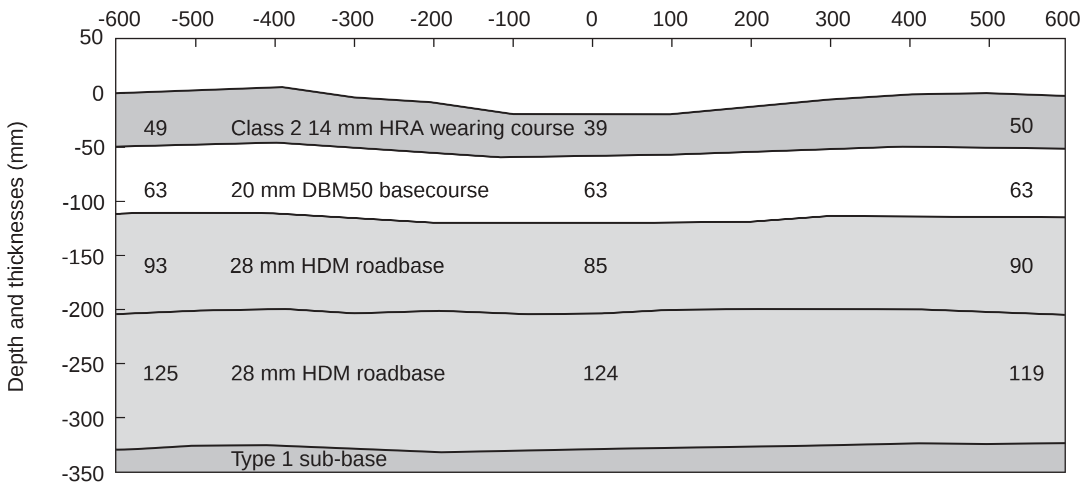

Figure B9a Section 1: Layer thickness after 21570 passes – 40 kN single wheel

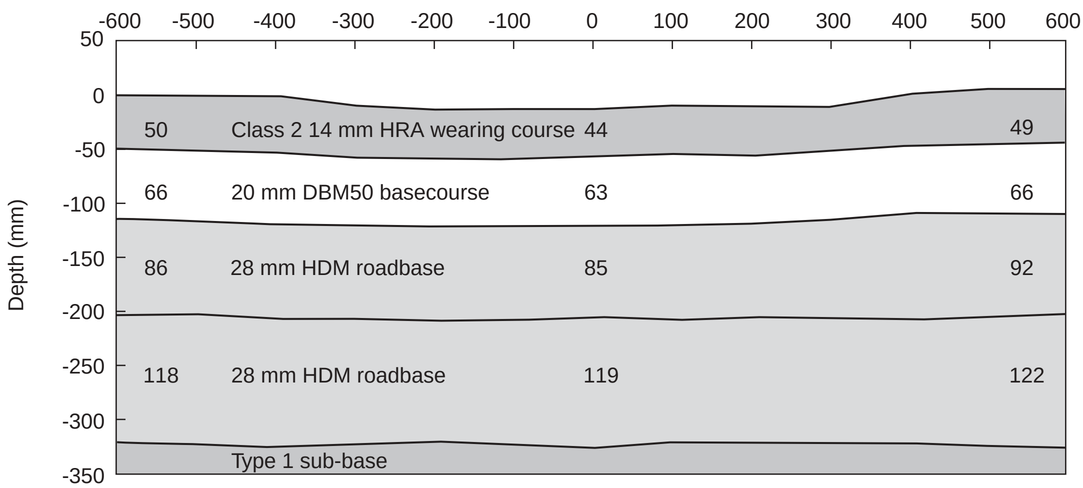

Figure B9b Section 1: Layer thicknesses after 44145 passes – 52 kN dual wheels

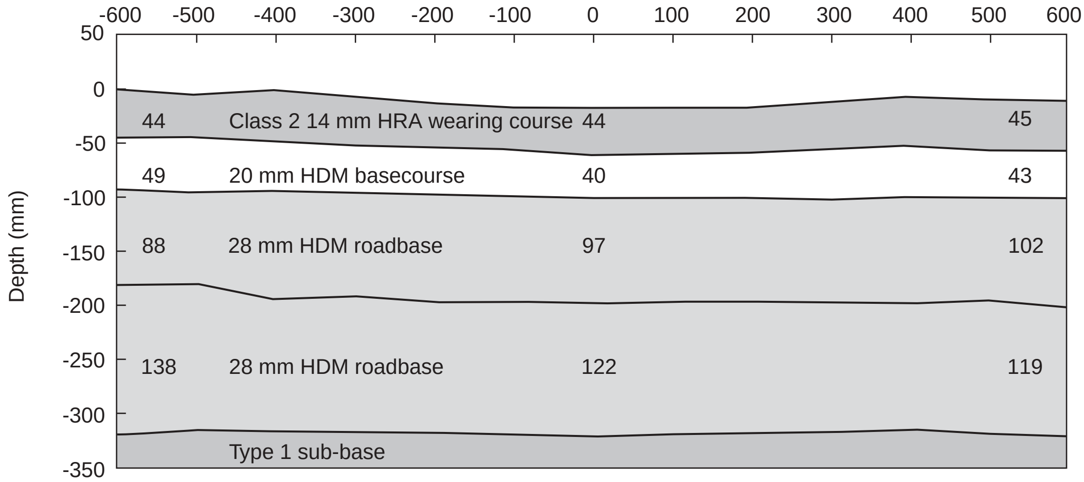

Figure B10a Section 2: Layer thicknesses after 21570 passes – 40 kN single wheel

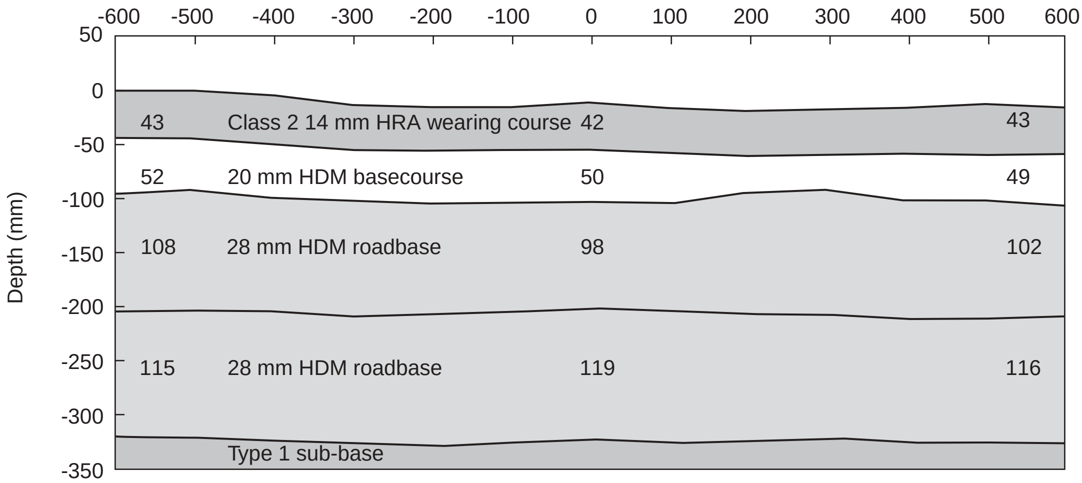

Figure B10b Section 2: Layer thicknesses after 44145 passes – 52 kN dual wheels

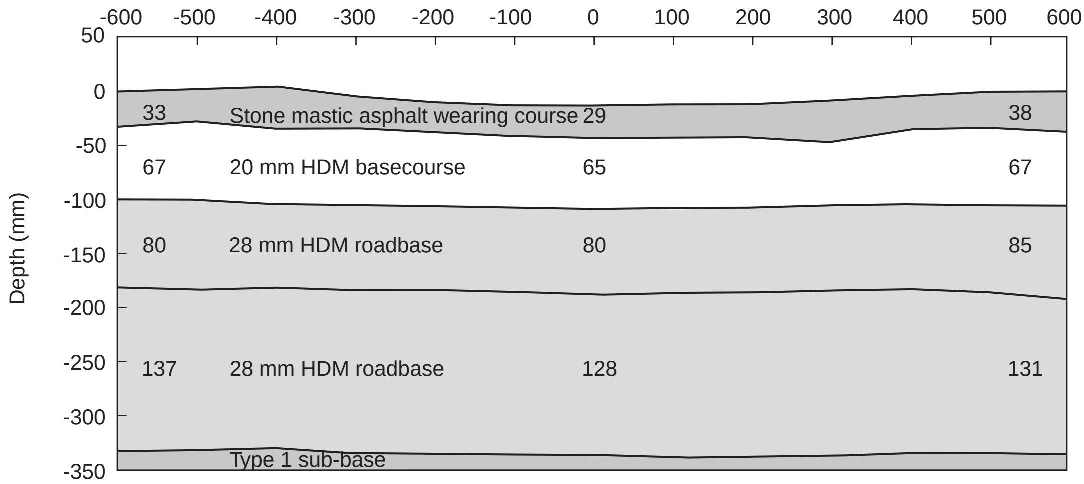

Figure B11a Section 3 Traffic: Layer thicknesses after 29970 passes – 40 kN single wheel

