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TRL Report
TRL674

Durability of thin asphalt surfacing systems. Part 4: Final report after nine years' monitoring

J C Nicholls, I Carswell, C Thomas and B Sexton

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Executive summary

Proprietary thin surfacing systems were first introduced to the UK from the continent in the early 1990s. The benefits of these materials (in particular speed of laying and reduced lane occupancy during application and reduced noise and spray during use), in conjunction with their ability to meet texture depth and skid resistance requirements for the trunk road and motorway network, have resulted in a significant increase in their use. Thin surfacing systems are currently the preferred surfacing option of the Highways Agency (HA) for both new construction and maintenance works.

An expected serviceable life of eight to ten years was typically assumed for maintenance planning when thin surfacing systems were first introduced on the HA network. In order to obtain a better estimate of serviceable life based on actual performance, in 2000 the HA commissioned research to assess the durability of thin surfacing systems and to identify factors affecting serviceable life and typical modes of failure. This research was based largely on the assessment of early trial sites and sites used for type approval trials because a large amount of data was already held for these sites. The principal conclusion from that work was that thin surfacing systems can routinely be constructed to provide a safe and durable surfacing. Estimates of serviceable lives were developed for each of the main types of thin surfacing system present in the sample of sites evaluated. These conclusions were supported by further monitoring between 2004 and 2006 of the extant sites plus some additional ones.

Additional monitoring was undertaken from 2007 to 2009 on the sites, again with some sites being added to replace those that had been resurfaced. Overall, data have been obtained from 137 sites or subdivisions of sites from both the HA national and local authority regional networks, although some sites have only provided a very limited amount of data. The data now gathered cover the various types of thin surfacing system after periods in service (although not necessarily in a serviceable condition) of up to 14 years for paver-laid surface dressing (PLSD), 16 years for thin asphalt concrete (TAC), 14 years for thin stone mastic asphalt (TSMA), 14 years for multiple surface dressing (MSD) and ten years for micro-surfacing (MS).

The principal conclusions that can be drawn from the results are:

- Estimates of the serviceable lives of thin surfacing systems to reach a *Suspect* visual condition based on analyses of visual condition measures using two different analysis techniques gave values of:

Thin surfacing system	*Nominal size (mm)*	*No. of sites*	*No. of observations*	*Rigorous statistical analysis*		*Combined estimate for serviceable lives (years)*
				Estimated serviceable lives (years)	*95 % confidence limits (years)*	
PLSD	14	9	32	12	9.1 – 15*	13
	10	7	33	11	9.5 – 13	9½
	6	1	6	5.5	4.7 – 6.5	6
TAC	14	32	82	16*	14* – 19*	>12
	10	33	134	17*	16 – 18*	>16
	6	8	34	14*	10 – 20*	>10
TSMA	14	49	197	19*	16* – 21*	>14
	10	9	30	26*	16* – 38*	>14
MSD	14	6	28	7.4	6.3 – 8.5	9
MS	6	4	22	7.8	2.8 – 13*	8½

Many of these values are extrapolations, being greater than the oldest site observation. These values are indicated with the addition of an asterisk.

- The life estimates are to the end of serviceable condition which has been defined in this study as the onset of *Suspect* condition. In case users require some indication of the lives to other condition states, the table below has been provided which is based on a combination of the results from the less rigorous analyses of the available visual condition data.

Visual condition	*Time in service (years) to reach for system type*									
	PLSD			*TAC*			*TSMA*		*MSD*	*MS*
	14 mm	*10 mm*	*6 mm*	*14 mm*	*10 mm*	*6 mm*	*14 mm*	*10 mm*	*14 mm*	*6 mm*
Moderate	5	4½	3½	7½	7	5	8	11	2½	–
Acceptable	9	7½	5½	>12	13	10	14	>14	5½	3
Suspect	13	9½	6	>12	>16	>10	>14	>14	9	8½
Poor	>14	>14	>6	>12	>16	>10	>14	>14	13	>10

Values being shown as greater than the maximum life are extrapolations; the dash for MS indicates that those systems usually have some defects when built.

- The similarity of results from the two approaches gives added confidence in the results but also emphasises the variability in the performance as highlighted by the 95 % confidence limits given in the table. However, it should be noted that, due to limited range of data and possible bias in their selection (such as traffic level, substrate condition and site geometry), the results can only be considered as a broad indication of likely lives.
- Skid resistance is not considered to be a major durability issue because statistical analysis indicates that, in general, there was no statistically significant decrease of MSSC as a uniform function with age of the surfacing, although there was considerable fluctuation.
- Texture depth is not considered to be a major durability issue because, apart from MSD systems, analysis indicates that there are reductions in texture depth as the surface ages but generally only in the early years. Towards the end of its serviceable life, the texture depth on a site can increase but as a symptom of particle loss rather than as the cause of failure.
- For the monitored sites that have been resurfaced or overlaid, the average life in service for all types is 9.9 years with a standard deviation of 3.0 years. However, this estimate is biased because sites still in service, and therefore likely to be the more durable sites, have not been included. The average is similar to that of sites reaching a visual condition of *Suspect* with a mean of 9.2 years and standard deviation of 3.1 years.
- For thin surfacing systems laid directly onto jointed concrete, the difference between the actual overall condition and that for the condition ignoring any reflection cracks is negligible for at least five years. After five years, there is still no difference for many sites (presumably where the joints are still in good condition) but, for others, the difference can be up to one and a half visual assessment marks, which implies that the time before the surfacing needs to be replaced will be significantly less.
- Whilst many claim that there are many instances of premature failure with thin surfacing systems, the response to a request for examples resulted in very few being put forward. Furthermore, one response was about low early-life skid resistance rather than durability.

Expected service lives are often used to influence a choice of surfacing, but another important aspect is the whole-life cost of its use. On this aspect the study concluded that, on average, thin surfacing systems and HRA have similar whole-life costs despite an assumed shorter serviceable life for thin surfacing systems than HRA. Furthermore, there are additional possible non-financial benefits from thin surfacing systems such as noise reduction. However, specific assessments would be needed for specific schemes in order to take account of any local conditions and other influencing factors.

With respect to the expected mode of failure of thin surfacing systems, the principal mode of failure or reason for reaching an unserviceable condition was the significant presence of one or more visual defects, of which the two most prevalent were particle loss and cracking. Long-term deterioration of skid resistance or texture depth was not generally found to be cause of unserviceability although loss was observed on some sites after the initial changes. Such levels are believed to be caused by poor specification of materials or construction defects.

With respect to determining a simple means of predicting failure, the study focused on identifying which parameters apparently most affected the estimated lives of the pavement. For this issue the study concluded that:

- The penetration and softening point of the thin surfacing material was related to the age and type of the material but the relationship was insufficiently clear to be used as a life predictor.
- Aggregate size and system were the most important influences on estimated lives in terms of visual condition, with binder content also important in some situations.

The above observations show that thin surfacing systems can routinely be constructed to provide a safe surfacing with adequate skid resistance, texture and visual condition and that these properties are maintained in service for a reasonable period.

Abstract

Thin surfacing systems, as the term is currently understood, were introduced into the UK in 1991. Many sites with thin surfacing systems have reached or are approaching the end of their assumed lives so that a review of the service that can be expected from such surfacings can now be made with some confidence. The information collected from a selection of sites with thin surfacing systems has been evaluated in order to establish this understanding of their serviceable life. In this TRL Report, the results from visual condition, SCRIMtex and recovered binder properties are given for sites monitored over the last three years of this nine-year review (begun in 2001) together with analysis of these data together with the results from preceding years, a total of 137 sites. The findings, now extended by a further three years' monitoring since the last published report, indicate that, if a thin surfacing system is in a good condition after its first year in service, it will be serviceable for at least five years and the typical life of a thin surfacing system is about ten years, depending on the type of thin surfacing system and the condition of the substrate. The estimated lives of the most commonly used systems (10 mm and 14 mm thin asphalt concrete and thin stone mastic asphalt systems), however, are all over 12 years.

1 Introduction

1.1 General

Asphalt surface course layers for major roads typically used to be at least 40 mm thick. Thinner surface course materials were available before 1990, but they were considered to be technically inferior and were only used on roads carrying low traffic levels within the county road networks. However, during the 1990s, various types of thin surfacing that have beneficial properties (in particular speed of laying and reduced noise and spray) were introduced into the UK, mostly from the continent (Nicholls, 2002). Thin surfacing systems (or "thin surfacing" for short) have gained a significant share of the surface course market in all parts of the network because of these improved properties.

The first of the currently used thin surfacing systems was imported from France in 1991. This ultra thin layer asphalt concrete (UTLAC) surfacing system had been modified slightly from the French design in order to achieve the texture depth required for high-speed trunk roads in the UK. A thin asphalt concrete (BBTM, from the French) surfacing system was introduced in 1992, with other systems following either directly from France or developed in the UK but based on similar concepts to those used in France (Nicholls *et al*., 1995). In 1994, stone mastic asphalt (SMA) was introduced from Germany and trialled in this country, from which a variety of thin stone mastic products were developed (Nunn, 1994). In 1995, a multiple surface dressing (MSD) was introduced into the UK that had properties more akin to asphalt materials although produced on site (Nicholls, 1998). Micro-surfacing (MS) with polymer-modified binders has also been developed in thin surfacing systems. Further variants on the basic theme of a thin surfacing system may emerge in the future.

Based on the product from which they were developed, thin surfacing systems can be subdivided into types (Laws, 1998) as follows:

- Paver-laid surface dressing (PLSD or UTLAC): Ultra-thin surfacings developed in France
- Thin asphalt concrete (TAC or BBTM): Generally with polymer-modified binder
- Thin stone mastic asphalt (TSMA or SMA): Generally unmodified bitumen with fibres
- Multiple surface dressing (MSD): Binder and aggregate applied separately
- Micro-surfacing (MS): Thick slurry surfacing, generally with modified binder

The first acronym for a system type in this list is the one used in previous reports in this series whilst the second one is the acronym used in the European Standards (the BS EN 13108 series) that were published in 2006. These alternative acronyms are ultra-thin layer asphalt concrete (UTLAC), bétons bitumineux très minces (BBTM) and stone mastic asphalt (SMA). For continuity with the previous reports in this series, the first acronym for each system type will be used in this report.

These system types can be grouped into (a) asphalt systems (mixtures of aggregate and bituminous binder mixed hot, generally off site) and (b) surface treatment systems. For this purpose, the asphalt systems are PLSD, TAC and TSMA and the surface treatment systems are MSD and MS.

Initially, thin surfacing systems needed to gain Highways Agency (HA) approval before they could be routinely used on trunk roads in England. This HA approval system was superseded by the Highways Authorities Product Approval Scheme (HAPAS) run by the British Board of Agrément (BBA).

Thin surfacing systems laid in the UK in the early and mid 1990s have passed their initially expected serviceable lives of eight to ten years. Therefore, from the late 1990s it has become possible to compare their predicted and actual levels of performance. In addition, it is also now possible to examine how these materials deteriorate as they reach the end of their serviceable lives.

In order to gain this knowledge, in 2000 the HA commissioned TRL to monitor some of the older UK sites in order to assess the durability of those systems. This monitoring, begun in 2001, has continued over a total of nine years. This report is the fourth in a series, extending the work with a further three years of monitoring, and should be read in conjunction with the three earlier reports; TRL557 (Nicholls *et al*., 2002), TRL606 (Nicholls and Carswell, 2004) and TRL660 (Nicholls *et al*., 2007).

1.2 Project aims

The principal aims of the project were to identify the expected length of the service lives of thin surfacing systems, the mode(s) by which they fail and if there are any simple means to predict their failure. In order to achieve these aims, a programme of monitoring the condition of over 100 sites was commenced. The main parameters gathered included the type of thin surfacing system, the aggregate size and polished stone value (PSV), the binder content, the surfacing depth, the road type, the initial and recovered penetration and softening point of the binder, the texture depth by patch- and sensor-measured methods, the mid-summer SCRIM coefficient, the visual condition including the observed defects and the age when measurements were made. Unfortunately, it was impossible to obtain all these data for all years on all sites. In particular, it was not practical to monitor the skid resistance, texture depth and recovered binder properties on as many sites as the visual condition. Therefore, those parameters were only collected on a subset of the included sites. The visual condition was recorded by an Inspection Panel using a marking system that is based on a seven-point scale of *Excellent*, *Good*, *Moderate*, *Acceptable*, *Suspect*, *Poor* and *Bad*; a full description of the Panel and the marking system and the defect indices is given in Appendix A.

This TRL Report presents the outcome of nine years or more of monitoring the sites in terms of skid resistance (Section 2), texture (Section 3) and visual condition (Section 4). The overall findings for serviceable life are given in Section 5 and for the mode of failure in Section 6. Data were also collected on the residual binder properties to try to identify a predictive tool for surfacing life (Section 7), and lastly a comparative analysis of the whole life cost of thin surfacings against hot rolled asphalt (HRA) is presented (Section 8).

1.3 Monitored sites

The sites chosen to be monitored for the project were initially taken from those sites that had been used to gain HA approval under the scheme used prior to the HAPAS system. These sites tended to be the oldest thin surfacing sites in the UK at that time and provided readily available data for inclusion in the study. Subsequently, when further sites were required, they were selected from those already being studied for other projects or nominated by contractors and/or local authority engineers. The numbers of sites that were monitored for this work using the different monitoring techniques employed are tabulated in Table 1.1, with data included from nine years' monitoring together with previous investigations.

All the sites in this report are identified by the acronym for the type of thin surfacing system followed by a number, using the same numbering as in the previous reports (Nicholls and Carswell, 2004; Nicholls *et al*., 2007). The numbers were allocated with a separate series for each type, but the order within each series is arbitrary, depending on when they were numbered and not any property of the site or system.

The full list of sites that have been monitored for all or part of the last three years (93 in total) is given in Appendix B. Wherever possible, the sites monitored previously (Nicholls *et al*., 2002; Nicholls and Carswell, 2004; Nicholls *et al*., 2007) continued to be monitored. However, several of the sites had been resurfaced during the monitoring period and, therefore, were not been available for the whole period. Those sites that were monitored previously but have become unavailable for monitoring are described briefly in Appendix C and the sites selected to replace them are described in Appendix D. In the description of the sites that have been lost for monitoring, the last visual condition marking has been quoted.

It is accepted that the sites that have been monitored form only a small subset of the sites that have been laid in the UK. Whilst every effort has been made to make these sites representative of the total population, it is appreciated that the selection has certain biases that, it is hoped, should approximately balance. These biases include:

Older sites

- More care was taken because thin surfacing systems were new, improving potential durability.
- Less experience was then available, so workmanship may have been less robust.

Replacement sites

- Sites had no problems when identified, so does not include potential for premature failure.
- Sites taken from other research projects should have had the extra care taken with trial sites.
- Sites notified by contractors are likely to be taken from what they believe to be their better sites.
- Sites notified by highway authorities are likely to be unusual sites.

Furthermore, it was not practical to investigate the substrates of the sites when selecting them despite their condition being important for durability, and this may have induced a further bias.

The sites that were monitored varied from motorways to minor roads across England and Wales. Although the traffic flows for many sites are known or could be obtained, analysis has not included traffic in previous reports because it was considered that this additional variable would overcomplicate the analysis. However, in this analysis it has been considered worthwhile categorising the sites by road category. The four categories of road that have been used are:

1) Motorway (13 sites)
2) Other trunk road (42 sites)
3) Non-trunk A road (70 sites)
4) Minor (B, C or unclassified) road (12 sites)

The number of sites listed is that for all sites for which any data have been collected, including some sites with very limited data and others where separate lanes have separate data requiring separate entries.

Table 1.1 Number of sites monitored and observations made

System type	*PLSD*	*TAC*	*TSMA*	*MSD*	*MS*	*Total*
Visually inspected	17 (71)	52 (250)	58 (227)	6 (28)	4 (22)	137 (598)
SCRIMtex surveyed	18 (75)	21 (81)	23 (97)	4 (18)	1 (6)	67 (277)
Cored for binder properties	4 (21)	11 (47)	12 (51)	2 (13)	2 (9)	31 (141)

Values in brackets are the total number of observations from those sites.
Data included from nine years' monitoring together with previous investigations.

2 Skid resistance

2.1 Data gathered

The Sideway-force Coefficient Routine Investigation Machine (SCRIM) is the standard equipment used for measuring skid resistance in the UK (Hosking, 1996). As explained in Section 1.3, it was neither practical nor economic to monitor all the sites for skid resistance. Therefore, a representative subset of 17 sites was chosen to be monitored over the three years of this part of the study.

Measurements to obtain SCRIM coefficients were taken three times on each of the sites during the summer measuring season to allow for seasonal variations during each year. The average of the three SCRIM coefficients measured during the summer months gives the Mean Summer SCRIM Coefficient (MSSC). The MSSC results for the sites are shown in Table E.1 in Appendix E. The results are given in terms of the number of measurements taken during the year, the MSSC value for subdivisions of the larger sites and the overall mean MSSC for each site. However, on some sites monitored under this project in previous years, fewer than three readings were made, and the MSSC for those (subdivisions of) sites has been estimated by adjusting the values by a ratio of the MSSC to the same SCRIM coefficient(s) for the average of sites with three measurements that year.

Skid resistance has a general variation between years, but these variations are not accounted for in the MSSC calculations. In order to allow for these variations, therefore, each value was factored by multiplying the average of all observations on all sites divided by the average of observations for the year in question on all sites. In deriving these factors, all initial and first year values were ignored because the sites were unlikely to have reached equilibrium. As a result, the factors for 1991 and 1992, from which all values were initial or first year, had to be set arbitrarily at unity. In the following analyses, it is the MSSC adjusted for between-year variation (referred to as the “adjusted MSSC”) that has been used.

The in-service skid resistance of a surfacing is dependent on the PSV of the aggregate, the volume of commercial traffic and the geometry of the site (such as junctions, slopes and bends). It would need considerable data to be able to consider the variation of skid resistance with each of these factors. However, by assuming that the PSV of the aggregate was selected appropriately for the other two factors, the adjusted MSSC can be plotted for different values of PSV. The results from Table E.1, together with data obtained previously (Nicholls *et al*., 2002; Nicholls and Carswell, 2004; Nicholls *et al*., 2007), are combined for each age by type of system and PSV range (<63, 63 – 67 and ≥68) and are shown graphically in Figure 2.1.