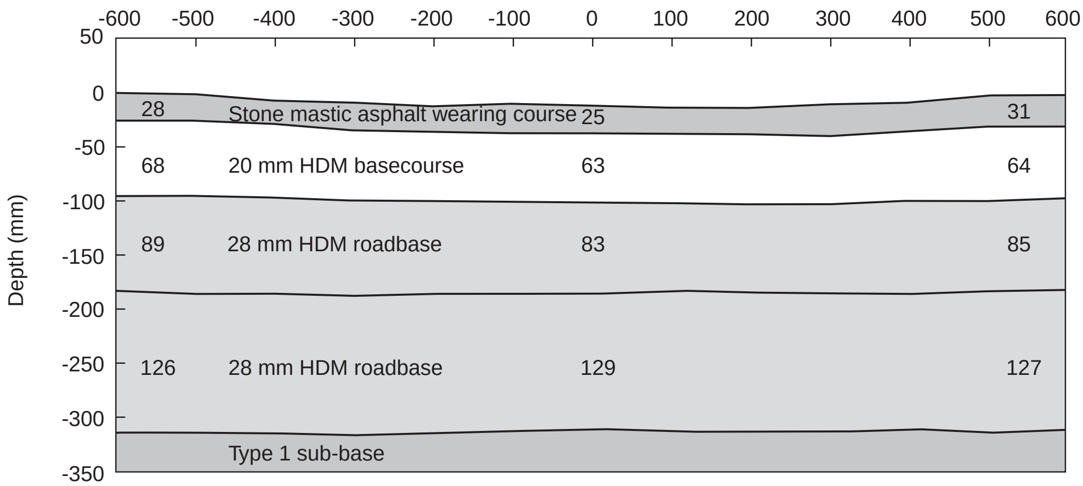

Figure B11b Section 3: Layer thicknesses after 44145 passes – 52 kN dual wheels

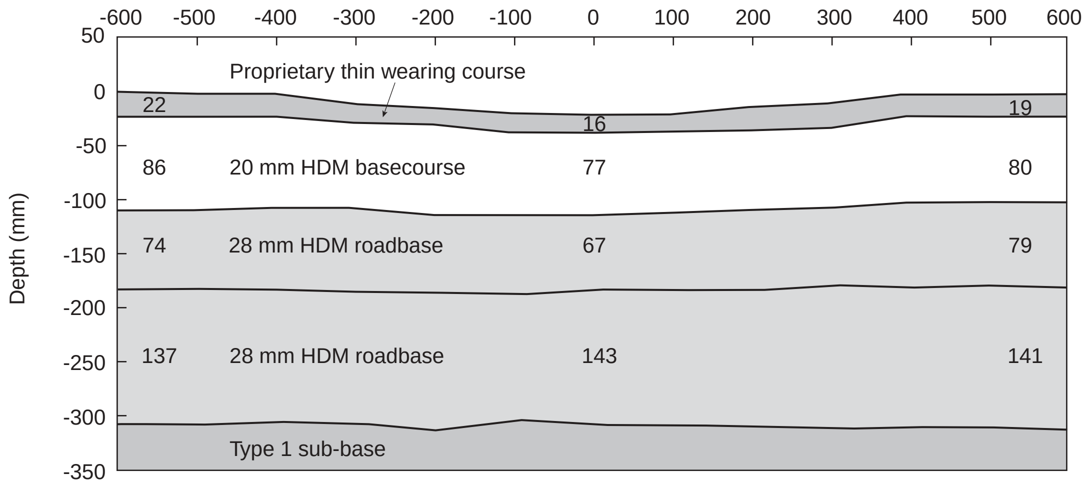

Figure B12a Section 4: Layer thicknesses after 29970 passes – 40 kN single wheel

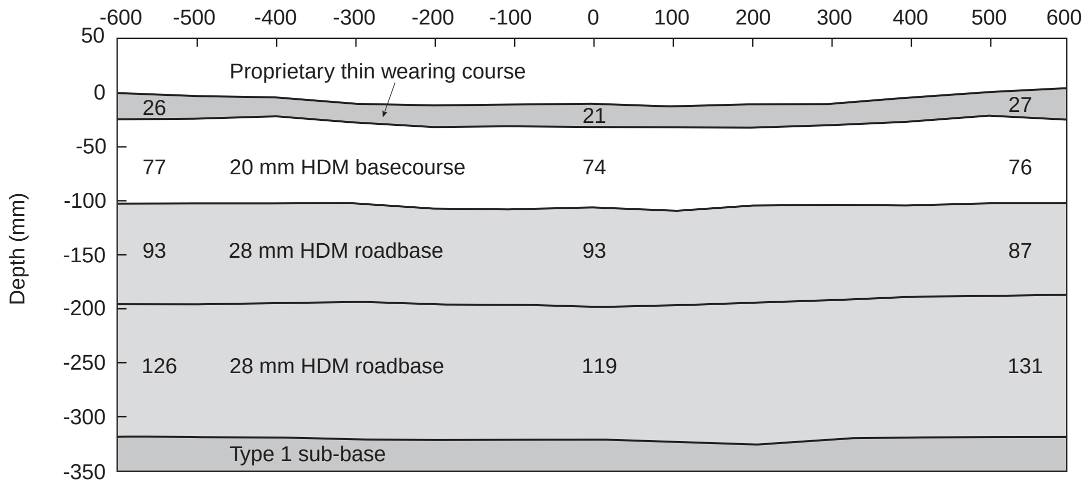

Figure B12b Section 4: Layer thicknesses after 44145 passes – 52 kN dual wheels

Appendix C: Road trial 1 – M6 J10 to J10A

Additional test results

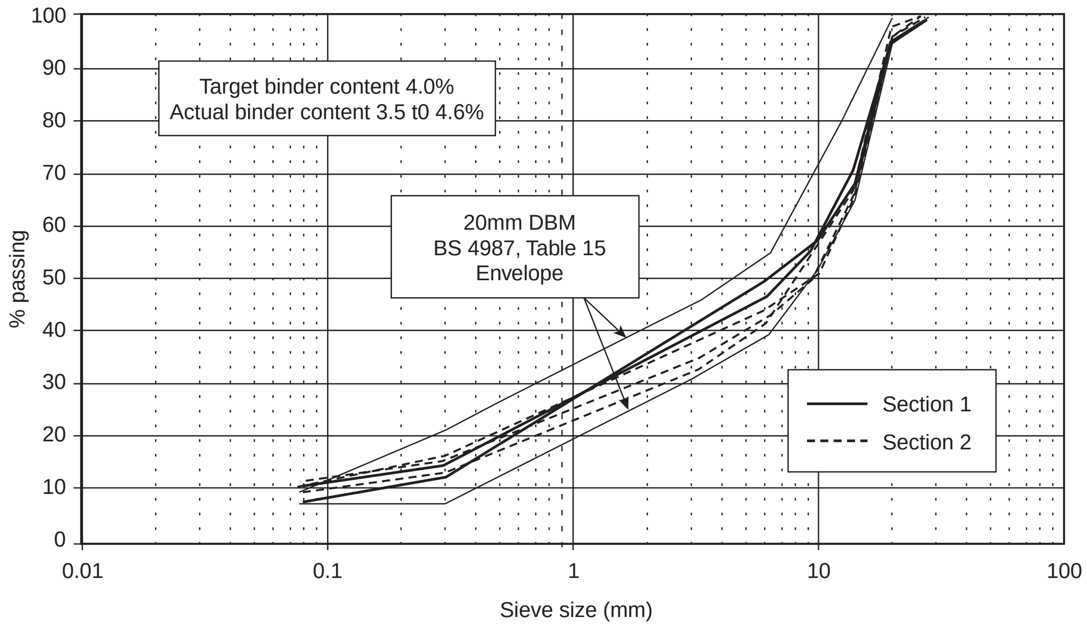

Figure C1 Trial 1: M6 J10 to J10A – 20mm HDM binder courses

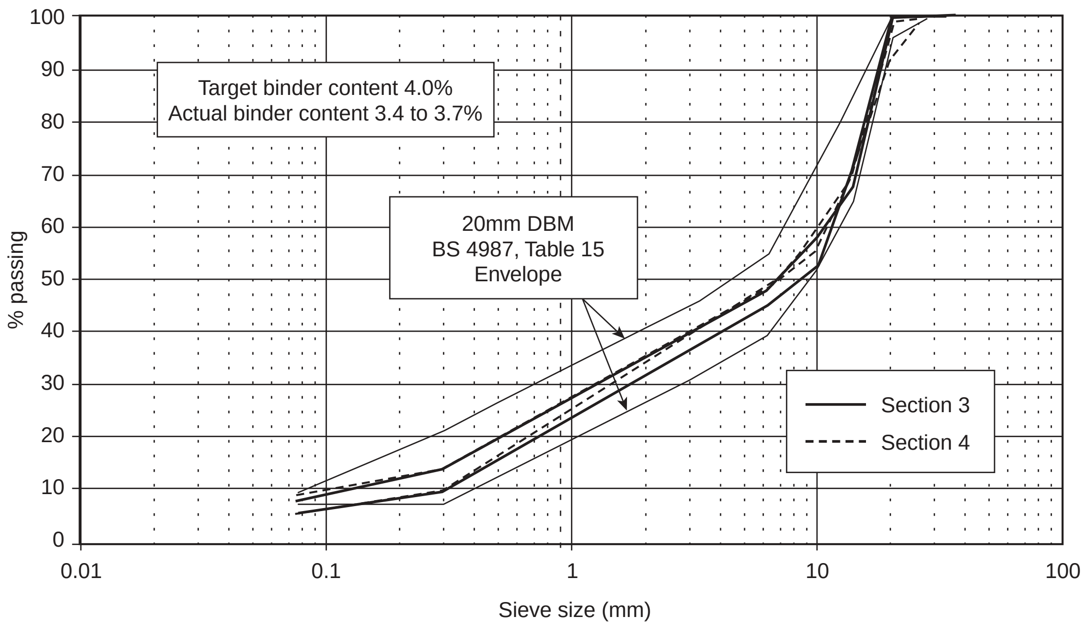

Figure C2 Trial 1: M6 J10 to J10A – 20mm DBM binder courses

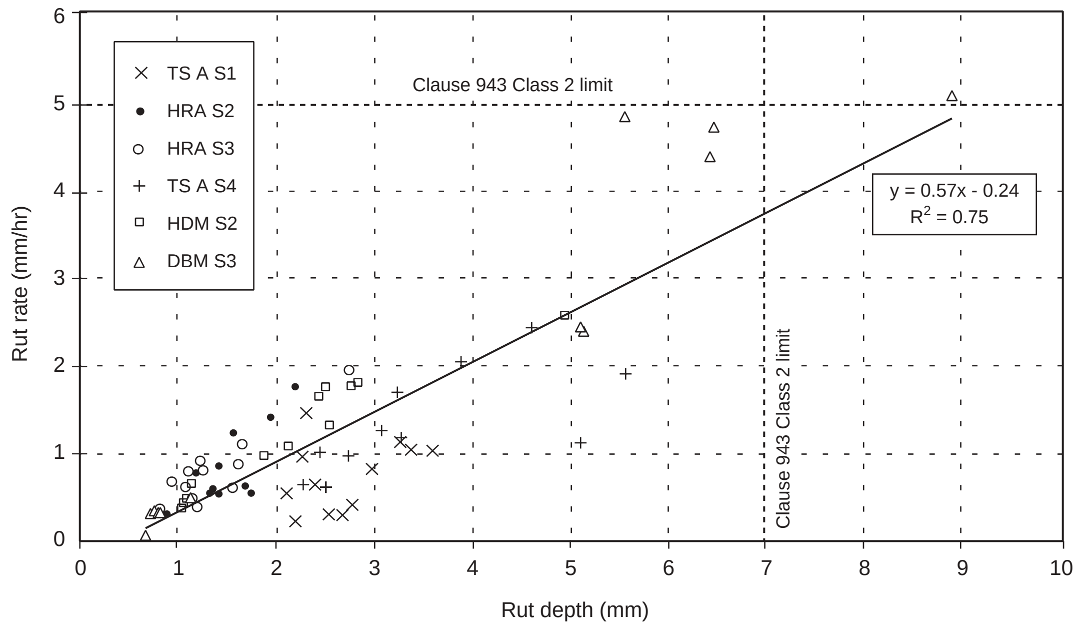

Figure C3 Trial 1: M6 J10 to J10A – WTT rut rate v. rut depth

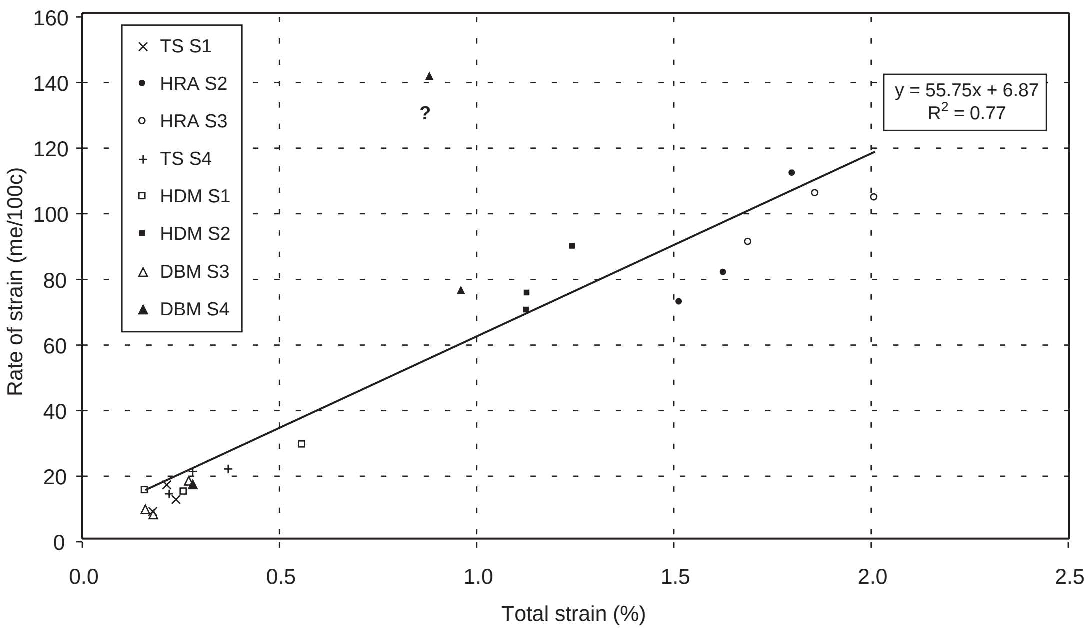

Figure C4 Trial 1: M6 J10 to J10A – VRLAT rate of strain v. total strain

Table C1 Trial 1 (M6 J10 to 10A): Wheel-tracking and Vacuum RLAT results for surface course

Section number and chainage	*Material type and source*	*Wheel-tracking @60°C* Rut rate (mm/hr)	**Mean** and SD (mm/hr)	Rut depth (mm)	**Mean** and SD (mm)	*Vacuum RLAT @ 45°C* Strain rate (με/100cs)	**Mean** Strain rate (με/100cs)	Total strain (%)	**Mean** Total strain (%)
1	Thin	0.64	**0.89**	2.40	**2.76**	9.2	**13.2**	0.18	**0.21**
	surfacing	1.46		2.31		12.9		0.24	
2500	'A'	0.22	*0.43*	2.20	*0.52*	17.4		0.21	
2780		0.82		2.98					
	Plant 1	1.13		3.27		Source not known			
		1.04		3.38					
	Thin	1.03	**0.59**	3.60	**2.66**				
	surfacing	0.30		2.54					
	'A'	0.41	*0.33*	2.78	*0.52*				
		0.96		2.27					
	Plant 2	0.29		2.68					
		0.54		2.11					
2	HRA	0.53	**0.89**	1.76	**1.60**	112.2	**94.7**	1.80	**1.56**
	Class 2	0.53		1.34		81.9		1.63	
2780		1.40	*0.57*	1.96	*0.47*	89.9		1.24	
3100	Plant 1	1.75		2.21					
		0.29		0.90		Source not known			
		0.84		1.43					
	HRA	0.76	**0.76**	1.20	**1.49**				
	Class 2	0.52		1.43					
		0.86	*0.26*	1.63	*0.19*				
	Plant 2	1.22		1.58					
		0.61		1.70					
		0.58		1.37					
3	HRA	0.60	**0.87**	1.09	**1.36**	104.8	**100.7**	2.01	**1.85**
	Class 2	0.79		1.27		91.2		1.69	
3100		0.66	*0.55*	0.95	*0.71*	106.1		1.86	
3400	Plant 1	1.94		2.76					
		0.35		0.83		Source not known			
		0.90		1.24					
	HRA	0.59	**0.69**	1.57	**1.39**				
	Class 2	1.09		1.67					
		0.37	*0.27*	1.21	*0.26*				
	Plant 2	0.86		1.63					
		0.47		1.16					
		0.78		1.12					
4	Thin	0.97	**1.16**	2.74	**3.58**	21.4	**19.4**	0.28	**0.29**
	Surfacing	0.64		2.28		22.2		0.37	
	'A'	1.91	*0.54*	5.57	*1.41*	14.6		0.22	
3400		1.70		3.24					
3800	Plant 1	0.61		2.51		Source not known			
		1.12		5.11					
	Thin	1.01	**1.43**	2.45	**3.30**				
	Surfacing	1.26		3.08					
	'A'	2.05	*0.68*	3.89	*0.83*				
		2.44		4.61					
	Plant 2	0.61		2.51					
		1.18		3.28					

Table C2 Trial 1 (M6 J10 to 10A): Wheel tracking, Vacuum RLAT and ITSM results for binder course

Section number and chainage	Material type and source	*Wheel Tracking @60°C*				*Vacuum RLAT @ 45°C*				*ITSM @ 20°C*	
		Rut rate (mm/hr)	***Mean** and SD (mm/hr)*	*Rut depth (mm)*	***Mean** and SD (mm)*	*Strain rate (με/100cs)*	***Mean** strain rate (με/100cs)*	*Total strain (%)*	***Mean** Total strain (%)*	*Stiffness (GPa)*	***Mean** and SD (GPa)*