When linear trend lines were applied to Figure 2.1 for the four system/PSV combinations with data from at least 12 years, all the trend lines fall with age although there is considerable scatter. When repeated without data from the first two years (during which the sites reach equilibrium), the trend lines again fall except for TAC/PSV 63 – 67. Previously (Nicholls and Carswell, 2004; Nicholls *et al*., 2007) there had been no such consistent trend.

The data set is, in terms of statistical analysis, incomplete because:

- Only one site has data up until 14 years.
- Many sites have gaps in monitoring.
- Several sites have only a few readings.
- Not all sites have initial readings.

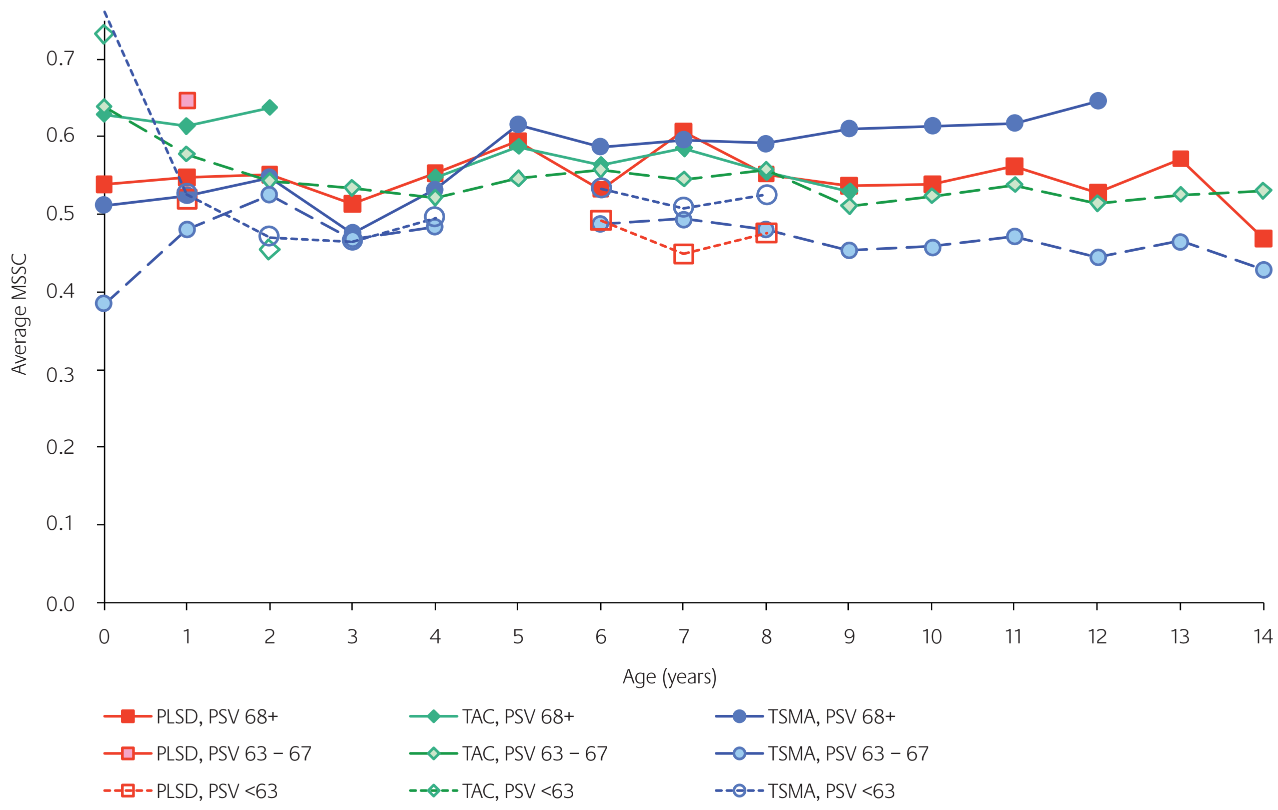
In order to minimise the bias from the inconsistency of data points in Figure 2.1, the results for the 12 sites with data for at least seven years are shown in Figure F.1 of Appendix F. These plots show a general slow reduction with time, but with some contrary points.

2.2 Rigorous statistical analysis

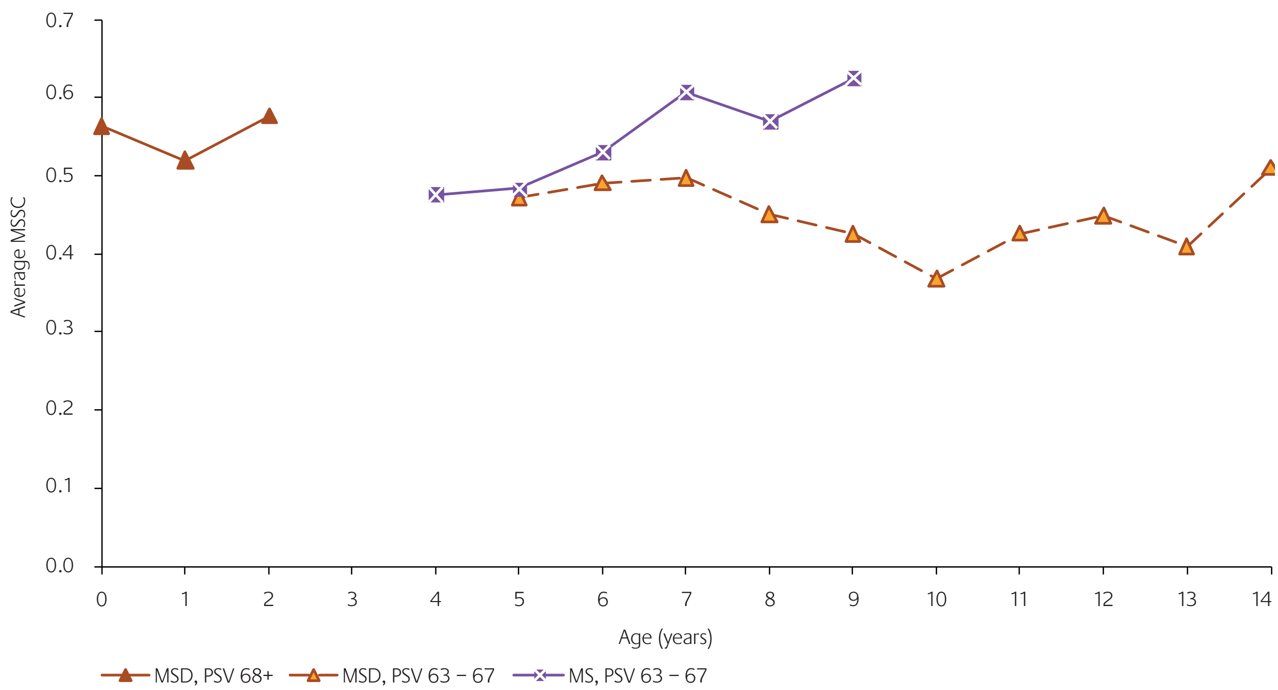
A rigorous statistical analysis to determine which variables are important in defining differences between adjusted skid resistance results is described in detail in Appendix G. The analysis indicates that, in general, there was no statistically significant decrease of MSSC as a uniform function with age of the surfacing. There is considerable fluctuation but no regular change in normalised MSSC values; some of the fluctuation in the data is possibly due to which of the sites that were included at each age. There is evidence that PSV does influence the MSSC measured, as would be expected, and that this influence appears to be quite consistent as the thin surfacing systems age.

2.3 Discussion

This parameter is unlikely to be a significant cause for replacing the surfacing because the skid resistance data showed no significant decrease of the value with the age of the surfacing. An early indication of replacement due to inadequate skid resistance would be if this parameter fell below the investigatory level for the site. This level, for each of the sites monitored for skid resistance, is provided in Table E.1. As can be seen, the measured values are below the investigatory level in only two sites and in these they are no more than half a unit below which cannot be considered a significant deficit. Therefore, on the basis of the 17 sites monitored, it is concluded that deterioration due to inadequate skid resistance is unlikely to be a reason for replacing the surfacings.



(a) Asphalt systems



(b) Surface treatment systems

Figure 2.1 Average adjusted MSSC results

3 Texture depth

3.1 Sand patch texture depth

In the UK, the texture depth of new surfacings on all trunk road sites is measured by the patch method, in accordance with BS EN 13036-1 (CEN, 2010), or previously the sand patch method to BS 598-105 (BSI, 2000), prior to the road being opened to traffic. Also, the sand patch texture depth after two years' trafficking was required from trial sites in order to gain the original HA approval and is now required to obtain a HAPAS certificate. For the monitored sites, the base data from such tests have been supplemented over the last three years with texture depth measurements from the representative subset of sites where cores were taken for the project, whenever weather conditions allowed. The results of these measurements, given in Table E.2 in Appendix E, together with data obtained previously (Nicholls *et al*., 2002; Nicholls and Carswell, 2004; Nicholls *et al*., 2007), have been combined for each age by type of system and nominal maximum aggregate size (10 mm and 14 mm) and are shown graphically in Figure 3.1.

Figure 3.1 shows that the texture depth drops over the first few years, although the amount of change and the time required to stabilise are unclear. However, the texture depth for all systems from an age of about four years appears to remain within a relatively controlled band between 0.75 mm and 1.5 mm. The two exceptions are 10 mm TAC at eight years with 2.1 mm and 14 mm MSD at 12 years with 0.5 mm.

An aspect of sand patch texture that is important for HAPAS certification is the loss of texture over the first two years. However, no additional data have been gathered for both initial and two year texture depths on the same site since the last report (Nicholls *et al*., 2007) because the additional sites either have not reached two years or their initial texture depths are not known.

3.2 Vehicle-mounted sensor-measured texture depth

For in-service monitoring of trial sites, it is not practical to close sites in order to measure the texture by the sand patch method (unless cores are being taken, as discussed in Section 3.1). Therefore, the texture depth is often monitored by laser-based texture-measuring equipment mounted on a vehicle such as SCRIM (SCRIMtex), which can travel at normal traffic speeds. The mean annual results from the 17 representative subset sites that have been monitored in this way are given in Table E.3 in Appendix E. These are the same subset for which SCRIM measurements were taken, as discussed in Section 2. The results from Table E.3, together with data obtained previously (Nicholls *et al*., 2002; Nicholls and Carswell, 2004; Nicholls *et al*., 2007), have been combined for each age by type of system and nominal maximum aggregate size (10 mm and 14 mm) and are shown graphically in Figure 3.2.

Figure 3.2 shows the sensor-measured texture depth (SMTD) to be generally constant or to steadily increase with age for asphalt thin surfacing systems. However, the more limited MSD data set from a single site suggests a steady decrease in texture with life, possibly due to the chipping embedment normally assumed in the early life of these systems as well as other surface dressings.

As for adjusted MSSC, the points in Figure 3.2 are from incomplete data because a different set of sites, if from the same population, was averaged for each year in service. Therefore, the results for the ten sites with data for at least seven years are shown in Figure F.2 in Appendix F. The results in Figure F.2 show considerable variations in performance between the sites. The general trend is for an increase in texture depth with age, particularly towards the end of the life in service, except for the MSD type which shows a significant decrease as discussed earlier. The general increase is the consequence of particle loss, as indicated by the "−" suffix in the Inspection Panel visual condition mark (Appendix A).

3.3 Rigorous statistical analysis

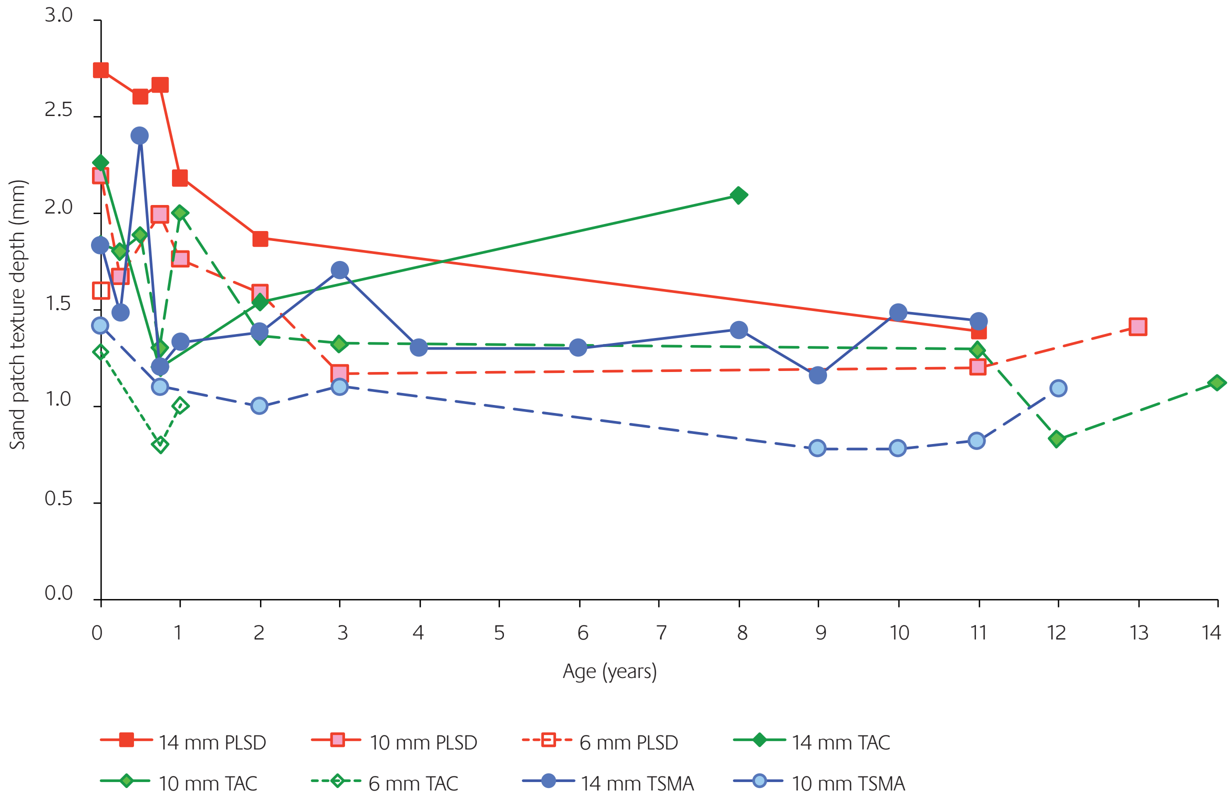
A rigorous statistical analysis to determine which variables are important in defining differences between texture depths is described in detail in Appendix H. The analysis indicates that there are reductions in texture depth as the surface ages but generally only in the early years. Understandably, the texture measures are influenced by aggregate size and binder contents. Different road types tend to use different aggregate sizes and an analysis of road type/aggregate subsets found that texture measures still differ with age of the surface. This trend suggests that there is a reasonably consistent pattern of reduction (within subgroups of sites) that is not influenced by other factors such as aggregate size, binder contents or particle loss.

3.4 Discussion

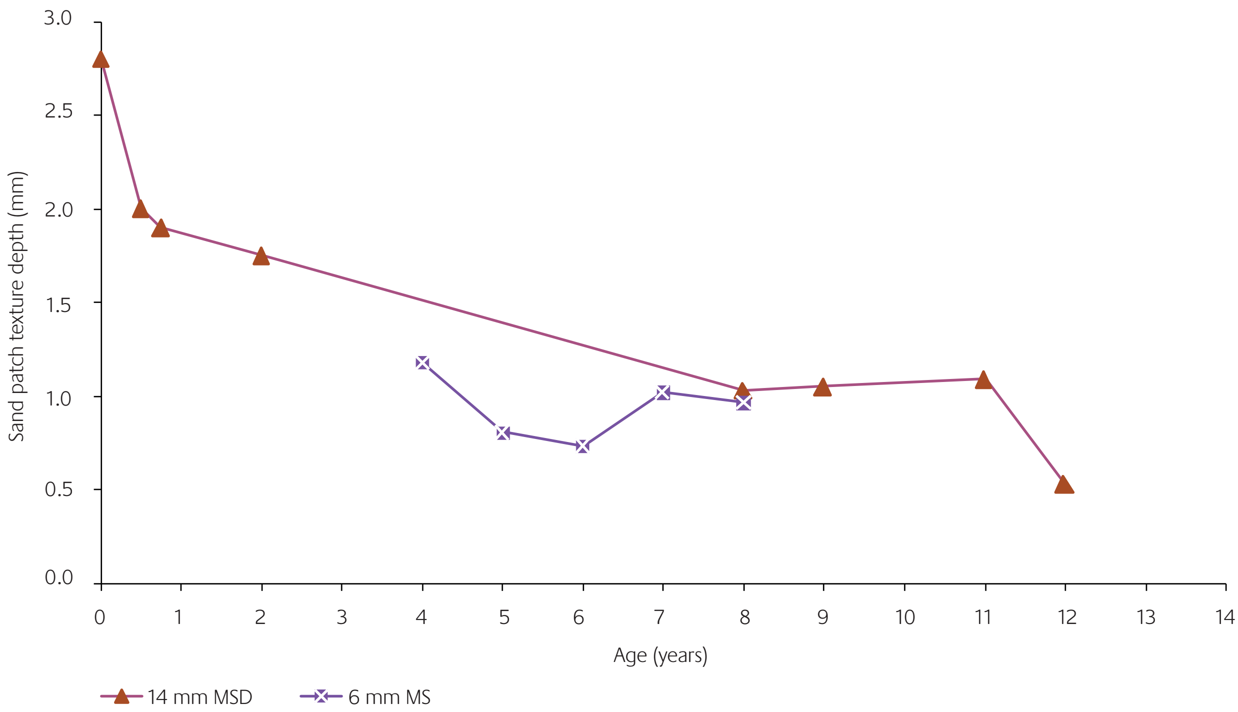
This parameter is unlikely to be a significant cause for replacing the surfacing because the texture data showed no significant decrease of the value with the age of the surfacing, apart from the initial reduction. An early indication of replacement due to inadequate texture would be if this parameter reached the level 3 condition category for the site, 0.8 mm SMTD, as defined for TRAffic-speed Condition Surveys (TRACS) in Table 2.1 and Table 2A.1 of Annex 2A in HD 29/08 (HA *et al*., 2008). As can be seen, the measured values are below this level for only a small proportion of the sites and, after the initial reduction and apart from MSD sites, do not trend downwards into this condition. Thus any failure to meet an acceptable condition is not due to a deteriorating trend but due to an inadequate initial construction.

In contrast, the MSD sites show a significant deteriorating trend throughout their life, (Figure 3.2). Surface dressings are expected to lose texture over the first few years, but this loss continued for longer. However, the data are from a single site.

Therefore, on the basis of the 17 sites monitored, it is concluded that deterioration due to inadequate texture depth is unlikely to be a reason for replacing the surfacings.

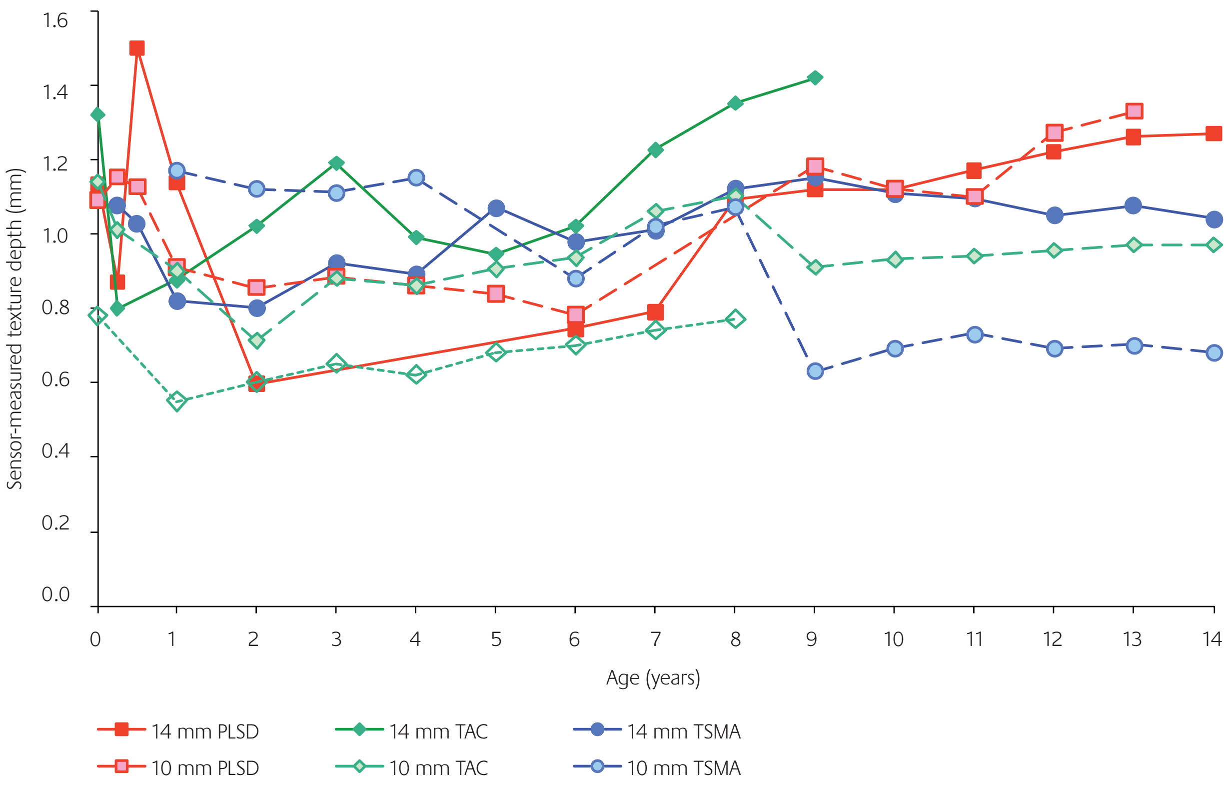


(a) Asphalt systems

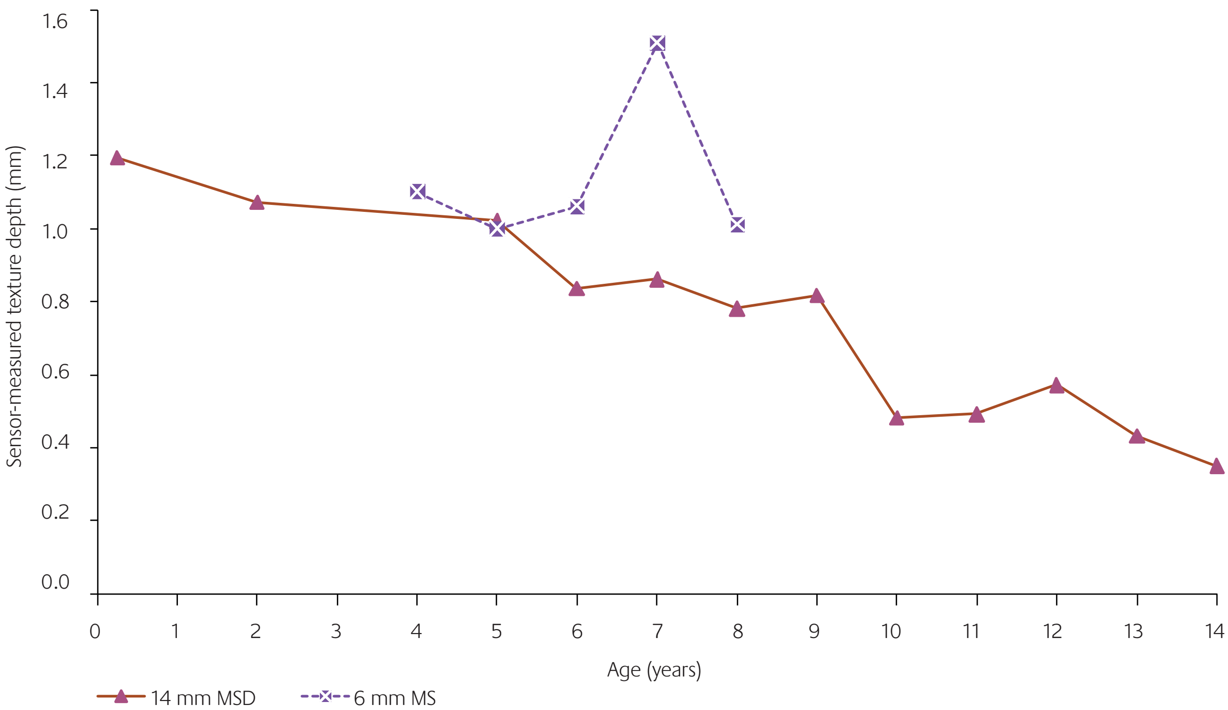


(b) Surface treatment systems

Figure 3.1 Average sand patch texture depths



(a) Asphalt systems



(b) Surface treatment systems

Figure 3.2 Average sensor-measured texture depths

4 Visual condition

4.1 Data gathered

The sites monitored as part of this research project were assessed visually by an Inspection Panel (comprising representatives from the HA, asphalt producers, bitumen suppliers, trade bodies and TRL) and ranked in accordance with the TRL Inspection Panel methodology (Nicholls, 1997). The assessment attributes a mark (*Excellent*, *Good*, *Moderate*, *Acceptable*, *Suspect*, *Poor*, *Bad* or midway between two adjacent marks) plus, when appropriate, defect suffixes to each site; the meaning of each mark (Table A.2) and defect suffix (Table A.1) are described in Appendix A. The results from the three years of monitoring are given in Table E.4 in Appendix E.

The total number of sites and the observations made of them from Table E.4 and previous reports (Nicholls *et al*., 2002; Nicholls and Carswell, 2004; Nicholls *et al*., 2007) that were available for analysis are given in Table 4.1. Of the 137 sites, 32 were only monitored once whilst 13 had nine or more visits.

The distribution of visual condition for each age of surfacing is given in Figure 4.1, which shows the expected trend of condition deteriorating with age but with considerable variability.

The results have been combined as mean values for each age by type of thin surfacing system and are shown graphically in Figure 4.2 together with linear trend lines for each type. The extent of the variation is shown in Figure 4.3 where maximum and minimum values are also shown for each data set from which the means were calculated. The maximum and minimum symbols have no fill whereas those for the means are solid.

Breaking the data down further, the mean visual condition marks have been plotted in Figure 4.4 for the three asphalt types of thin surfacing system (PLSD, TAC and TSMA) with 14 mm, 10 mm and 6 mm aggregate sizes; again linear trend lines are shown. For both these figures, the trend lines are based on unweighted means and, as such, strictly they are not statistically valid.

As for adjusted MSSC and SMTD, the data points in Figures 4.1 to 4.3 are not strictly comparable from year to year because a different set of sites, if from the same population, was averaged for each year in service. The results for the 13 sites with data for at least nine years are shown in Figure F.3 of Appendix F. The trend of these plots is generally a reduction with time but, for several sites, there is a strong plateau after an initial loss on several of the sites as there is for skid resistance and texture depth.

The visual condition data have been analysed in a number of ways. Appendix I presents a number of simple statistical analyses. The main findings are:

- The trends for sites grouped by system type using the mean values at each age showed that quadratic equations do not significantly improve the modelling of serviceable life relative to linear equations, which produced correlation coefficients (excluding MS) between 0.80 and 0.97.
- When the systems are split by aggregate size, the correlation coefficients (excluding MS) were between 0.98 and 0.50.
- When individual data points were used with the systems split by aggregate size, the correlation coefficients (excluding MS) were between 0.31 and 0.93.
- An analysis of median values implies that, if sites can be allowed to deteriorate to a *Suspect* condition, there would be no defects on TAC and TSMA systems until eight years in service.
- Using multiple regression analysis on the asphalt systems shows that the binder content is the most significant factor after age. The system and, to a lesser extent, the binder type and the aggregate size also influence the rate of deterioration. The category of road, however, does not appear to affect the deterioration.

Table 4.1 Number of sites and observations of visual condition by system type and aggregate size

System type	*PLSD*		*TAC*		*TSMA*		*MS/MSD*	
	Sites	*Observations*	*Sites*	*Observations*	*Sites*	*Observations*	*Sites*	*Observations*
14 mm	9	32	21	82	49	197	6	28
10 mm	7	33	23	134	9	30	–	–
6 mm	1	6	8	34	–	–	4	22

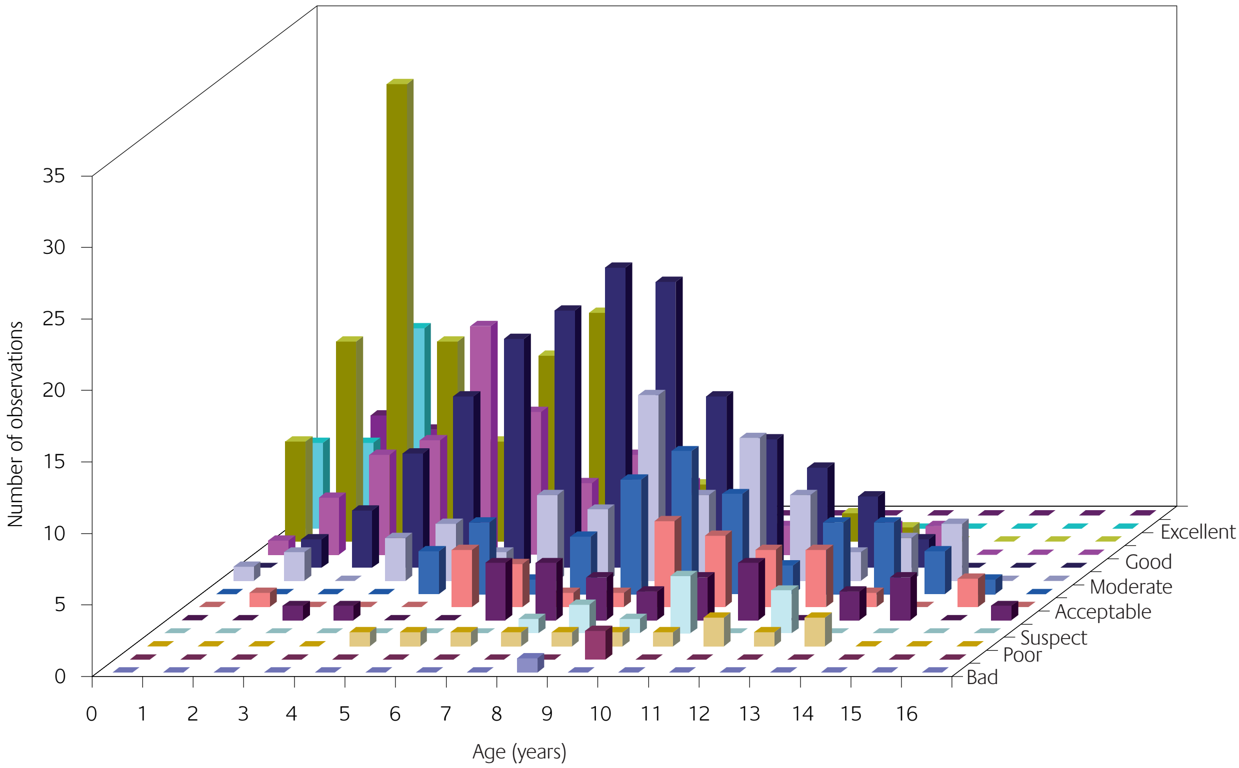
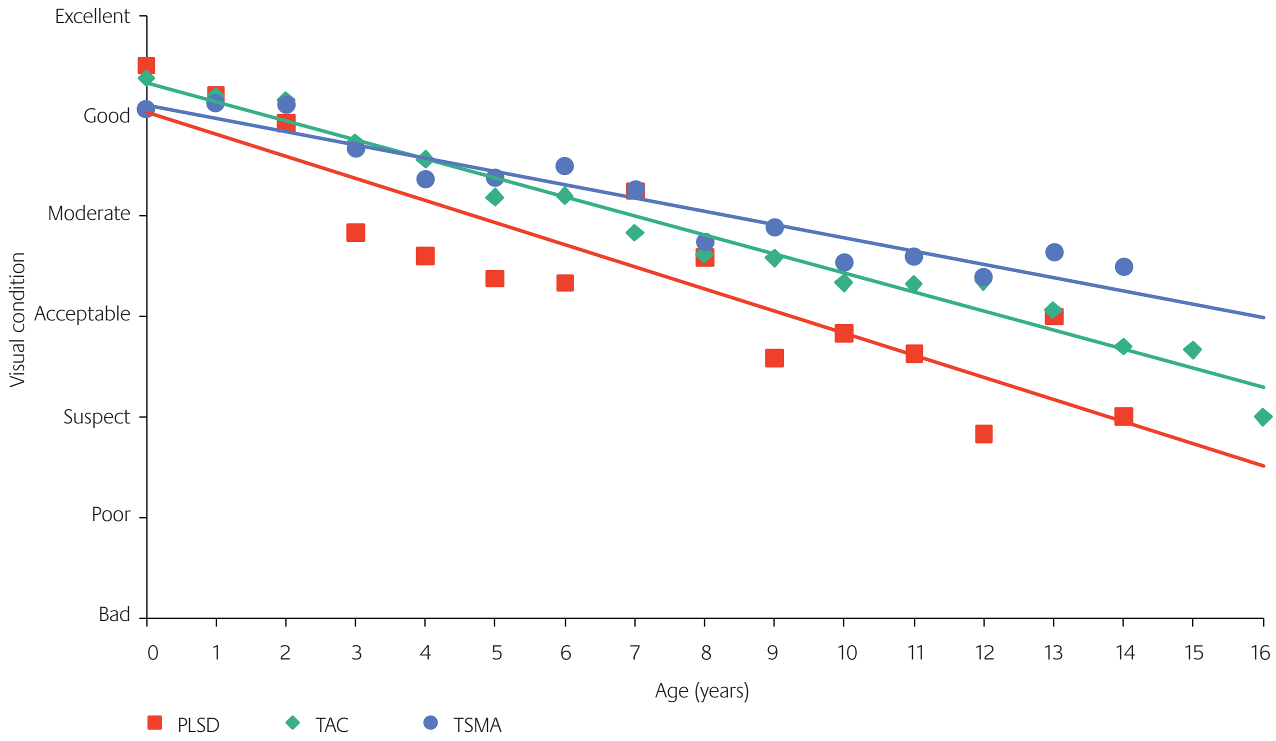
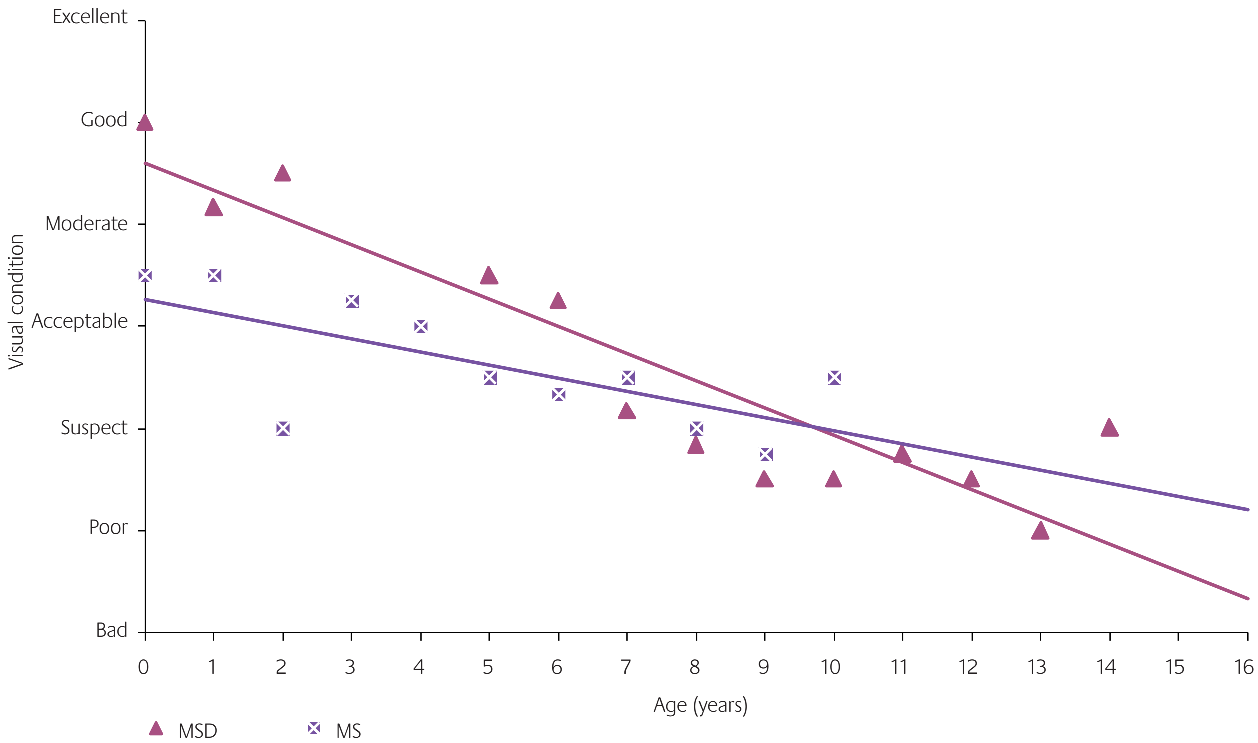