1	20mm					15.1	**20.0**	0.26	**0.33**	3.87	**3.73**
	HDM					29.5		0.56		3.72	
2500			No data			15.5		0.16		3.58	*0.13*
2780	Plant 1									3.74	
								Source not known		3.88	
										3.57	
	20mm									3.30	**3.60**
	HDM									3.12	
			No data							3.89	*0.32*
	Plant 2									3.79	
										3.67	
										3.82	
2	20mm	0.47	**0.71**	1.1	**1.51**	89.9	**78.6**	1.24	**1.17**	3.51	**3.55**
	HDM	0.64		1.15		70.4		1.13		3.40	
2780		1.07	*0.39*	2.14	*0.66*	75.6		1.13		3.48	*0.25*
3100	Plant 1	1.31		2.56						3.97	
		0.36		1.05				Source not known		3.26	
		0.42		1.07						3.70	
	20mm	2.57	**1.74**	4.96	**2.91**					3.58	**3.44**
	HDM	1.8		2.85						3.41	
		0.96	*0.51*	1.89	*1.06*					2.84	*0.37*
	Plant 2	1.64		2.45						3.84	
		1.75		2.52						3.52	
		1.76		2.78							
3	20mm	2.4	**3.99**	5.14	**6.27**	18.6	**12.3**	0.27	**0.20**	2.76	**2.49**
	DBM	4.86		5.56		9.9		0.16		2.64	
3100		2.45	*1.23*	5.11	*1.42*	8.3		0.18		2.56	*0.23*
3400	Plant 1	5.1		8.9						2.38	
		4.4		6.43				Source not known		2.49	
		4.74		6.47						2.11	
	20mm	0.06	**0.3**	0.67	**0.82**					2.04	**2.05**
	DBM	0.49		1.13						1.81	
		0.31	*0.14*	0.72	*0.16*					2.06	*0.12*
	Plant 2	0.34		0.76						2.11	
		0.32		0.8						2.13	
		0.32		0.82						2.16	
4	20mm					17.5	**78.8**	0.28	**0.71**	1.26	**1.46**
	DBM					142.1		0.88		1.41	
3400			No data			76.8		0.96		1.52	*0.11*
3800	Plant 1									1.51	
								Source not known		1.54	
										1.54	
	20mm									2.07	**2.03**
	DBM									2.22	
			No data							2.13	*0.16*
	Plant 2									1.76	
										1.95	
										2.05	