Figure 4.1 Visual condition observations from all sites

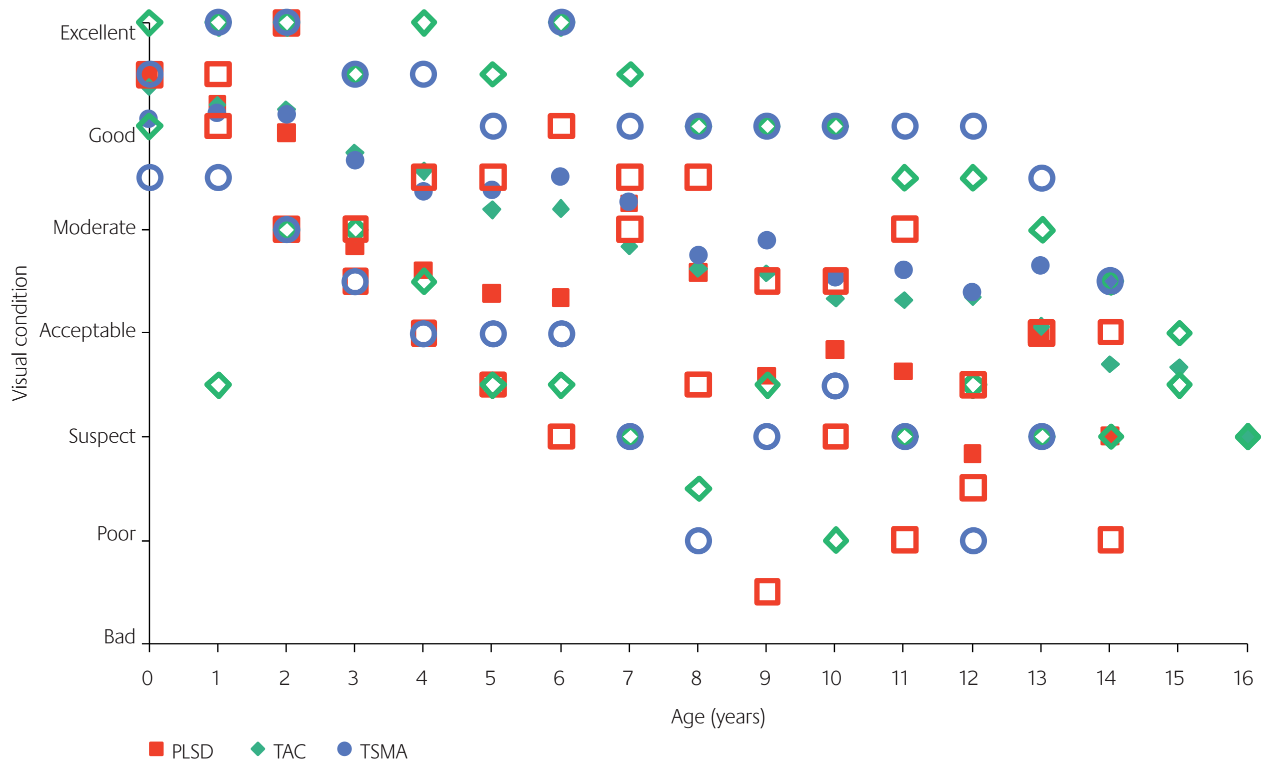


(a) Asphalt systems

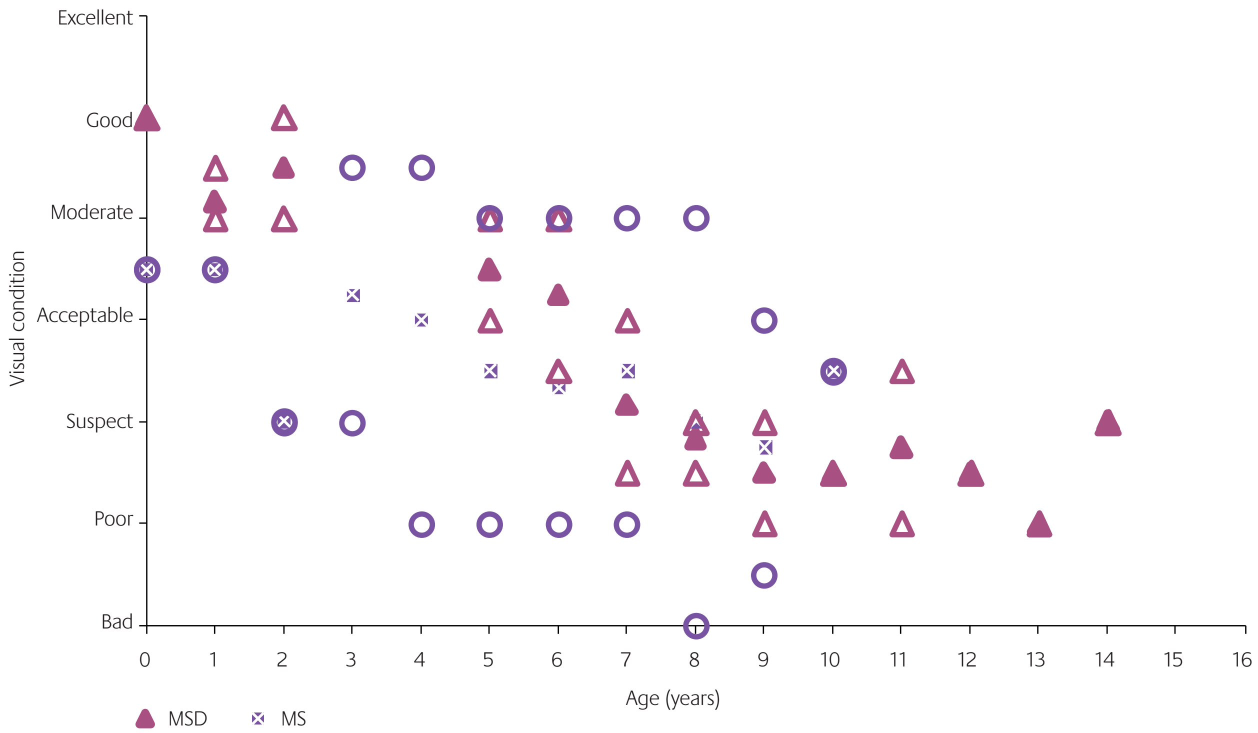


(b) Surface treatment systems

Figure 4.2 Average visual condition markings

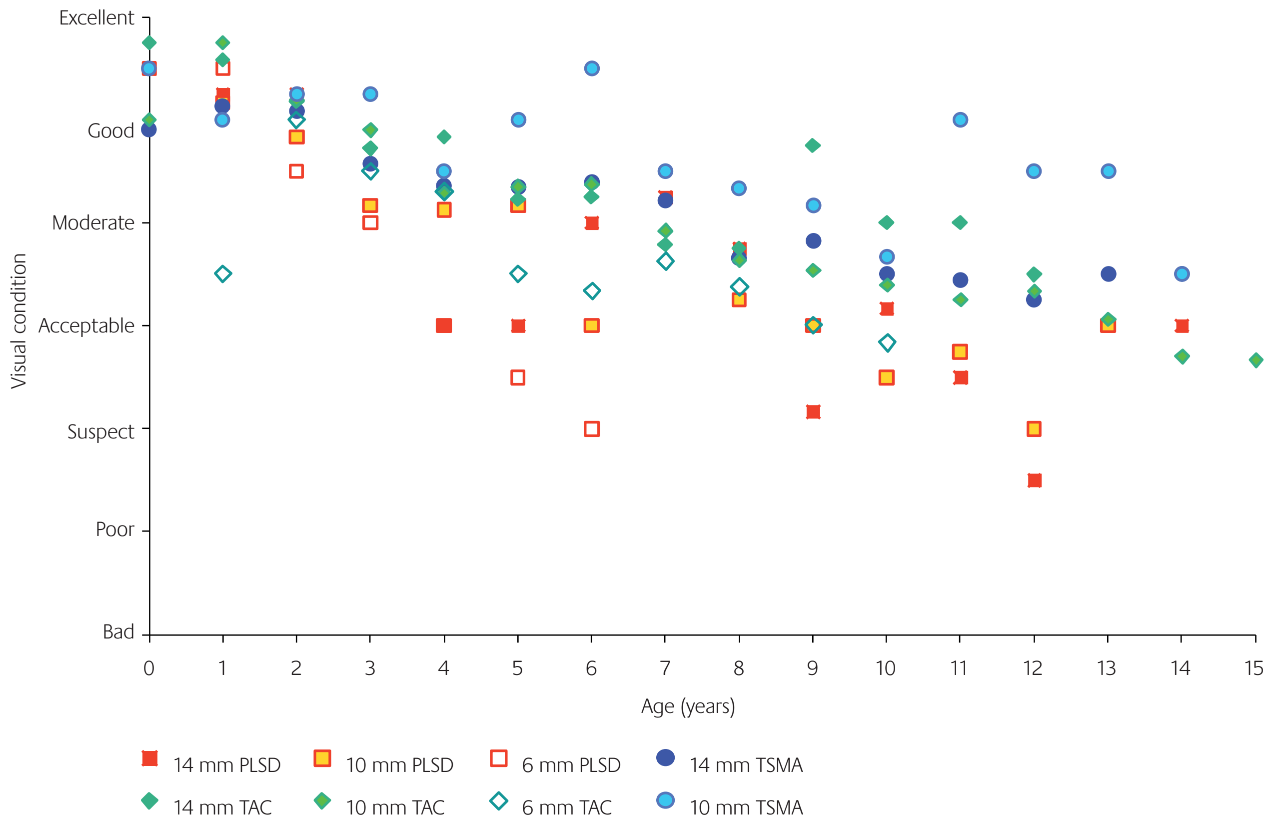


(a) Asphalt systems

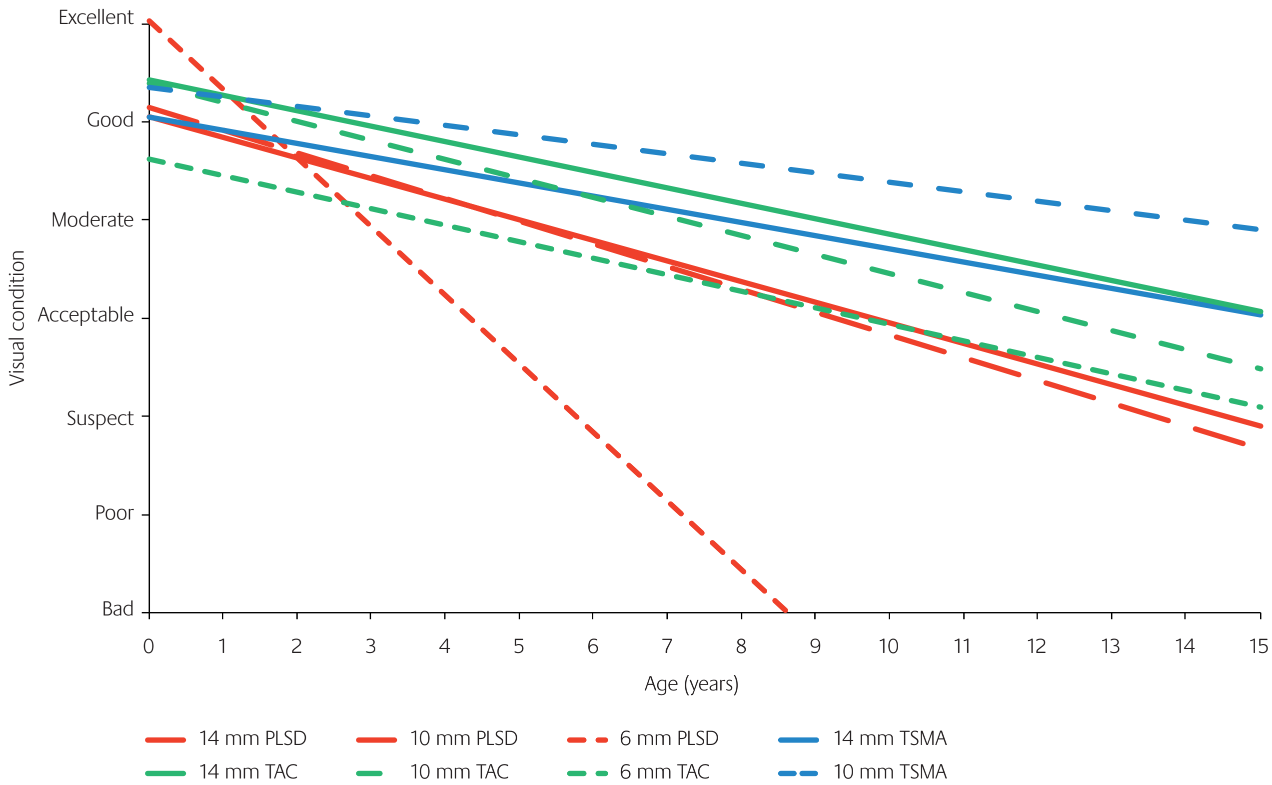


(b) Surface treatment systems

Figure 4.3 Range of visual condition markings



(a) Points



(b) Trend lines

Figure 4.4 Average visual condition markings of asphalt systems subdivided by aggregate size

4.2 Rigorous statistical analysis

A rigorous statistical analysis to determine which variables are important in defining differences between visual condition results is described in detail in Appendix J. The analysis found that it was important to consider aggregate size and system type when analysing changes in visual condition. Further, the binder content was also found to be important for some combinations of variables. In contrast to the simple statistical analysis presented in Appendix I, this more rigorous approach uses a logistic transform of visual condition in the regression equations in order to estimate the expected serviceable life of the sites (defined here as the life whilst the site is better than *Suspect* condition) with the results given in Table 4.2 and Figure 4.5.

The estimated serviceable lives varied between six years (PLSD with 6 mm aggregate) and 26 years (TSMA with 10 mm aggregate) depending on the system type and aggregate size. The size of the confidence interval on the estimated life varied considerably, reflecting the sample size used for the regression calculation and the consistency of performance within each category. The relationship between the visual condition and either of the recovered binder properties is reasonably consistent but the correlations are not particularly strong.

The results suggest that TSMA systems with 10 mm aggregate should last longest before becoming unserviceable. However, this regression is based on just 30 data points and only 29 % of the variation has been explained, so that there are wide confidence intervals on the 26-year estimate (which is also beyond the data range used to determine the regression) of 16 to 38 years for 95 % confidence intervals. In contrast, the TSMA 14 mm estimate of life of 19 years is based on 105 data points with a consequent narrower confidence interval of 17 to 21 years and with 37 % of the variability explained.

The estimated ages and associated confidence intervals should be used with care when the estimate exceeds the data range used to derive the regression equations. Any predictions beyond 16 years involve extrapolating beyond the data, there being no data for sites older than 16 years (and most for somewhat less), and are to be viewed with caution.

4.3 Continental comparison

The Inspection Panel made a visit to Germany in 2008, where serviceable lives in excess of 16 years are expected for SMA surfacings. One site on a busy Autobahn was considered to be *Good* to *Moderate* after 19 years' service. The German SMA mixtures have lower air voids and higher binder contents than UK surfacing materials. However, it is appreciated that the relatively high texture depth specified on high-speed trunk roads in the UK currently preclude the use of such mixtures. A summary of this visit is given in Appendix K. The visit demonstrated the advantage in terms of durability of reducing the air voids content of SMA mixtures. However, this change could have safety implications because there will be a reduction in texture depth, which is a potential issue at high speed. Further research is being carried out in the UK on these materials by Transport Scotland and data from these trials will be invaluable in future considerations of safety versus durability.

Table 4.2 Predicted serviceable life of surface

Site type and aggregate size	*Predicted serviceable life in years with 95 % confidence intervals*		
	Estimate	*Lower 95 %*	*Upper 95 %*
6 mm PLSD	5.5	4.7	6.5
10 mm PLSD	11.0	9.5	12.5
14 mm PLSD	11.8	9.1	14.7
6 mm TAC	14.3	9.6	19.6
10 mm TAC (5.5 % binder)	16.9	15.7	18.1
14 mm TAC (5.5 % binder)	16.4	14.1	19.0
10 mm TSMA	25.9	15.9	38.3
14 mm TSMA	18.9	16.5	21.4
MSD	7.4	6.3	8.5
MS	7.8	2.8	13.3

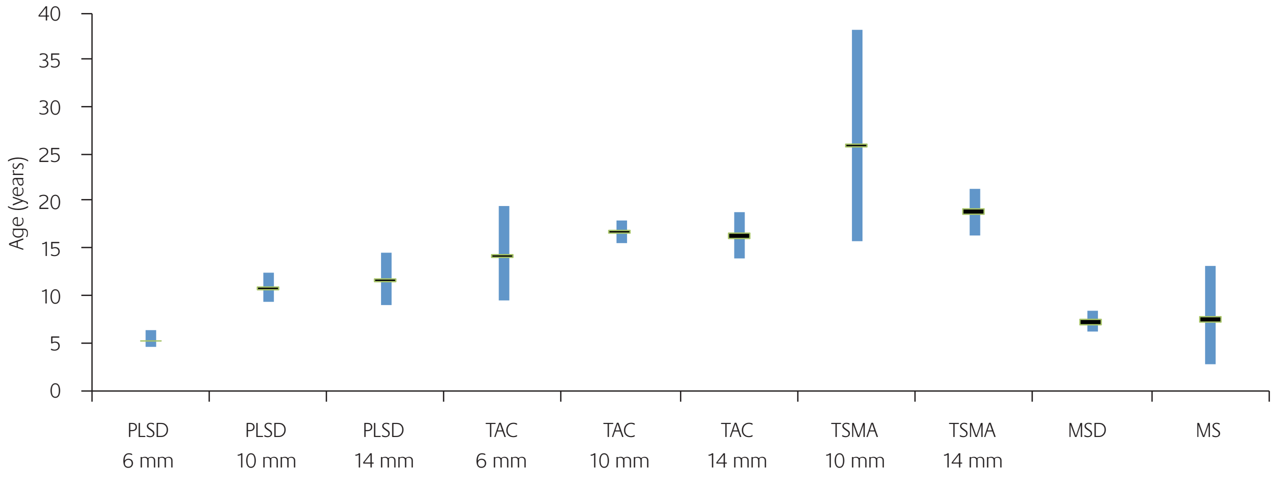


Figure 4.5 Estimated serviceable life with 95 % confidence intervals

4.4 Influence of jointed concrete substrate

Of the sites monitored for this project, 15 (PLSD7, PLSD8, PLSD10, PLSD14, TAC1, TAC2, TAC25, TAC26, TSMA8, TSMA15, TSMA22, MSD5, MSD6, MS3 and MS4) had thin surfacing systems laid over a jointed concrete substrate (generally directly without a bituminous binder course). As expected, reflective cracks appeared over the joints which detracted from the visual condition assessments. Once that stage was reached on any site, two marks were given, one with and one without the reflection cracks and associated defects. The latter assessments have been included in the main data set, tabulated in Table E.4 in Appendix E, on the basis that defects at the joints for such a thin layer would be independent of the material type.