Appendix D: Road trial 2 – M6 J1 to J2

Additional test results

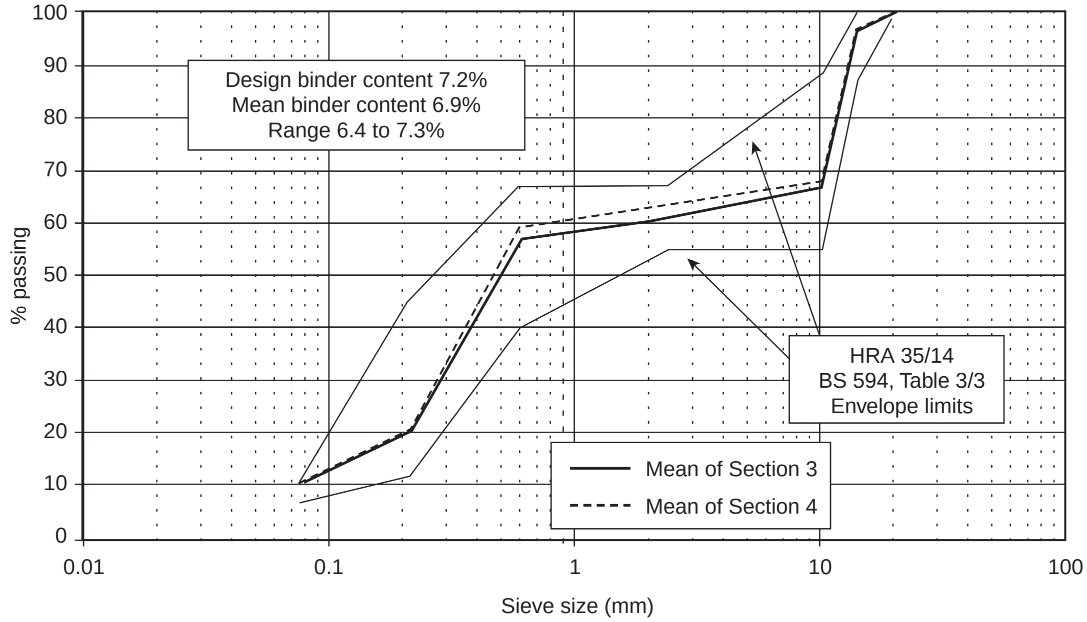

Figure D1 Trial 2: M6 J1 to J2 – HRA surface course

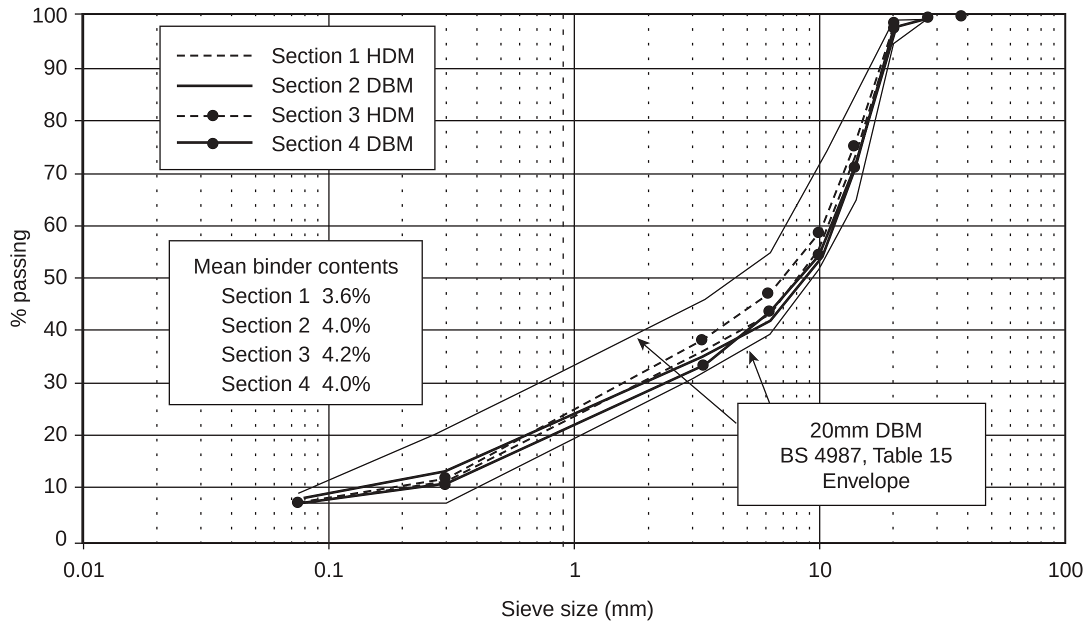

Figure D2 Trial 2: M6 J1 to J2 – Mean gradings of binder courses

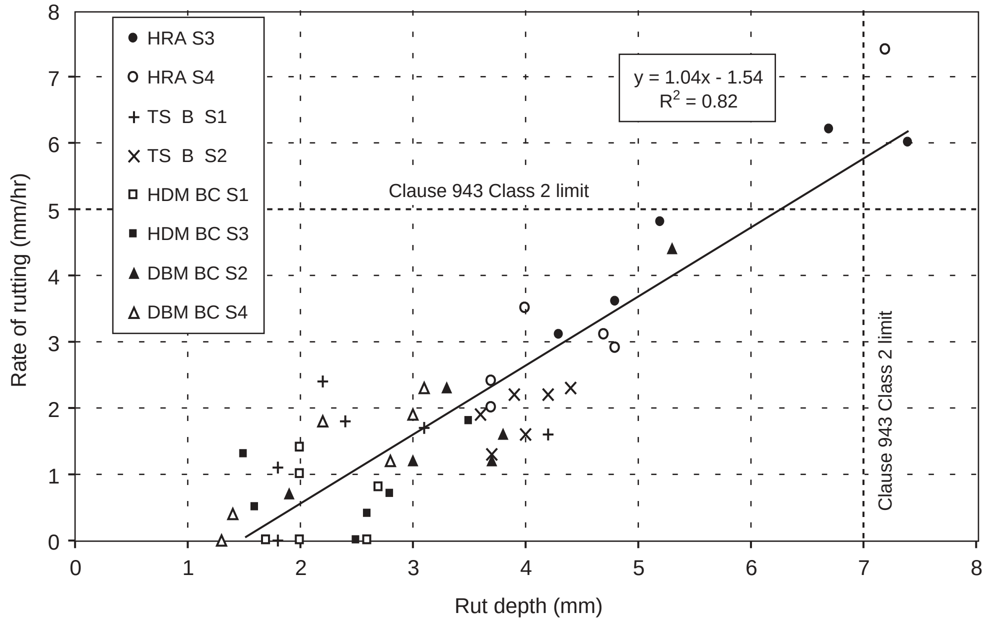

Figure D3 M6 J1 to J2: Wheel tracking – rate of rutting v. rut depth

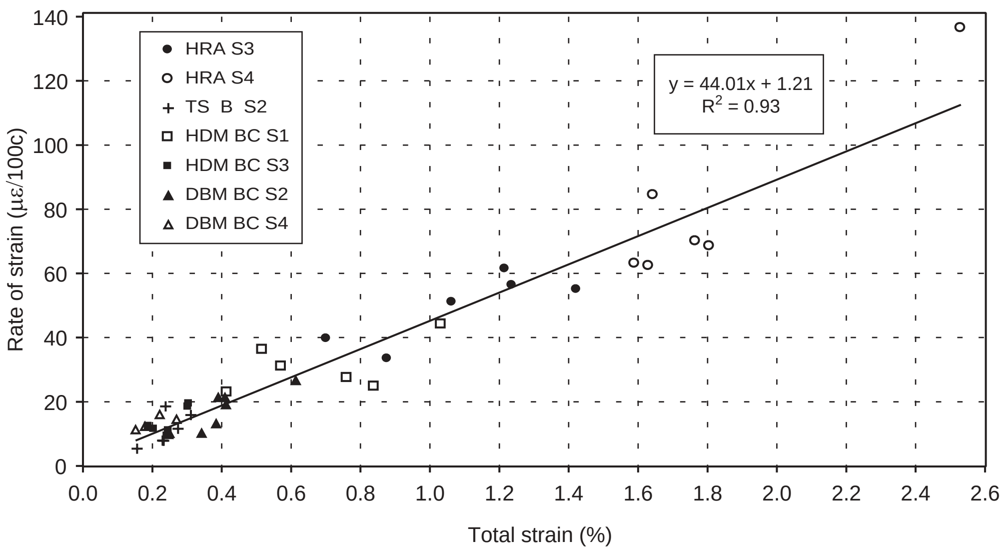

Figure D4 M6 J1 to J2: Vacuum RLAT – rate of strain v. total strain

Table D1 Trial 2 (M6 J1 to J2) Wheel tracking and vacuum RLAT results for surface course

Section number and chainage	*Material type and source*	*Wheel-tracking @60°C*				*Vacuum RLAT @ 45°C*			
		Rut rate (mm/hr)	*Mean and SD (mm/hr)*	*Rut depth (mm)*	*Mean and SD (mm)*	*Strain rate (με/100cs)*	***Mean** Strain rate (με/100cs)*	*Total strain (%)*	***Mean** Total strain (%)*
1	Thin	2.4	**1.43**	2.2	**2.58**				
	surfacing	1.1		1.8		No data			
4000	‘B’	1.6	*0.82*	4.2	*0.93*				
4500		0		1.8					
		1.7		3.1					
		1.8		2.4					
2	Thin	1.9	**1.92**	3.6	**3.97**	7.90	**11.19**	0.230	**0.24**
	surfacing	1.3		3.7		11.60		0.274	
3500	‘B’	1.6	*0.40*	4.0	*0.30*	15.85	*5.14*	0.311	*0.05*
4000		2.2		4.2		5.37		0.156	
		2.2		3.9		7.86		0.233	
		2.3		4.4		18.56		0.238	
3	HRA	6.0	**4.88**	7.4	**5.77**	51.01	**49.43**	1.064	**1.09**
	Class 2	5.6		6.2		39.62		0.702	
2500		3.1	*1.29*	4.3	*1.19*	54.94	*10.72*	1.423	*0.26*
3000		4.8		5.2		33.40		0.878	
		6.2		6.7		61.35		1.217	
		3.6		4.8		56.26		1.237	
4	HRA	2.0	**3.55**	3.7	**4.68**	84.41	**80.78**	1.644	**1.83**
	Class 2	7.4		7.2		136.44		2.530	
3000		3.1	*1.96*	4.7	*1.32*	62.34	*28.40*	1.631	*0.35*
3500		2.4		3.7		63.03		1.591	
		2.9		4.8		69.99		1.766	
		3.5		4.0		68.48		1.806	

Table D2 Trial 2 (M6 J1 to J2) Wheel tracking and vacuum RLAT results for binder course

Section number and chainage	*Material type and source*	*Wheel tracking @60°C*				*Vacuum RLAT @ 45°C*				*ITSM @ 20°C*	
		Rut rate (mm/hr)	*Mean and SD (mm/hr)*	*Rut depth (mm)*	*Mean and SD (mm)*	*Strain rate (με/100cs)*	***Mean** Strain rate (με/100cs)*	*Total strain (%)*	***Mean** Total strain (%)*	*Stiffness (GPa)*	*Mean and SD (GPa)*
1	20mm	0.0	**0.53**	2.6	**2.17**	36.17	**31.05**	0.518	**0.69**	4.71	**4.02**
	HDM	0.0		2.0		24.72		0.840		4.65	
4000		0.8	*0.62*	2.7	*0.39*	30.98	*7.95*	0.573	*0.23*	3.45	*0.62*
4500		1.0		2.0		22.92		0.416		3.17	
		1.4		2.0		44.10		1.033		4.03	
		0.0		1.7		27.40		0.762		4.08	
2	20mm	2.3	**1.90**	3.3	**3.50**	19.12	**18.64**	0.412	**0.43**		
	DBM	1.2		3.7		26.65		0.613		No data	
3500		4.4	*1.34*	5.3	*1.12*	13.19	*5.99*	0.384	*0.10*		
4000		0.7		1.9		10.23		0.342			
		1.6		3.8		21.34		0.390			
		1.2		3.0		21.33		0.409			
3	20mm	1.3	**0.78**	1.5	**2.42**	11.42	**13.60**	0.205	**0.25**	4.39	**3.69**
	HDM	0.5		1.6		12.30		0.190		3.60	
2500		0.4	*0.66*	2.6	*0.76*	18.35	*4.18*	0.304	*0.05*	4.53	*0.69*
3000		0.0		2.5		19.32		0.306		3.62	
		0.7		2.8		10.94		0.248		3.36	
		1.8		3.5		9.29		0.244		2.65	
4	20mm	1.8	**1.27**	2.2	**2.30**	9.82	**12.37**	0.246	**0.22**	3.18	**3.20**
	DBM	1.2		2.8		14.54		0.270		2.88	
3000		0.4	*0.91*	1.4	*0.80*	11.30	*2.47*	0.152	*0.05*	3.50	*0.58*
3500		0.0		1.3		12.37		0.179		2.67	
		1.9		3.0		16.01		0.221		4.22	
		2.3		3.1		10.16		0.249		2.76	