The mean values of the overall visual condition including reflection cracks from this subset of sites are shown graphically in Figure 4.6 for each type of thin surfacing system. The linear trend lines for the whole data set of sites as shown in Figure 4.2 are also shown for comparison and show that, other than for MS systems, there is no significant difference from the general behaviour of the full data set.

Taking the difference between the two measures for each site, as shown in the vertical axis of Figure 4.7 (where one unit indicates a difference of one mark, say *Moderate* excluding joints and *Acceptable* including them), shows that reflective cracking did not make any difference for at least five years, and even then the three sites where a difference was seen showed no difference again until year 11 whilst another started showing a difference at year 9. The majority of observations showed no difference because the reflection cracking had not shown through and were, therefore, the same assessments.

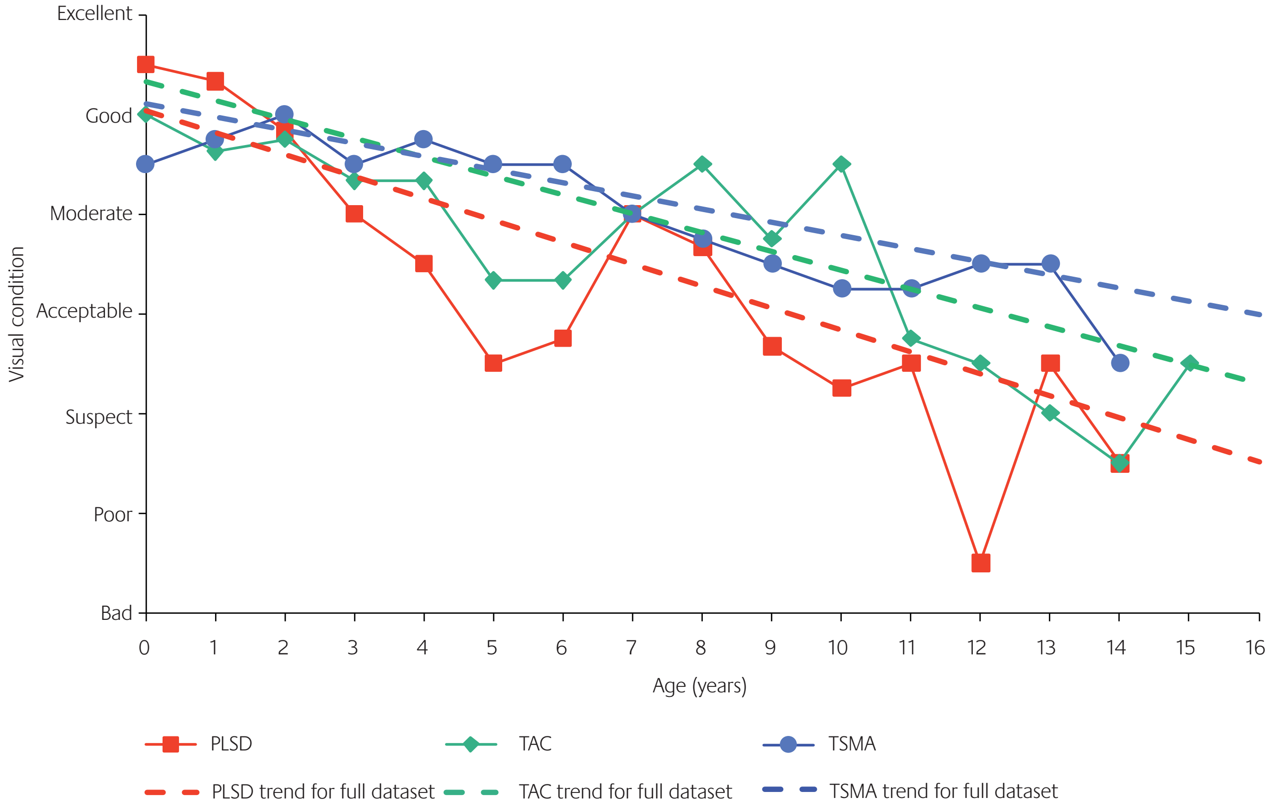
Although differences were not observed on all sites, the emergence of reflection cracks on some sites when they became older could impair the visual condition by up to one and a half marks, which in turn implies that the time before the surfacing will need to be replaced will be significantly reduced.

4.5 Examples of sites with extreme performance

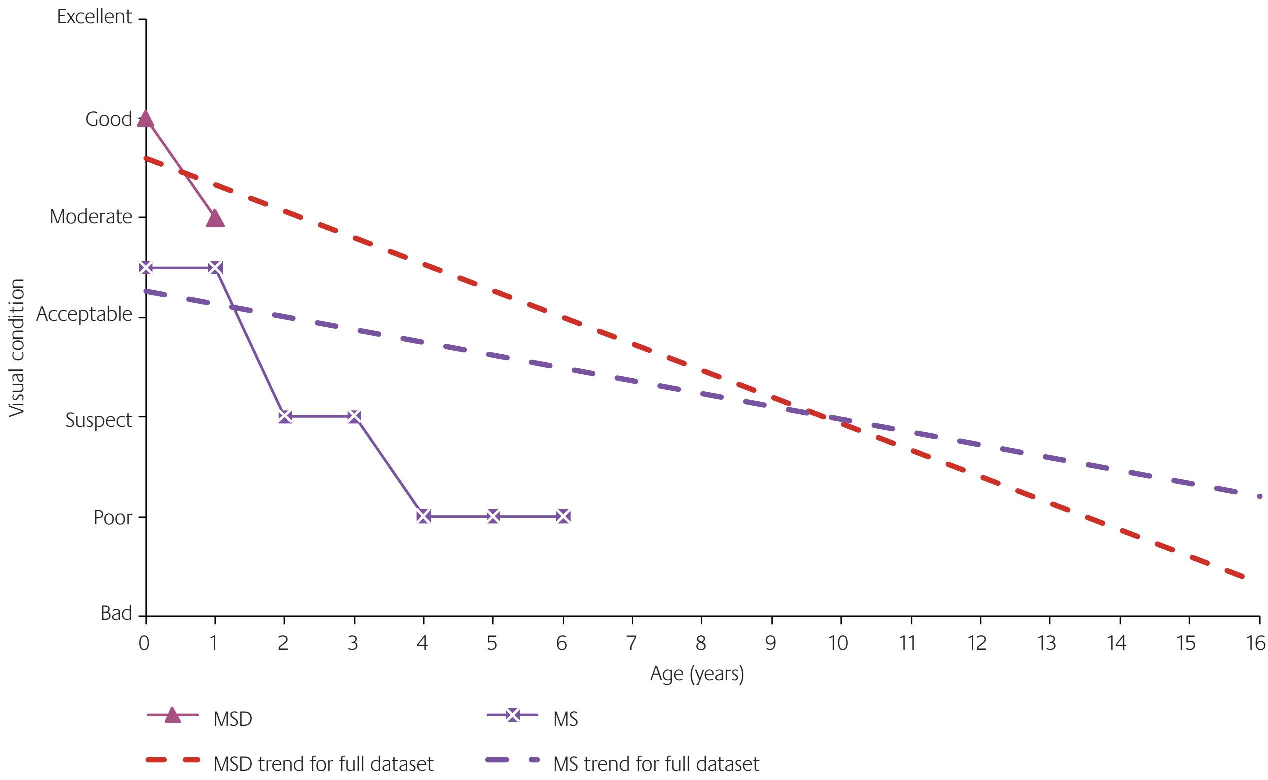
There have been several reported claims that thin surfacing systems do not perform as well as expected from the results from this work. Therefore, an attempt was made to substantiate these claims by asking for extreme examples of thin surfacing systems at sites where the surfacing has either failed within five years (based on the recently introduced five-year warranty period) or have survived for more than 12 years (the systems having only been introduced into the UK in 1991). The request was sent to representatives of the HA Area Agents and relevant HA staff in 2007. The limited results from this request are given in Appendix L with three "poor" and one "good" example. These examples provided are:

- The A590 in Barrow-in-Furness where TSMA was laid in 1995 and which was still in *Moderate* condition in 2007.
- The A5 at Shotatton where TAC was laid in 2000 and which started to deteriorate noticeably in early 2004 with major particle loss that had developed into potholes by 2005. The primary reason for premature failure is suggested to be the inability to dry the stone adequately in winter conditions.
- Two roundabouts in HA Area 7 had an early life skidding problem rather than a durability problem.
- A review of thin surfacing systems in Cumbria demonstrated that the installed systems were generally performing satisfactorily but that there were problems identified with a number of common factors. These relate to initial treatment selection for the site, the designer's assessment of the site, selection of systems and workmanship.

The overall implication appears to be that, whilst many claim that there are numerous instances of premature failure with thin surfacing systems, such failures are not as common as often believed.



(a) Asphalt systems



(b) Surface treatment systems

Figure 4.6 Mean overall visual condition of thin surfacing systems overlaying jointed concrete substrates

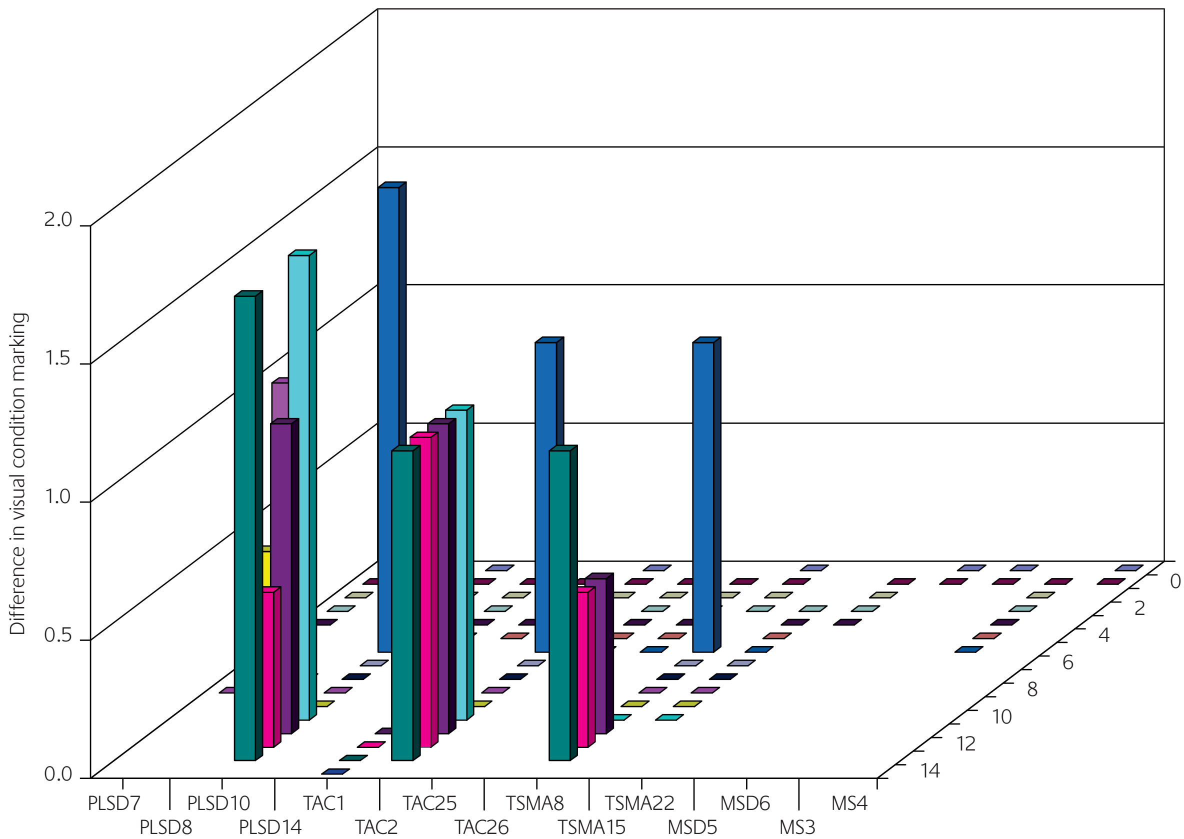


Figure 4.7 Difference in visual condition marks on sites with jointed concrete substrates when not excluding the reflection cracks

5 Overall durability

5.1 Definition of durability

A definition of the durability of asphalt pavements is given in Road Note RN42 (Nicholls *et al.*, 2008) as:

- asphalt durability – maintenance of the structural integrity of compacted material over its expected serviceable life when exposed to the effects of the environment (water, oxygen, sunlight) and traffic loading
- pavement durability – retention of a satisfactory level of performance over the structure's expected serviceable life without major maintenance for all properties that are required for the particular road situation in addition to asphalt durability

For this report, the measure of durability is taken to be by visual assessment with sites assessed as better than *Suspect* being judged to be still serviceable. Measures of acceptable skid resistance and texture depth were discussed earlier in Sections 2 and 3. These analyses showed that deterioration due to inadequate skid resistance or texture depth was unlikely to be a reason for replacing a surfacing and thus a measure of durability.

5.2 Sites with known lives

As has been shown in earlier sections, the serviceable life of a pavement can be estimated beyond available data by the use of trend lines. However, these estimates have a degree of uncertainty due both to the variability in performance of the same type of surfacing and, particularly, because projecting trend lines beyond available data will increase the uncertainty. The nature of deterioration in pavements is that failure can occur suddenly and not necessarily in a smooth, predictable fashion. Therefore, another method of estimating serviceable lives is to consider known serviceable lives. These can be defined in two main ways:

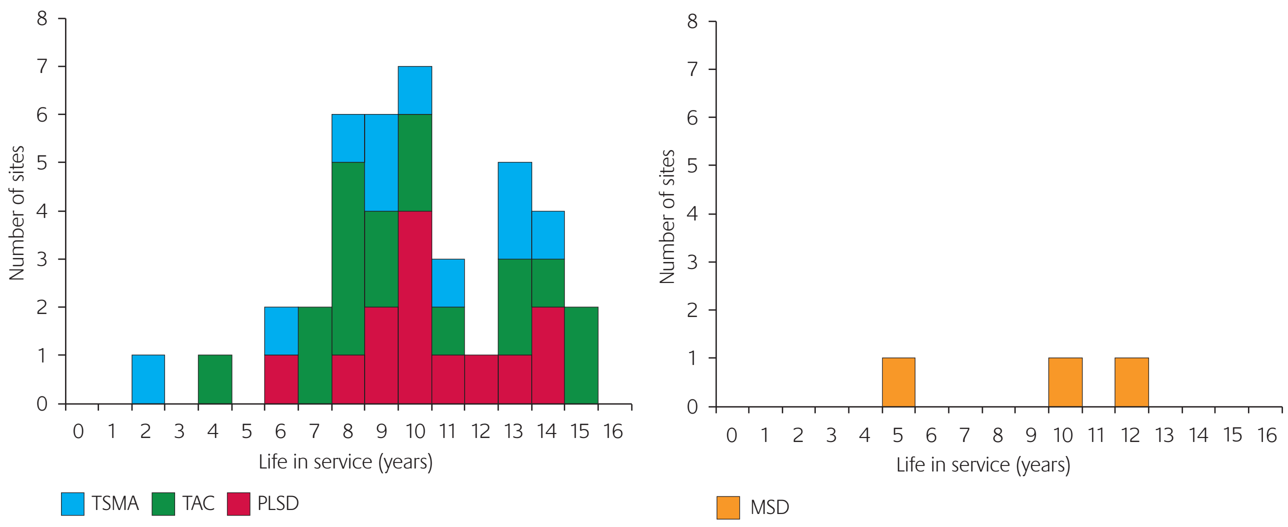
- When the site has been resurfaced or overlaid (termed "life in service" in this report), or
- When the visual condition of the site has dropped to *Suspect*, as assessed by the Inspection Panel (termed "serviceable life" in this report).

The disadvantage of the first definition is that some of the sites being monitored remained in service long after the Inspection Panel had deemed them unserviceable whilst others were removed when still in what was considered to be a serviceable condition. The reasons for the former could include shortage of funds to carry out the ideal maintenance treatment and for the latter could include the surfacing being replaced because it was located within a section for which a major maintenance scheme was being implemented and the surfacing being surface dressed whilst still in good enough condition to benefit from the treatment.

In addition, it should be noted that estimates of known lives are not totally representative of the lives of total population because thin surfacing systems have not been used in the UK for long enough to include the durable tail of the population.

The known serviceable lives for sites from which data has been collected but which have either subsequently been replaced/overlaid or dropped to a visual condition of *Suspect* or less are tabulated in Appendix M.

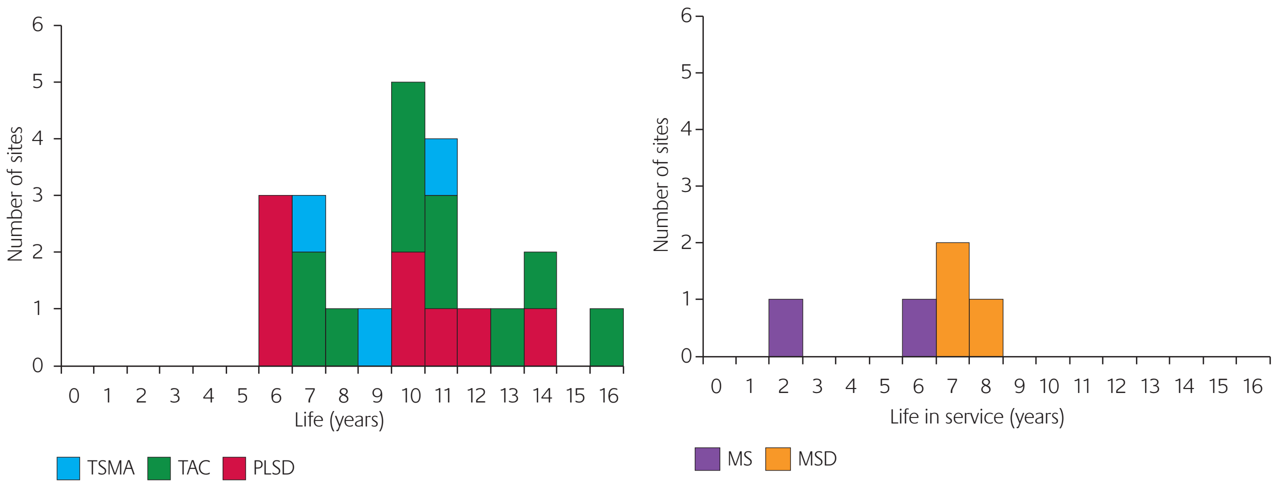
The life in service of a material at a site can be either greater (if replaced early) or less (if the material was allowed to remain in place after it had become unserviceable) than the serviceable life as assessed independently. The histograms of the lives in service achieved are shown in Figure 5.1, divided into asphalt systems and surface treatment systems.



(a) Asphalt systems

(b) Surface treatment systems

Figure 5.1 Histogram of lives in service



(a) Asphalt systems

(b) Surface treatment systems

Figure 5.2 Histogram of serviceable lives

The data from Figure 5.1 are, however, biased to giving lower than typical lives in service because sites that are still serviceable are not included in the data set. Nevertheless, the average life in service for all types is 9.9 years with a standard deviation of 3.0 years and the lives in service for individual types are 10.5 years for PLSD, 9.9 years for TAC, 9.4 years for TSMA and 9.0 years for MSD. No allowance is made for road category.

As discussed above, estimates of serviceable life can also be derived directly from the visual observations of the Inspection Panel. A histogram of this data where the visual condition has dropped to *Suspect* is seen in Figure 5.2. As for "lives in service", the data from Figure 5.2 are biased to giving lower than typical lives in service because sites that are still serviceable are not included in the data set. The average for all types is 9.2 years with a standard deviation of 3.1 year whilst the lives for individual types are 9.4 years for PLSD, 10.0 years for TAC, 9.1 years for TSMA, 6.8 years for MSD and 4.0 years for MS. Most of these values are similar to those of the lives in service, indicating the serviceable level broadly reflects current maintenance practice.

5.3 Visual deterioration

The more rigorous non-linear statistical analysis (Appendix J) provides estimated service lives and 95 % confidence limits on those estimates for the thin surfacing systems to reach the serviceable condition of a visual condition of *Suspect*. The values, together with the number of sites and observations on which they are based, are given in Table 5.1.

Several other analytical methods have been used to assess the serviceable life. Table I.5 of Appendix I gives estimates of the typical serviceable life of a surfacing for a range of system types and aggregate sizes to reach a specified visual condition using these approaches. Combining these values to give an estimate of the typical lives produces Table 5.2. There is limited confidence in any values that have been extrapolated beyond the available data. Therefore, these values are not shown but are replaced with a greater than (>) sign in front of the age at the last survey.

Table 5.1 Predicted serviceable lives from non-linear statistical analysis of visual data

Thin surfacing system	*Nominal size (mm)*	*No. of sites*	*No. of observations*	*Estimated serviceable lives (years)*	*95 % confidence limits (years)*
PLSD	14	9	32	12	9.1 – 15*
	10	7	33	11	9.5 – 13
	6	1	6	5.5	4.7 – 6.5
TAC	14	32	82	16*	14* – 19*
	10	33	134	17*	16 – 18*
	6	8	34	14*	10 – 20*
TSMA	14	49	197	19*	16* – 21*
	10	4	30	26*	16* – 38*
MSD	14	6	28	7.4	6.3 – 8.5
MS	6	4	22	7.8	2.8 – 13*

Many of these values are extrapolations, being greater than the oldest site observation. These values are indicated with the addition of an asterisk.

Table 5.2 Typical predicted serviceable lives from combined results from linear and quadratic statistical analysis of visual data

Panel mark	*Serviceable life (years) for system type*									
	PLSD			*TAC*			*TSMA*		*MSD*	*MS*
	14 mm	*10 mm*	*6 mm*	*14 mm*	*10 mm*	*6 mm*	*14 mm*	*10 mm*	*14 mm*	*6 mm*
Moderate	5	4½	3½	7½	7	5	8	11	2½	–
Acceptable	9	7½	5½	>12	13	10	14	>14	5½	3
Suspect	13	9½	6	>12	>16	>10	>14	>14	9	8½
Poor	>14	>14	>6	>12	>16	>10	>14	>14	13	>10

The dash in the cell indicating the time for MS to reach *Moderate* condition results from those systems usually having some visual defects when constructed.

6 Mode of failure

Defects were monitored in terms of whether they were present rather than the extent to which they were present. The number of sites on which each of the monitored categories of defect were found during inspections of sites, both during 2007 to 2009 and previously (Nicholls, 1998; Nicholls *et al*., 2002; Nicholls and Carswell, 2004; Nicholls *et al*., 2007), for each system type have been compiled in Appendix N. For sites with thin surfacing systems that are laid directly onto jointed concrete pavements where two marks were given, the monitored categories of defects ignoring the effects of those joints are used on the basis that defects at the joints for such a thin layer would be independent of the material type.

Table N.2 of Appendix N shows that the time before the average of the number of categories of defects that were identified on each site reached one was only a few years, with 10 mm TSMA taking the longest at nine years and 14 mm TSMA next at seven years. After ten years, the upper age to which thin surfacing systems were hoped to reach when first introduced to the UK (eight to ten years), on average sites with TSMA systems exhibited between one and two categories of defect, sites with PLSD and TAC systems exhibited between two and three categories of defect and the sites with surface treatment systems exhibited around four categories of defect. This relative performance is typical through the life of the surfacings.

With regard to the most common categories of defect, particle loss and cracking were first and second whilst, of the next two most common categories, delamination became more prevalent than fatting up after about four years when any excess binder had been worn off. However, because it is a transient defect for asphalt systems (the fatted up binder gets worn away by the traffic in time), fatting up is not likely to lead to failure.

Particle loss, the most prevalent category of defect, occurred from year one on the surface treatment systems, MSD and MS, but the relatively limited number of sites with these systems increases the possibility that the presence on some atypical sites may have biased the situation. On high-speed sites, the loss of material in early life was fairly common. Of the asphalt systems, the defect started to appear after one to three years other than for the 10 mm TSMA systems, from which there was no discernable particle loss from any site until seven years. Overall of the three asphalt systems, PLSD generally had the largest proportion of sites with particle loss and TAC had the smallest, but this was not consistent at all ages across the range of sites monitored.

The appearance of cracks took longer than particle loss to become visible. Both the surface treatment systems exhibited cracks in year one, but then a distinct delay before further sites with cracks appeared, for which no explanation is offered other than the limited number of systems monitored at that age. Ignoring the first year, these systems took the longest to exhibit cracking (six and five years for MSD and MS systems, respectively) but, once the defect appeared, it quickly became prevalent for all sites with the MSD systems. The emergence of cracks on the fewer sites with MS systems was less consistent. The asphalt systems (PLSD, TAC and TSMA) started to exhibit cracks a year earlier, but the proportion with cracks never reached much above half until year 13 or 14. Cracking of the thin surfacing system layer will generally be a function of the substrate on which it is laid more than of the overlying thin surfacing system. Therefore, an assessment of the material's ability to cope with cracking, once it had occurred, was made by the Inspection Panel before assigning it as a defect. That is, if the surfacing starts to spall, fret or ravel back from the crack, then a suffix "c" would be applied to the visual marking.

Of the asphalt systems: PLSD sites had no delamination until year five and then its prevalence on sites varied but, overall, increased with time; TAC showed a similar pattern but with fewer sites exhibiting delamination generally; whilst TSMA sites showed practically no signs of delamination. The sites with the surface treatment systems, MSD and MS, took seven and two years, respectively, to show any signs but thereafter delamination became prevalent.

Fatting up occurred most frequently with the MSD systems, where it occurred on most sites after five years. The MS systems have significant fatting up initially and in the first year, but this defect was not observed again for reasons discussed earlier in this section. With the asphalt systems, where it would be expected to be predominately an early life situation, it was seen at varying times but only on a minority of sites.

Stripping (when the binder strips from the aggregate particle and, as such, is very local and difficult to spot) was only observed occasionally, never being evident on more than 5 % of the sites at any age. Therefore, it is not considered to be a major problem on thin surfacing systems.

Variability is not a defect in itself, but an indication about the uniformity of the presence of one or more other defects (i.e. whether the defect is present in places but not throughout the complete length). There was considerable variability with most types of system, but all observations with MSD systems generally showed more significant variability than any of the other system types.

7 Recovered binder properties

7.1 Approach

Data were also collected on the residual binder properties in an attempt to understand the influence of material properties on surfacing life which might be used in the development of a predictive tool for surfacing life. Therefore, a number of cores were taken from a representative selection of the sites during the course of the study. A total of 141 of these cores were taken from 31 of the sites with the distribution of cores taken from each type of surfacing was provided earlier in Table 1.1.

Sets of cores were cut from the selected sites and the binder recovered from the cores using the rotary evaporator method in accordance with BS EN 12697-3 (CEN, 2005) before being combined to produce sufficient sample for subsequent testing. These samples were then tested for penetration and softening point in accordance with BS EN 1426 (CEN, 2000a) and BS EN 1427 (CEN, 2000b), respectively. The results of these analyses are given in Table E.5 of Appendix E.

7.2 Analysis

A standard statistical computer program was used with the complete data set of penetration values to assess the null hypothesis that the recovered penetration results were not affected by the thin surfacing system type and/or the age at the time of measurement (Table J.2 of Appendix J). The analysis found that there was a zero probability of the null hypothesis for either parameter or their combination. Therefore, it is highly probable that the type of thin surfacing system and the age of the surfacing both have an effect on the recovered penetration.

Similarly, the program was used with the complete data set of softening point values to assess the null hypothesis that the recovered softening point results were not affected by the thin surfacing system type and/or the age at the time of measurement (Table J.2 of Appendix J). The analysis found that there was a zero probability of the null hypothesis for either parameter but a 0.28 probability of their combination. Therefore, it is highly probable that the type of thin surfacing system and the age of the surfacing both have an effect on the recovered softening point, as would be expected.

The results were studied to identify if the binder properties were correlated with the age or visual condition of the surfacings, as given in Appendix N. This analysis is presented in Appendix O. It was expected that the type of thin surfacing system and the age of the surfacing would both have an effect on the penetration and softening point of the binder recovered from thin surfacing systems. However, no clear relationship could be found for either:

- the change of binder properties with time; or
- the visual condition of the surfacing with binder properties.

8 Economics

8.1 Approach

The choice of pavement surfacing should not only be based on the properties it delivers and its serviceable life but also on its whole-life cost. This section estimates comparable whole-life costs for both thin surfacing systems and HRA surfacings over a 60-year period to aid this choice.

8.2 Whole-life cost implications

The HA has a business commitment to manage the trunk road network on a minimum whole-life cost basis. Whole-life cost analysis is a technique to aid the economic appraisal of alternative options with differing initial and future maintenance costs. The whole-life costs of major road maintenance schemes on the trunk road network are currently assessed using a software package called SWEEP.S (Software for Whole-life Economic Evaluation of Pavements – Schemes). SWEEP.S is a part of the Highways Agency Pavement Management System (HAPMS) and is used by Managing Agents to demonstrate "value for money" for their proposed scheme maintenance options for input to the annual value management process for the development of roads renewal schemes. Within this process, the current condition of the pavement is assessed and maintenance options are identified including future maintenance requirements. The SWEEP.S analysis evaluates the works cost and the costs to the road users due to increased delays at roadworks for different initial options.

The works cost of applying a treatment depends on a number of factors, including the cost of materials, the work involved and the time it takes to apply the treatment. Material costs vary depending on material quantity and type. For example, thin surfacing systems may require larger quantities of more expensive, higher PSV aggregates compared with earlier conventional surfacings such as HRA. Different materials utilise different techniques for their application which will also affect the cost of the treatment.

The duration of the maintenance works and the work pattern used affect road users through increased delays at roadworks. Night working reduces user delays and, therefore, user costs due to lower traffic levels but may have implications for works cost (night working can be more expensive) and for the quality of workmanship (Nicholls *et al*., 2008) and hence future performance. Time constraints and difficulties in controlling temperature and humidity during night working may affect the ultimate serviceable life of surfacings (particularly thin surfacing systems) and, therefore, the time to the next maintenance intervention.

In January 2006, the Office of Government Commerce introduced mandatory minimum standards for procurement which require a value-for-money assessment to consider whole-life cost evaluation in tandem with the "fitness for purpose", that is the whole-life value of the option. Whole-life value requires a broader range of criteria to be considered in the decision making process.

In addition to works and user costs, there may be other properties that affect the treatment's "value". It may not always be possible to consider the value parameters in quantitative terms but they are, nevertheless, important in terms of meeting user needs and may influence the decision to use a certain type of surfacing. The value may be related to safety or social or environmental benefits. Examples include:

- The ability to reuse materials at the end of life can add value by making the process more sustainable. Materials may be reused in the same application or may be reused elsewhere if their properties have changed, although asphalt materials are generally considered capable of being completely recycled. Where maintenance interventions are required frequently or materials are difficult or expensive to obtain, the value may be even greater. Reducing the number of journeys to deliver and dispose of materials not only reduces direct costs but also delivers environmental benefits due to reduced carbon dioxide emissions.
- Thin surfacing systems are generally quieter than HRA surfacings. Delivering quieter surfacings to meet customer requirements may have benefits in sensitive urban environments, but they could also be considered on roads outside urban areas where there is a need not only to repair, but also to "improve", an existing surfacing.
- If certain materials reduce road spray, reduced accident rates and improved customer satisfaction may be two possible indicators of value.

To maximise the value of any treatment, it must be used appropriately so that an appropriate treatment for a particular condition that is being addressed is selected. If a particular type of surfacing treatment is not appropriate (such as a thin surfacing system laid directly over a cracked pavement surface or to a jointed concrete surface), it is unlikely to deliver the expected performance.

For an accurate and robust assessment of the whole-life value of thin surfacing systems and HRA surfacings to be made, the following information is required:

- The works costs of the alternative surfacings.
- Working practices, including the duration of works and the variability of workmanship.
- Serviceable lives of the surfacings.
- The "value" parameters and their assessment in whole-life value analysis.

The appraisal of value parameters such as noise reduction or other environmental benefits is outside the scope of this study and the whole-life cost evaluation described in Section 8.3 is based on the cost of works and costs to road users at roadworks.

8.3 Example whole-life cost analysis

TRL660 (Nicholls *et al*., 2007) presented an example whole-life cost analysis over a period of 60 years for a 1,000 lane-kilometre road network. Three surfacing treatments were considered: a thin surfacing system; an HRA surfacing; and a surface dressing treatment. Typical values for works costs and serviceable lives were derived from both the data presented in the report and from external sources of data. The calculations were performed using a simple spreadsheet, and followed the same approach as that used by the HA's SWEEP.S software.

Since 2007, a number of additional sites have reached the end of their lives in service leading to increased certainty in the expected life of thin surfacing systems. For this report, the whole-life cost analysis has been repeated using the revised serviceable life figures obtained from the sites monitored since 2007 in addition to using revised and more up-to-date figures for costs, output rates and other relevant parameters.

The analysis presented here is an example whole-life cost analysis over a period of 60 years, for a network of 1,000 lane-km in length and of 3.65 m lane width. The surface dressing option that was considered in TRL660 has not been repeated due to insufficient cost or serviceable life information being available to make an accurate assessment of its whole-life cost.

It is assumed that the 1,000 lane-km network is of long-life pavement standard and, therefore, requires surface course treatment only and no structural treatments throughout the 60-year analysis period. The estimation of works costs are based on the following assumptions:

- HRA surfacing – planing off and replacing the surface course.
- Thin surfacing system – applying the thin surfacing system directly onto the existing pavement surface.

However, in the case of thin surfacing systems, it is expected that additional works will be required periodically within the 60-year analysis period. The thin surfacing system treatments, which overlay the existing pavement and thus increase its overall height, will at some point require planing off and replacing and it is, therefore, assumed that at every second treatment the surface will be planed and replaced.

User delays costs, which are dependent upon traffic flow, works duration and traffic management type, have been calculated on the basis of the network being made up of three road classes (50 % single carriageway, 20 % dual carriageway, 30 % motorway) and assuming typical traffic flows and traffic management arrangements. The cost to road users due to increased delays at roadworks sites has been calculated using look-up tables created at TRL using the QUADRO 4 (QUeues And Delays at ROadworks) software (DfT, 2006). Traffic flow is expected to grow with time, but there is some uncertainty over predicting traffic for the 60-year evaluation period. The 1997 National Road Traffic Forecasts (NRTF) predict traffic growth rates only until 2031. An average growth rate of 1.1 % per year, based on the NRTF values, has been used until 2031 (years 0 to 24) and a zero growth rate used thereafter.

All future works and user delay costs are discounted at the Treasury Discount rate of 3.5 % to calculate the net present value (NPV) of each of the strategies.

The surfacing types being considered achieve a wide range of serviceable lives depending on the specific product being used and individual site conditions. The HAPMS database holds condition and maintenance data for the trunk road network. Data for all end-dated (expired) HRA surfaces over the entire trunk road network have been used to examine the range of lives HRA achieves in service. It is assumed that, in general, the end dates represent the year when they were resurfaced due to having reached the end of their useful lives, but we believe that, for some of the sites, de-trunking and road layout improvements may be two possible alternative reasons for end dates being applied. Therefore, the distribution obtained from approximately 11,600 lane-km of data covering a period of 50 years is shown in Figure 8.1 and has been used to represent the performance of HRA in the analysis.

Data collected for this study (Section 5.1) give lives in service from a number of trial sites where modern thin surfacing systems have been used. Where the surface has reached the end of its life in service and subsequently been maintained or resurfaced, its life is known. To ensure a like-for-like comparison, the lengths of the sites were taken into consideration; very short sites with unusually high or low lives would not therefore bias the results. The distribution of lives shown in Figure 8.1 is obtained from the 32 studied sites that have been resurfaced and had accurate site length data available. It is assumed that the distribution of the types of surfacing systems used on the trial sites is typical although this assumption is not necessarily the case due to the limited data set used.

In the case of either surfacing treatment, all data indicating a life of three years or less have been ignored. It is assumed that contractor guarantees would be in place to ensure that the costs of any early-life failures would be borne by the contractor rather than by the highway authority.