Appendix E: Road trial 3 – A12 Boreham

Additional test results

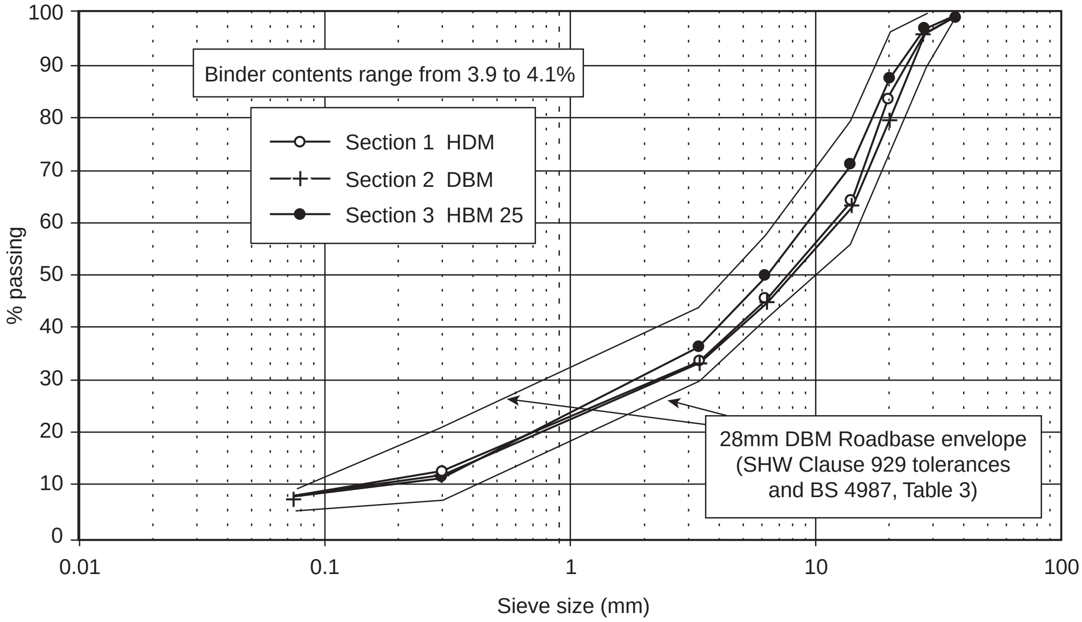

Figure E1 Trial 3: A12 Boreham – mean gradings of binder courses

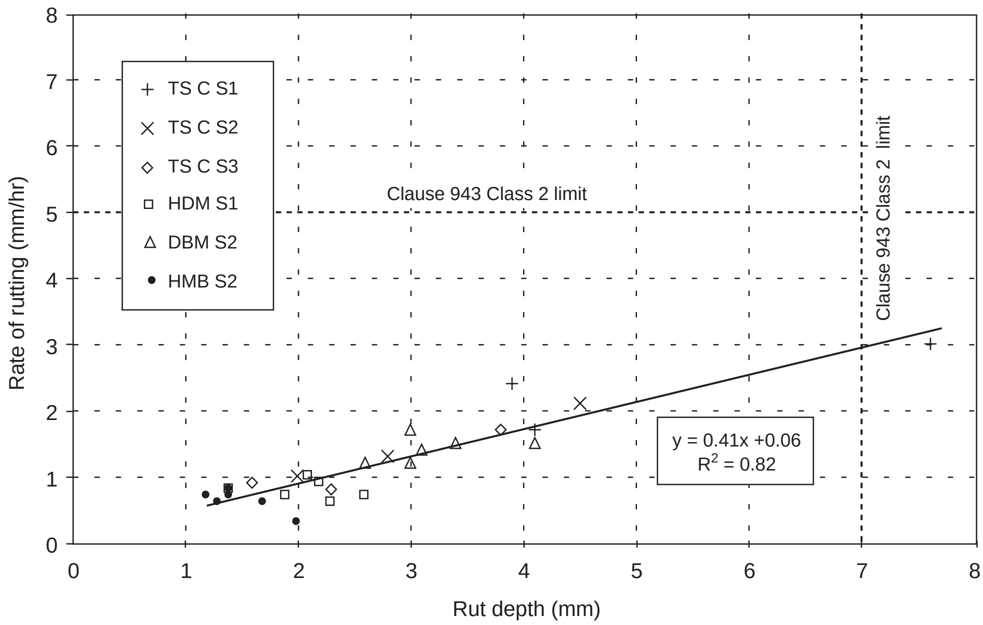

Figure E2 A12 Boreham: Wheel tracking – rate of rutting v. rut depth

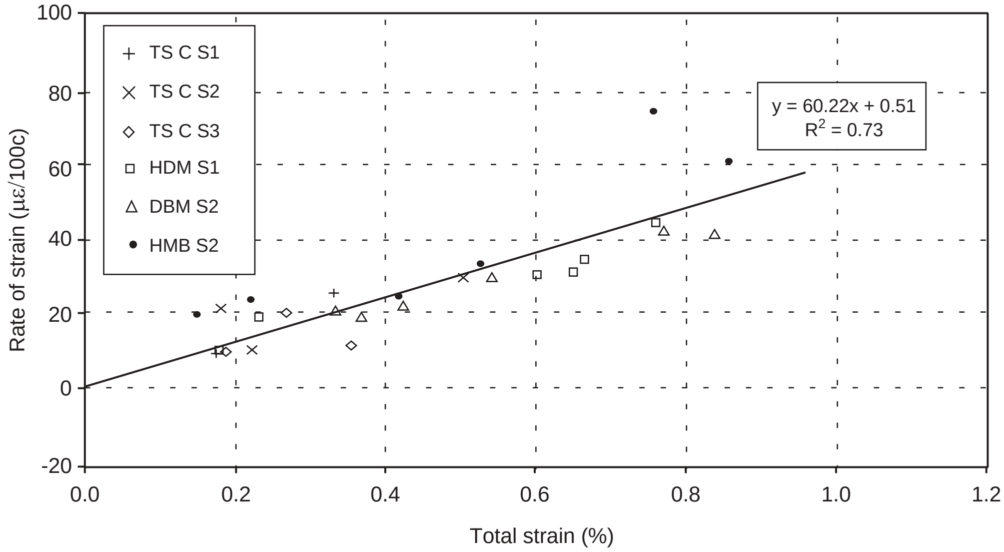

Figure E3 A12 Boreham: Vacuum RLAT – rate of strain v. total strain

Table E1 Trial 3 (A12 Boreham): Surface course: Wheel tracking and vacuum RLAT Results

Section number and chainage	*Material type and source*	*Wheel-tracking @60°C* Rut rate (mm/hr)	Mean and SD (mm/hr)	Rut depth (mm)	Mean and SD (mm)	*Vacuum RLAT @ 45°C* Strain rate (με/100cs)	***Mean*** Strain rate (με/100cs)	Total strain (%)	***Mean*** Total strain (%)
1	Thin	3.0	**2.37**	7.6	**5.20**	25.70	**10.06**	0.331	**0.222**
2300	surfacing	2.4		3.9		9.41		0.174	
2000	'C'	1.7		4.1		-4.92		0.162	
2	Thin	2.1	**1.47**	4.5	**3.10**	29.82	**20.59**	0.503	**0.302**
2000	surfacing	1.3		2.8		10.40		0.222	
1650	'C'	1.0		2.0		21.53		0.181	
3	Thin	1.7	**1.13**	3.8	**2.57**	20.37	**13.94**	0.268	**0.270**
1650	surfacing	0.9		1.6		11.57		0.354	
1350	'C'	0.8		2.3		9.87		0.187	
Mean of all results			**1.66**		**3.62**		**14.86**		**0.265**
Std dev. of all results			*0.74*		*1.81*		*10.57*		*0.113*

Table E2 Trial 3 (A12 Boreham): Wheel tracking and vacuum RLAT results for binder course

Section number and chainage	*Material type and source*	*Wheel tracking @60°C* Rut rate (mm/hr)	Mean and SD (mm/hr)	Rut depth (mm)	Mean and SD (mm)	*Vacuum RLAT @ 45°C* Strain rate (με/100cs)	***Mean*** Strain rate (με/100cs)	Total strain (%)	***Mean*** Total strain (%)	*ITSM @ 20°C* Stiffness (GPa)	Mean and SD (GPa)
1	28mm	0.7	**0.78**	2.6	**2.08**	19.16	**28.38**	0.233	**0.515**	4.96	**3.72**
2300	HDM	0.8		1.4		10.17		0.180		4.41	
2000		0.9	*0.15*	2.2	*0.41*	31.27	*12.08*	0.651	*0.245*	3.77	*0.82*
		1		2.1		34.64		0.666		3.27	
		0.7		1.9		30.48		0.602		3.06	
		0.6		2.3		44.54		0.760		2.85	
2	28mm	1.2	**1.42**	3	**3.20**	20.97	**29.44**	0.333	**0.545**	1.71	**1.86**
2000	DBM	1.7		3		19.30		0.367		1.91	
1650		1.2	*0.19*	2.6	*0.51*	41.58	*10.42*	0.837	*0.213*	1.86	*0.08*
		1.4		3.1		42.48		0.769		1.88	
		1.5		3.4		22.30		0.423		1.91	
		1.5		4.1		29.98		0.541		1.87	
3	28mm	0.8	**0.62**	1.4	**1.50**	74.34	**39.41**	0.757	**0.489**	6.17	**6.58**
1650	HMB25	0.7		1.4		60.90		0.857		5.54	
1350		0.6	*0.17*	1.7	*0.30*	33.31	*22.70*	0.527	*0.283*	6.82	*0.68*
		0.6		1.3		24.58		0.419		6.81	
		0.3		2		19.68		0.151		7.55	
		0.7		1.2		23.67		0.222		6.60	

Appendix F: Proposed performance-related surfacing specification

Surface course

1 The surface course shall consist of one of the following materials, unless otherwise specified in Appendix 7/1:

- Porous asphalt surface course (Clause 938).
- Thin wearing course (Clause 942).
- Hot rolled asphalt (Performance-related design mix) (Clause 943).