The lives of the two alternative surfacings have been estimated using different data sets. The available data for HRA span a greater number of years than for thin surfacing systems and, hence, the results may tend to represent a pessimistic view for the latter because of the longer-lasting thin surfacing systems not having yet reached the end of their lives. From the distributions shown in Figure 8.1, it appears that thin surfacing systems have, on average, a shorter life than HRA.

As discussed earlier, works costs and output rates vary significantly between different treatment types. Representative values (based on figures used within the HA's SWEEP.S software) are shown in Table 8.1. The treatment costs comprise the cost of all the work required to carry out the treatment including preliminaries as well as traffic management.

The net present values (works and user costs) from the whole-life cost analysis are shown in Figure 8.2.

As with the previous analysis (Nicholls *et al*., 2007), the thin surfacing system and HRA have similar whole-life costs despite the thin surfacing system having, on average, a shorter life than HRA. However, this comparison ignores any pessimism in the assumed life of thin surfacing systems as well as the possible positive value of noise reduction and other environmental benefits.

The results show that, for the figures chosen, thin surfacing systems can offer comparable performance in terms of whole-life cost to HRA surfacings. However, local factors can have a large influence on results and schemes need to be assessed on an individual basis for meaningful results.

In practical terms it is important to note that the example does not show a clear advantage of one surfacing material over another, rather it shows that the thin surfacing systems can offer comparable performance in terms of whole-life cost to HRA surfacings

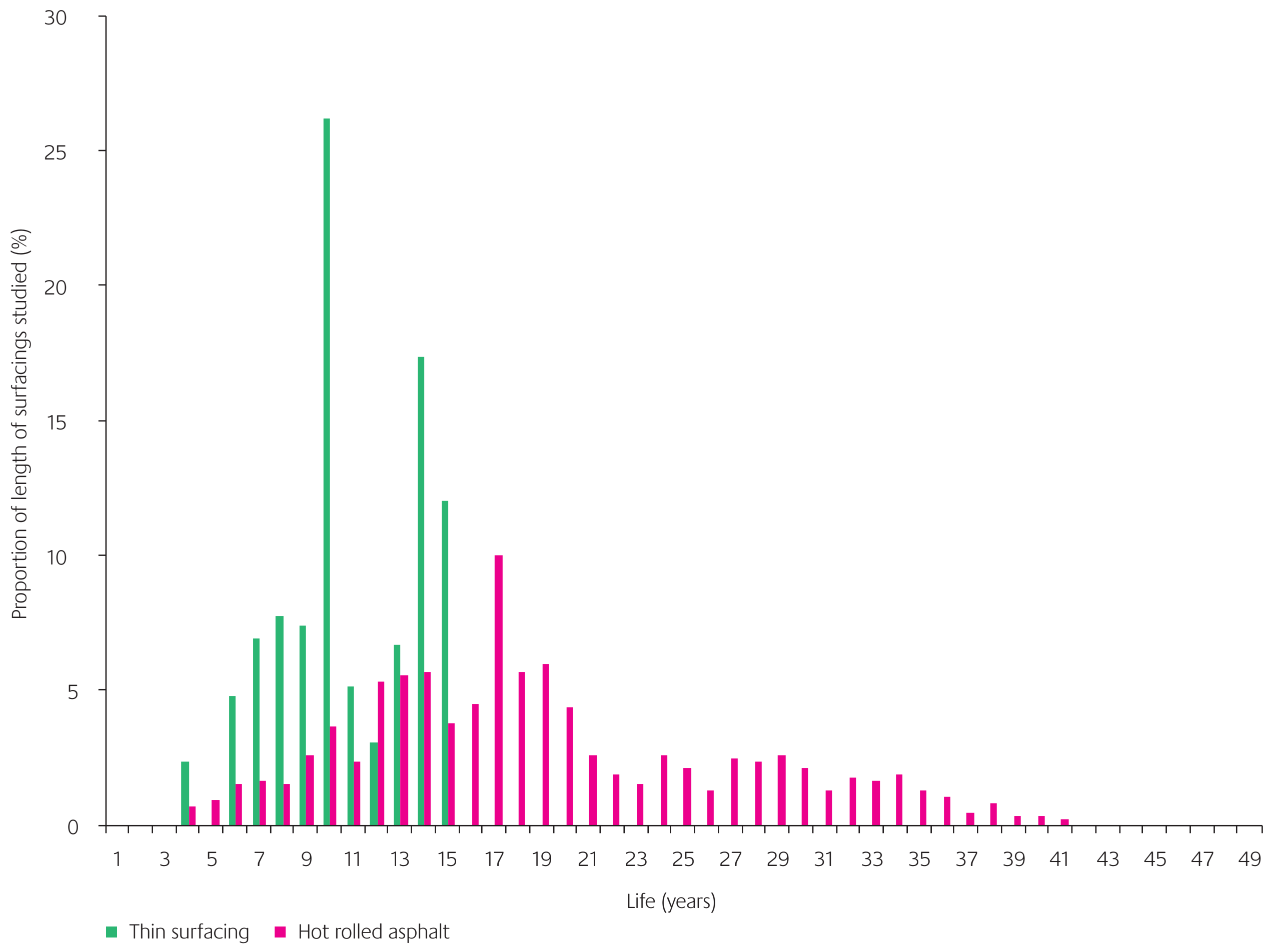


Figure 8.1 Distribution of lives of thin surfacing systems and HRA

Table 8.1 Costs and output rates

Parameters	*Units*	*Thin surfacing system*	*HRA*
Works cost	£/m^2	13.2	20.2
Output rate	m^2/h	600	500

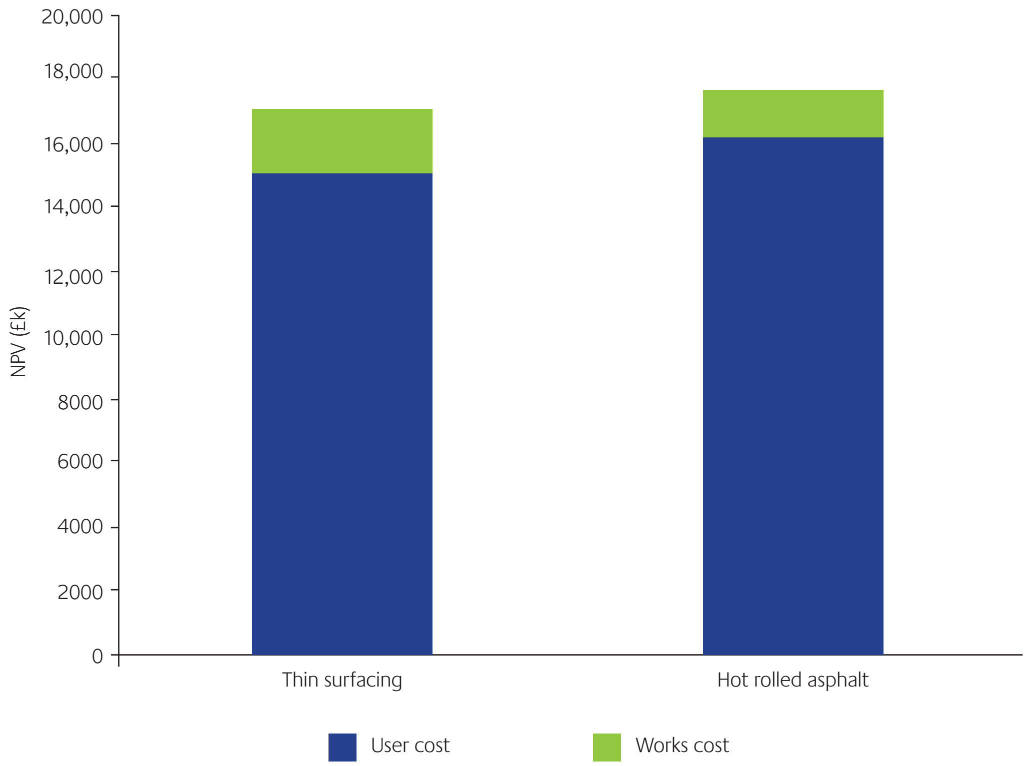


Figure 8.2 Net present value for each treatment option

9 Conclusions

The principal aims of the project were to identify the expected length of the service lives of thin surfacing systems, the mode(s) of failure by which they fail and if there are any simple means to predict their failure.

With respect to the expected serviceable lives of thin surfacings from almost 1,000 observations of condition (skid resistance, texture depth and visual condition) collected over more than nine years on 137 sites, the principal conclusions are:

1) Estimates of the serviceable lives of thin surfacing systems to reach a *Suspect* visual condition based on analyses of visual condition measures using two different analysis techniques gave values of:

Thin surfacing system	*Nominal size (mm)*	*No. of sites*	*No. of observations*	*Rigorous statistical analysis*		*Combined estimate for serviceable lives (years)*
				Estimated serviceable lives (years)	*95 % confidence limits (years)*	
PLSD	14	9	32	12	9.1 – 15*	13
	10	7	33	11	9.5 – 13	9½
	6	1	6	5.5	4.7 – 6.5	6
TAC	14	32	82	16*	14* – 19*	>12
	10	33	134	17*	16 – 18*	>16
	6	8	34	14*	10 – 20*	>10
TSMA	14	49	197	19*	16* – 21*	>14
	10	9	30	26*	16* – 38*	>14
MSD	14	6	28	7.4	6.3 – 8.5	9
MS	6	4	22	7.8	2.8 – 13*	8½

Many of these values are extrapolations, being greater than the oldest site observation. These values are indicated with the addition of an asterisk.

2) The above life estimates are to the end of serviceable condition, which has been defined in this study as the onset of *Suspect* condition. In case users require some indication of the lives to other condition states the table below has been provided which is based on a combination of the results from the less rigorous analyses of the available visual condition data.

Visual condition	*Time in service (years) to reach for system type*									
	PLSD			*TAC*			*TSMA*		*MSD*	*MS*
	14 mm	*10 mm*	*6 mm*	*14 mm*	*10 mm*	*6 mm*	*14 mm*	*10 mm*	*14 mm*	*6 mm*
Moderate (Figure 9.1)	5	4½	3½	7½	7	5	8	11	2½	–
Acceptable (Figure 9.2)	9	7½	5½	>12	13	10	14	>14	5½	3
Suspect (Figure 9.3)	13	9½	6	>12	>16	>10	>14	>14	9	8½
Poor (Figure 9.4)	>14	>14	>6	>12	>16	>10	>14	>14	13	>10

Values being shown as greater than the maximum life are extrapolations; the dash for MS indicates that those systems usually have some (minor) defects when built.

Figure 9.1 Example of site in *Moderate* condition

Figure 9.2 Example of site in *Acceptable* condition

Figure 9.3 Example of site in *Suspect* condition

Figure 9.4 Example of site in *Poor* condition

(Further photographs of sites in different visual conditions are shown in Appendix P)

3) The similarity of results from the two approaches, tabulated in conclusion 1, gives added confidence in the results but also emphasises the variability in the performance as highlighted by the 95 % confidence limits given in the table. However, it should be noted that, due to the limited range of data and possible bias in its selection, the results can only be considered as a broad indication of likely lives.
4) Skid resistance is not considered to be a major durability issue because statistical analysis indicates that, in general, there was no statistically significant decrease of MSSC as a uniform function with age of the surfacing, although there was considerable fluctuation.
5) Texture depth is not considered to be a major durability issue because, apart from MSD systems, analysis indicates that there are reductions in texture depth as the surface ages but generally only in the early years. Towards the end of its serviceable life, the texture depth on a site can increase but as a symptom of particle loss rather than as the cause of failure.
6) For the monitored sites that have been resurfaced or overlaid, the average life in service for all types is 9.9 years with a standard deviation of 3.0 years. However, this estimate is biased because sites still in service and, therefore, likely to be the more durable sites, have not been included. This average is similar to that of sites reaching a visual condition of *Suspect*, with a mean of 9.2 years and a standard deviation of 3.1 years.
7) For thin surfacing systems laid directly onto jointed concrete, the difference between the actual overall condition and that for the condition ignoring any reflection cracks is negligible for at least five years. After five years, there is still no difference for many sites (presumably where the joints are still in good condition) but, for others, the difference can be up to one and a half visual assessment marks, which implies that the time before the surfacing needs to be replaced will be significantly less.
8) Whilst many claim that there are numerous instances of premature failure with thin surfacing systems, the response to a request for examples resulted in very few being put forward. Furthermore, one response was about low early-life skid resistance rather than durability.

Expected service lives are often used to influence a choice of surfacing, but another important aspect is the whole-life cost of its use. On this aspect the study concluded that, on average, thin surfacing systems and HRA have similar whole-life costs despite an assumed shorter serviceable life for thin surfacing systems than HRA. Furthermore, there are additional possible non-financial benefits from thin surfacing systems such as noise reduction. However, specific assessments would be needed for specific schemes in order to take account of any local conditions and other influencing factors.

With respect to the expected mode of failure of thin surfacing systems, the principal mode of failure or reason for reaching an unserviceable condition was the significant presence of one or more visual defects, of which the two most prevalent were particle loss and cracking. Long-term deterioration of skid resistance or texture depth was not generally found to be a cause of unserviceability although loss was observed on some sites after the initial changes. Such levels are believed to be caused by poor specification of materials or construction defects.

With respect to determining a simple means of predicting failure, the study focused on identifying which parameters apparently had the most influence on the estimated lives of the pavement. For this issue the study concluded that:

- The penetration and softening point of the thin surfacing material was related to the age and type of the material but the relationship was insufficiently clear to be used as a life predictor.
- Aggregate size and system were the most important influences on estimated lives in terms of visual condition, with binder content also important in some situations.

The above observations show that thin surfacing systems can routinely be constructed to provide a safe surfacing with adequate skid resistance, texture depth and visual condition and that these properties are maintained in service for a reasonable period.

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- Paul Collins (Aggregate Industries Limited)
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- Jeff Farrington (Concultant)
- Arthur Hannah (CEMEX UK Materials/Consultant/TRL)
- Alistair Jack (Road Surface Treatments Association)
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Appendix A: Inspection Panel marking system

The Inspection Panel is a body organised by TRL on behalf of the HA with the objective of assessing the serviceability of road surfacings by way of detailed visual inspection. An individual Panel consists of a TRL staff member acting as Convenor and a representative from the HA with other members being drawn from industry according to availability comprising 17 members in total but with at least four of them in attendance in order to consider the observations valid.

The Panel utilises a seven-point scale, ranging from *Bad* to *Excellent*, to assess surface condition as it is seen to affect serviceability. In considering the serviceability of the surfacing, each Panel member considers whether any of the relevant defects in Table A.1 are evident to a significant degree on the section. If so, the relevant defect suffix from Table A.1 is taken forward when selecting the basic marking.

Once any appropriate defect suffixes have been assigned, each Panel member allocates the basic mark from the seven-point scale provided in Table A.2. Intermediate markings between scales are not given at the individual level. When considering the markings, any sections that warrant a suffix cannot have a basic mark of *Good* or better.

Photographs of sites in various visual conditions are shown in Appendix P.

When each individual Panel member has reported their individual result, the Convenor converts the findings into the overall basic Panel marking. Suffixes are applied to the Panel marking when at least a quarter of the Panel members, rounded up, give it on their individual markings provided that the basic Panel marking is not *Good* or better (as then no suffixes can be applied). Intermediate Panel marks are permitted when at least a quarter of the Panel members, rounded up, provide the same basic mark.

Table A.1 Defects and associated suffixes

Description of defect	*Suffix*
Fatting up	+
Chipping loss/loss of aggregate	–
Cracking	c
Delamination from substrate	d
Fretting of the mortar	f
Stripping	s
Variability with traffic intensity, marked transverse differences caused by variations in traffic intensity between lanes.	t
Variable with random variations from point to point within the section only, not “traffic laning” or obvious variations from load to load.	v

Table A.2 Basic seven-point scale

	Mark	*Description*	
E	*Excellent*	No discernible defect	Termed serviceable
G	*Good*	No significant defect	
M	*Moderate*	Some defects but insufficient for serious problem	
A	*Acceptable*	Several defects but would usually be just acceptable	
S	*Suspect*	Seriously defective but still serviceable in the short term	Termed unserviceable
P	*Poor*	Requires remedial treatment	
B	*Bad*	Requires immediate remedial treatment	

Appendix B: Sites monitored in 2007 – 2009

Site no.	*Year laid*	*Road category**	*Depth (mm)†*	*Aggregate size (mm)*	*PSV*	*Binder (%)*	*Years monitored*			*Year replaced‡*
							Visual	SCRIMtex	Coring	
PLSD7b	1992	1	14.8	10	68	4.9	2007	–	2007	2007
PLSD10	1995	1	20	14	68	4.9	2007, 2008, 2009	2007, 2008, 2009	2007, 2008, 2009	–
PLSD14	2003	1	–	–	–	4.9	2007, 2008, 2009	–	–	2009
PLSD15	1997	1	–	14	65	4.9	2007, 2008	–	–	–
PLSD16	2002	1	–	10	65	4.9	2008, 2009	–	–	–
PLSD17	2004	2	19.2	10	65	5.5	2008, 2009	–	–	–
TAC1a	1992	1	19.2	10	65	5.5	2007	–	2008	2007
TAC1b	1992	1	30	10	66	5.5	2007	–	2007	2007
TAC2	1995	1	–	14	62	5.5	2007, 2008, 2009	2007, 2008, 2009	2007, 2008, 2009	–
TAC4b	1997	2	–	10	65	5.7	2007, 2008, 2009	–	–	–
TAC7	1996	3	–	10	68	5.5	2007, 2008, 2009	–	–	–
TAC9	1997	0	–	14	–	5.5	2007, 2008, 2009	–	–	–
TAC11	2002	2	–	10	–	5.5	2007, 2008, 2009	–	–	–
TAC12	1993	2	25	10	65	5.5	2007, 2008, 2009	–	–	–
TAC13	1998	1	–	10	65	5.0	2007, 2008	–	–	2008
TAC14	1997	2	40	14	65	–	2007	–	–	2007
TAC15	2000	2	20	10	65	5.5	2007, 2008	–	–	2008
TAC17	1994	2	–	10	–	5.3	2007	–	–	2007
TAC18	1996	1	–	6	65	5.5	2007	–	–	2007
TAC19	2001	1	30	10	65	–	2007, 2008, 2009	2007, 2008, 2009	–	–

* Road category, where 0 = motorway, 1 = trunk A road, 2 = non-trunk A road, 3 = other road.
† Depth is either the nominal thickness or the average depth as measured when coring.
‡ The year replaced is given for those surfacings that have been removed or overlaid.