2 These materials shall also comply with the general requirements of Series 900 clauses of the SHW.

3 Details of the proposed surface course mixture shall be submitted to the Overseeing Organisation.

Sampling, Testing and Compliance of Surface Course from the Permanent Works

4 The requirements of Clauses 938, 942 or 943, as appropriate, shall apply.

Binder course

5 The binder course shall consist of one of the following materials: unless otherwise specified by Appendix 7/1:

- Dense Macadam basecourse (Clause 906).
- Heavy Duty Macadam basecourse (Clause 933) .
- Dense Bitumen Macadam basecourse with grade 50 pen binder (Clause 934).
- High Modulus Base basecourse (Clause 936).
- Stone Mastic Asphalt binder course and regulatory course (Clause 937)

6 In addition to satisfying the general requirements of Series 900 clauses, where applicable, and the specific material type clauses, all of the permitted binder course materials shall comply with Clause 944 (stiffness) and one of the following deformation requirements:

Either *Wheel-Tracking test* (BS 598:Part 110)

Temperature (degrees C)	Max. rut rate (mm/hr)	Max. rut depth (mm)
60	5.0	7.0

Or *Vacuum Repeated Load Axial Test (Vacuum RLAT)* (BS DD 226 and TRL PA3287/97)

Temperature (degrees C)	Max. strain rate (microstrain / 100 cycles)	Max. strain (%)
45	100	1.5

7 The thickness of wheel-tracking test specimens shall be between 45 and 55mm and the specimens shall be tested ‘rightway up’. The thickness of the vacuum RLAT specimens shall be between 45 to 55mm

8 All binder course material to a depth of at least 100mm from the completed pavement surface shall comply with the stated deformation limits.

9 The level of stiffness to be achieved in accordance with Clause 944 shall be as specified in Appendix 7/1.

10 Binder courses laid under any surface course except hot rolled asphalt surface course (Clause 943) shall comply with the following:

i The average in situ air void content calculated from any six consecutive nuclear density readings shall not exceed 7.0 %.

ii The average in situ air void content of pairs of cores shall not exceed 8.0 %.

11 Details of the proposed binder course mixture shall be submitted to the Overseeing Organisation. Evidence that the material meets the wheel-tracking or vacuum RLAT requirements shall be provided either from the use of the mixture on a previous contract or by carrying out a job mixture trial. Where a trial is carried out the trial area shall be not less than 30m and not more than 60m in length and 3 to 4 m in width, unless specified otherwise in Appendix 7/1.

12 At three locations in the trial area two cores, one in each wheel track zone, shall be taken for wheel-tracking or vacuum RLAT testing.

13 Stiffness tests, as required by Clause 944 and wheel-tracking tests shall be carried out as part of the Clause 929 Job Mixture approval trial.

Job Mixture Approval Trial Compliance Requirements

14 In addition to the requirements of the specific material type clauses, Clause 929 and Clause 944, the mean values of the six determinations of the Wheel-Tracking or Vacuum RLAT tests shall not exceed the specified values. Individual values of wheel-tracking or Vacuum RLAT measurements shall not exceed the specified values by more than 50%.

Sampling and Testing Binder Course from the Permanent Works

15 The requirements of the specific material type clauses shall apply and wheel-tracking or vacuum RLAT testing shall also be carried out at the following frequencies:

i 6 cores from the first lane-kilometre from a mixing plant;

ii thereafter, at least one core from each lane-kilometre or one core from each day’s production if less than one lane-kilometre is laid.

Compliance requirements

16 In addition to the requirements of the specific material type clauses, Clause 929 and Clause 944, the mean values of the six determinations of the wheel-tracking or Vacuum RLAT tests shall not exceed the specified values. Individual values of wheel-tracking or Vacuum RLAT measurements shall not exceed the specified values by more than 50%.

Regulating course

17 Any regulating course lying within 100mm of the pavement surface shall meet the same requirements as for binder course.

Notes for guidance

Performance-related surfacing specification

1 This Specification is intended for use only in high traffic stress situations similar to those which justify the use of either Class 1 or 2 Clause 943 HRA surface course. The circumstances for use of this surfacing specification are given in Table NG 1.

2 Rolled Asphalt wearing course (Clauses 910 and 911) with standard 50 pen binder would not be expected to achieve the Clause 943 Class 1 deformation resistance and is therefore not included.

3 The level of stiffness to be achieved in accordance with Clause 944 shall be specified in Appendix 7/1 and will normally be the same as that of the underlying roadbase.

4 The permeability of thin surfacings are variable and depend on several factors including porosity and the richness of any tack coat. As the surfacing may not always be as impermeable as traditional HRA a slightly lower limit of the binder course air voids is desirable to limit water ingress and ageing effects.

Table NG 1 Sites where surfacing specification should apply (based on TABLE NG 9/33 from Volume 2 of the SHW)

		Traffic at design life (commercial vehicles per lane per day)				
Site category	*Site definition*	*Up to 250*	*251 - 500*	*501 – 1000*	*1001 - 1500*	*> 1500*
I & II						
A	Motorway (main line)					
B	Dual carriageway (all purpose) non-event sections					
D	Dual carriageway (all purpose) minor junctions					
C	Single carriageway non-event sections					
E	Single carriageway minor junctions					
IA & IIA	As I and II, above, but with contraflow anticipated during summer months					
III						
F	Approaches to and across major junctions (all limbs)					
G1	Gradient 3 per cent to 10 per cent, longer than 50 m:	Clause 929 only			Clause 929 and Wheel tracking or Vacuum RLAT	
L	Dual (uphill and downhill)					
	Single (uphill and downhill)					
	Roundabout					
IIIA	As III, above, but with contraflow anticipated during summer months or in a south-facing cutting uphill					
IV						
G2	Gradient steeper than 10 per cent, longer than 50 m: Dual (uphill and downhill) Single (uphill and downhill)					
IVA	As IV, above, but with contraflow anticipated during summer months or in a south-facing cutting uphill					
V						
J/K	Approach to roundabout, traffic signals, pedestrian crossings, railway level crossings and similar					

Abstract

A performance-based specification has been developed primarily to prevent excessive rutting occurring in the surface course and the binder course in heavily trafficked pavements under adverse trafficking conditions. This specification was developed by:

- assembling information to establish which layers are at risk;
- examining the role of the surfacing layers;
- investigating, in the TRL accelerated pavement test facility (PTF), the performance of rut-resistant pavement design solutions that have the potential to perform well under severe traffic loading and high pavement temperatures;
- comparing results from laboratory deformation tests with the performance of materials in the PTF;
- assessing the practicability of the specification under contractual conditions and using this experience to make appropriate amendments.

The proposed new specification for the asphalt surfacing will ensure that future roads designed for heavy traffic will continue to have excellent deformation resistance even under extreme trafficking conditions. The specification will encourage better design of the asphalt surface course and the binder course and, should any problems occur in the future, it will be possible to review the performance criteria.

Related publications

TRL250 *Design of long-life flexible pavements for heavy traffic* by M E Nunn, A Brown, D Weston and J C Nicholls. 1997 (price £50, code L)

TRL163 *Valuation of road accidents* by J M Hopkin and H F Simpson. 1995 (price £25, code E)

PR37 *A review of the accident risk associated with major roadworks on all-purpose dual carriageway roads* by M R Hayes and P J Taylor. 1993 (price £50, code N)

CR38 *Methods for predicting permanent deformation in flexible pavements* by E N Thrower, S Mortazavi and J W Dougill. 1986 (price £20, code C)

LR1132 *The structural design of bituminous roads* by W D Powell, J F Potter, H C Mayhew and M E Nunn. 1984 (price £20)

SR706 *Pavement thickness, surface evenness and construction practice* by J C McLellan. 1982 (price £20)

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