Site no.	Year laid	Road category*	Depth (mm)†	Aggregate size (mm)	PSV	Binder (%)	Years monitored			Year replaced‡
							Visual	SCRIMtex	Coring	
TAC20	2000	2	22	10	65	5.5	2007, 2008, 2009	–	–	–
TAC21	1995	1	–	10	60	–	2007, 2008, 2009	–	–	–
TAC22	1999	1	–	10	60	–	2007, 2008, 2009	–	–	–
TAC23a	1999	1		10	60	–	2007, 2008, 2009	–	–	–
TAC23b	1999	1	30	14	71	–	2007, 2008, 2009	–	–	–
TAC24	1999	1		6	–	–	2007	–	–	2008
TAC25	2003	1	18	6	72	5.5	2007, 2008, 2009	–	–	–
TAC26	2003	1	30	14	62	–	2007, 2008, 2009	–	–	–
TAC27	2000	1	30	14	68	5.5	2007, 2008, 2009	–	–	–
TAC28	2003	1	40	14	68	5.5	2007, 2008, 2009	2007, 2008, 2009	–	–
TAC29	2004	1	22.5	6	–	–	2007, 2008, 2009	–	–	–
TAC30	1999	3	22.5	6	–	–	2007, 2008, 2009	–	–	–
TAC31	1999	3	20	6	–	–	2007, 2008, 2009	–	–	–
TAC32	1999	2	–	6	68	6.3	2007, 2008, 2009	–	–	–
TAC33	2005	1	45	14	65	5.5	2007, 2009	–	–	–
TAC34	2004	1	45	14	65	5.5	2007, 2008, 2009	–	2007, 2008, 2009	–
TAC35	2004	1	45	14	65	5.5	2007, 2008, 2009	–	2007, 2008, 2009	–

* Road category, where 0 = motorway, 1 = trunk A road, 2 = non-trunk A road, 3 = other road.
† Depth is either the nominal thickness or the average depth as measured when coring.
‡ The year replaced is given for those surfacings that have been removed or overlaid.

Site no.	*Year laid*	*Road category**	*Depth (mm)†*	*Aggregate size (mm)*	*PSV*	*Binder (%)*	*Years monitored*			*Year replaced‡*
							Visual	*SCRIMtex*	*Coring*	
TAC36	2004	1	30	10	65	5.2	2007, 2008, 2009	–	2007, 2008, 2009	–
TAC37	1998	2	30	14	65	5.6	2007, 2008, 2009	–	2007, 2008	–
TAC38	2005	1	30	6	65	5.7	2007, 2008, 2009	2007, 2008, 2009	–	–
TAC39	2005	1	30	10	65	5.3	2007, 2008, 2009	2007, 2008, 2009	–	–
TAC40	2005	0	40	14	68	5.2	2007, 2008, 2009	2007, 2008, 2009	–	–
TAC41	2006	0	40	14	68	5.2	2007, 2008, 2009	–	2009	–
TAC42	2006	1	40	14	60	4.7	2007, 2008, 2009	–	2007, 2008, 2009	–
TAC43	2008	1	40	14	–	–	2008, 2009	–	–	–
TAC44	2003	1	40	14	–	–	2009	–	–	–
TAC45	2003	1	–	14	68	6.5	2009	–	–	–
TSMA3	1993	2	40	10	–	–	2007, 2008	–	–	2008
TSMA5	1995	2	17	14	67	6.0	2007, 2008, 2009	2007, 2008, 2009	2007, 2008, 2009	–
TSMA8	1996	1	–	14	65	6.1	2007, 2008, 2009	2007, 2008, 2009	2007, 2008, 2009	–
TSMA9	1996	0	25.8	14	67	6.3	2007, 2008, 2009	–	–	–
TSMA10	1996	2	–	14	68	6.0	2007, 2008, 2009	2007, 2008, 2009	2007, 2008, 2009	–
TSMA11	1996	2	–	14	68	–	2007, 2008, 2009	–	–	–
TSMA12	1997	2	36.7	14	68	6.0	2007, 2008, 2009	–	–	–
TSMA13	1997	0	–	14	67	6.5	2007, 2008, 2009	2007, 2008, 2009	2007, 2008, 2009	–

* Road category, where 0 = motorway, 1 = trunk A road, 2 = non-trunk A road, 3 = other road.
† Depth is either the nominal thickness or the average depth as measured when coring.
‡ The year replaced is given for those surfacings that have been removed or overlaid.

Site no.	Year laid	Road category*	Depth (mm)†	Aggregate size (mm)	PSV	Binder (%)	Years monitored			Year replaced‡
							Visual	SCRIMtex	Coring	
TSMA14	1998	2	32.5	14	68	6.0	2007, 2008	–	–	2008
TSMA15	1998	1	–	14	65	6.0	2007, 2008, 2009	2007, 2008, 2009	2007, 2009	–
TSMA17	1998	1	–	14	–	6.0	2007, 2008, 2009	–	2007, 2008, 2009	–
TSMA18	2000	2	–	–	–	–	2007, 2008	–	–	2009
TSMA20	1999	2	–	10	–	–	2007, 2008, 2009	–	–	–
TSMA21	1999	1	–	14	65/60	–	2007, 2008, 2009	–	–	2009
TSMA22	2003	1	–	–	–	–	2007	–	–	–
TSMA23	2003	2	40	14	60	6.0	2007, 2008, 2009	–	–	–
TSMA24	1999	2	–	14	60	6.0	2007, 2008, 2009	–	–	–
TSMA25	2004	1	45	14	65	6.1	2007, 2008, 2009	–	2007, 2008, 2009	–
TSMA26	2004	1	45	14	65	6.1	2007, 2008, 2009	–	2007, 2008, 2009	–
TSMA27	2004	1	45	14	65	6.1	2007, 2008, 2009	–	2007, 2008, 2009	–
TSMA28	2005	2	–	14	65	6.0	2007, 2008, 2009	–	–	–
TSMA29	2005	1	–	10	62	–	2007, 2008, 2009	2007, 2008, 2009	–	–
TSMA30	2005	1	–	14	62	–	2007, 2008, 2009	2007, 2008, 2009	–	–
TSMA31	2001	2	–	14	63	6.0	2007, 2008, 2009	–	–	–
TSMA32	2000	3	–	14	61	–	2007, 2008, 2009	–	–	–

* Road category, where 0 = motorway, 1 = trunk A road, 2 = non-trunk A road, 3 = other road.
† Depth is either the nominal thickness or the average depth as measured when coring.
‡ The year replaced is given for those surfacings that have been removed or overlaid.

Site no.	*Year laid*	*Road category**	*Depth (mm)†*	*Aggregate size (mm)*	*PSV*	*Binder (%)*	*Years monitored*			*Year replaced‡*
							Visual	*SCRIMtex*	*Coring*	
TSMA33	2002	2	–	14	65	–	2007, 2008, 2009	–	–	–
TSMA34	1995	1	–	14	62	7.0	2007, 2008, 2009	–	–	–
TSMA35	2008	0	–	14	–	6.0	2009	–	–	–
TSMA36	2008	0	–	14	–	6.0	2009	–	–	–
TSMA37	2001	1	30	14	–	–	2009	–	–	–
TSMA38	2001	1	30	14	–	–	2009	–	––	–
TSMA39	2001	1	30	14	–	–	2009	–	–	–
TSMA40	2002	1	20	10	–	–	2009	–	–	–
TSMA41	2001	1	30	14	–	–	2009	–	–	–
TSMA42	2002	1	30	14	–	–	2009	–	–	–
TSMA43	2001	1	30	14	–	–	2009	–	–	–
TSMA44	2001	1	30	14	–	–	2009	–	–	–
TSMA46	2009	1	–	10	–	6.6	2009	–	–	–
TSMA47	2009	1	–	10	–	6.6	2009	–	–	–
MSD1	1995	1	6	14	65	2.3 l/m^2	2007, 2008, 2009	2007, 2008, 2009	2007, 2008, 2009	–
MSD5	2008	3	15	6	65	–	2008, 2009	–	–	–
MSD6	2008	1	10	6	65	–	2008, 2009	–	–	–
MS1	1999	1	–	6	65	–	2007, 2008, 2009	–	2007, 2008, 2009	–
MS2	2000	3	–	6	65	–	2007, 2008, 2009	2007, 2008, 2009	2007	–
MS3	2003	1	–	6	65	–	2007, 2008, 2009	–	–	–
MS4	2008	1	18	6	65	–	2008, 2009	–	–	–

* Road category, where 0 = motorway, 1 = trunk A road, 2 = non-trunk A road, 3 = other road.
† Depth is either the nominal thickness or the average depth as measured when coring.
‡ The year replaced is given for those surfacings that have been removed or overlaid.

Appendix C: Details of sites replaced or resurfaced in 2007 – 2009

C.1 Introduction

Several of the sites monitored in earlier phases of the study have been resurfaced during the current monitoring period. Those sites that were monitored previously but have become unavailable for monitoring over the full period are described briefly in the following sections in terms of those replaced due to poor condition (Section C.2), those replaced with limited deterioration (Section C.3) and those no longer monitored for other reasons (Section C.4).

C.2 Sites replaced due to poor condition

PLSD7a, PLSD7b, TAC1a and TAC1b were laid in September 1992 with 10 mm TAC on one carriageway and 10 mm PLSD on the other carriageway, although the PLSD had to be re-laid the following year because of poor initial installation. Part of the length of both sites was over a viaduct (PLSD7a and TAC1a), where the wear was more severe due to the presence of underlying construction joints, and PLSD7a was replaced in 2003 by a generic SMA, TSMA22. The remaining sites were assessed as *Poor*, *Acceptable* to *Suspect* and *Acceptable*, respectively, in 2007 and were surface dressed soon after cores had been extracted for binder testing that year. SCRIMtex surveys had not been carried out in 2007 because maintenance had originally been programmed for earlier that year. The lives in service for the site were ten years, 14 years, 15 years and 15 years, respectively.

PLSD10, TAC2 and TSMA8 were laid as 14 mm PLSD, 10 mm TAC and 14 mm TSMA, respectively, directly onto a jointed concrete substrate in June 1995 on different sections of a two-lane dual-carriage trunk road. The overall sections were marked as *Acceptable* to *Suspect*, *Acceptable* to *Suspect*, and *Moderate*, respectively, in 2006 dropping to *Suspect* to *Poor*, *Poor*, and *Acceptable* to *Suspect*, respectively, in 2009. However, much of the deterioration occurred over the joints which, when excluded from the observations, produced markings of *Moderate*, *Moderate* to *Acceptable*, and *Moderate*, respectively, in 2006, dropping to *Acceptable*, *Suspect*, and *Moderate* to *Acceptable*, respectively, in 2009. Regular maintenance was being undertaken, but plans to replace the surfacing in 2007 were postponed. However, the work had started on the opposite carriageway when the sites were monitored in 2009, giving an extended life in service for the sites of 14 years despite being laid over jointed concrete.

PLSD15 was laid in 1997 on one carriageway of a two-lane dual-carriage trunk road. The section was marked as *Acceptable* to *Suspect* in 2005 and 2006, apparently recovering to *Acceptable* in 2007 but being classified as *Poor* in 2008. Therefore, it was not surprising that it had been replaced after 12 years in service at the 2009 inspection.

TAC14 was laid with 10 mm TAC in October 1997 and was assessed as *Poor* on the last occasion on which it was monitored in 2007, when the site was understood to be scheduled for imminent replacement. The site had reduced by about a mark per year for its last four years (*Moderate* in 2004, *Acceptable* in 2005 and *Acceptable* to *Suspect* in 2006) so its replacement was timely. The life in service for the site was ten years.

TAC15 was laid at 40 mm depth with 14 mm TAC on a busy four-lane single-carriageway trunk road in 2000. It had been dropping by half a mark a year from being *Acceptable* in 2005 to *Suspect* to *Poor* in 2008, so it was not surprising that the outside lane was replaced that year after eight years in service.

TSMA3 was laid on an extended two-lane single carriageway and roundabout in June 1995. The site had been varying between *Acceptable* and *Suspect* since 2004 so that it was no surprise when it had been replaced by HRA when visited in 2009. The life in service for the site was 13 years.

TSMA18 was laid as a 14 mm TSMA on a busy two-lane single carriageway where a minor road crossed it at a staggered junction in February 2000. The visual condition had been dropping by nearly a mark a year from *Moderate* in 2004 to *Poor* in 2008, so it was not surprising that it was found to have been replaced when visited in 2009. The life in service of the site was eight years.

TSMA21 was laid on a two-lane dual carriageway as a 14 mm TSMA in 1999. The visual condition had been dropping slowly from *Good* in 2006 to *Good* to *Moderate* in 2007 and 2008 until the 2009 inspection, when work had just started to replace it but the mark had dropped dramatically to *Acceptable*. The life in service of the site was ten years.

MSD3 was laid in August 1996 and had deteriorated to a *Suspect* to *Poor* condition for the 2006 inspection, so it was not unexpected that the site was resurfaced after that inspection but before any cores could be taken that year. The surfacing was ten years old when replaced.

C.3 Sites replaced with limited deterioration

TAC13 was laid with 10 mm TAC at 25 mm depth on a country two-lane single-carriageway trunk road in September 1998. The visual condition was deteriorating slowly from *Good* in 2004, *Moderate* from 2005 to 2007 and *Moderate* to *Acceptable* in 2008, but the site was found to have been replaced when visited in 2009. The life in service of that site was 11 years.

TAC16 was laid with 10 mm TAC in September 1993 and was still in *Moderate* condition when it was monitored in 2006. However, it was reported that it had been surface dressed “by mistake” at the end of 2006. The site should have been capable of giving further service in its rural location, but it is appreciated that it may not have been suitable for surface dressing if it had been allowed to deteriorate further. The surfacing was 13 years old when replaced.

TAC24 was laid with 14 mm TAC in November 1999 on a two-lane dual carriageway, although the nearside had been replaced early with a material that was not identified despite enquiries being made. The offside lane was assessed as being *Moderate* and the nearside lane as being *Good* to *Moderate* when inspected in 2007, but both lanes had been replaced at the 2008 inspection. This replacement was unexpected, but the site is extremely exposed and strategically important with 7,125 commercial vehicles per lane per day and, as such, probably warranted this early intervention. The life in service of the offside lane was nine years.

C.4 Sites no longer monitored

TAC17 was laid with 10 mm TAC in September 1994 and was assessed as *Acceptable* to *Suspect* with particle loss, cracks and variability when last monitored in 2007. However, over half the site had been replaced in patches and that mark was not included in the data set. It is understood that the rest of the site has now been replaced, although it had already been categorised as having failed in 2007 for the analysis in Section 5.1. The life in service of the site was 13 years.

TSMA14 was laid as 14 mm TSMA on a two-lane single carriageway in a market town with 14 mm TSMA in June 1997. The presence of several trenches and underlying structural problems made the marking difficult, but it was reducing by half a mark a year from *Moderate* to *Acceptable* in 2006 to *Acceptable* to *Suspect* in 2008. By 2008, a significant proportion of the surfacing had been replaced, although it had already been categorised as having failed in 2007 for the analysis in Section 5.1. The life in service of the site was 11 years.

TSMA22 was laid in 2003 as replacement for PLSD7b, which had deteriorated to the level of *Acceptable* with chip loss, cracks and delamination. Although TSMA22 was assessed as *Excellent* to *Good* when monitored in 2007, the site has not been visited in 2008 or 2009 when the other, older materials at this location had been replaced.

MSD2 was laid in October 1995 and had been assessed as being *Suspect* to *Poor* or *Poor* since 2002 and, as such, in need of maintenance in the near future. Therefore, although there have been no reports of it being resurfaced, the site was considered not to be worth further monitoring after 2006 and 2007 was considered to be the end of its life in service for the analysis in Section 5.1. The surfacing was 12 years old when replaced.

Appendix D: Details of sites added in 2007 – 2009

PLSD16 is a two-lane dual carriageway which was laid with 14 mm PLSD in June 2002. The mixture used coarse aggregate from Bwich Ffos quarry with a PSV of 65 and polymer-modified binder. The site was monitored from 2008.

PLSD17 is a single-carriageway bypass which was laid with 10 mm PLSD in September 2004. The mixture used coarse aggregate from Bwich Ffos quarry with a PSV of 65 and polymer-modified binder. The site was monitored from 2008.

TAC33 was laid with 6 mm TAC in May 2005 using Bantry Bay quartzite coarse aggregate. It had been planned to include it in the monitoring process from 2006 but the site was actually monitored from 2007.

Six trial lengths of thin surfacing systems incorporating different proportions of reclaimed asphalt (RA) – TAC34, TAC35, TAC36, TSMA27, TSMA28 and TSMA29 – were laid in August 2004 as part of the Feasibility of Recycling Thin Surfacings project. The sections were TAC and TSMA with 0 %, 15 % and 30 % RA and were monitored for the Best Practice for Recycling Asphalt Thin Surfacings project in 2006 although the results were not included in the analysis for this project that year (Nicholls *et al*., 2007). The assessments from 2006 are now included.

TAC37 was laid in September 1998 with 10 mm TAC. The site has a binder course of Colbase, a proprietary mixture akin to EME2, that was laid at the same time and is currently also being monitored under the Feedback on Superior Asphalts in High Performance Roads project. The site was monitored from 2007.

TAC38, TAC39 and TAC40 were laid in December 2005 with 10 mm, 6 mm and 14 mm TAC, respectively. The sites are part of the current joint research project for the HA, the Mineral Products Association (MPA) and the Refined Bitumen Association (RBA). The sites were monitored from 2007.

TAC41 and TAC42 were laid in August 2006 with 14 mm TAC containing 25 % RA, when the laying was monitored as part of the Best Practice for Recycling Thin Surfacings project. The first site, TAC41, is the control section with no RA. The sites were monitored from 2007.

TAC43 was laid 40 mm thick with 14 mm TAC in March 2008 as a replacement for TAC24. The coarse aggregate was sandstone from Ingleton quarry with a PSV of 60 and polymer-modified bitumen. The site was monitored from 2008.

A series of sites were identified by the Mid Wales Trunk Road Agency as having relatively poor performance. A subset of the sites (TAC44, TAC45 and TSMA37 to TSMA44) were selected for monitoring to check how poor that performance was relative to the overall population. The selected sites were constructed at different dates between 2001 and 2003, mainly used 14 mm aggregate and were mostly laid to a nominal 30 mm depth. The sites were only monitored in 2009.

TSMA29 and TSMA30 were laid in December 2005 with 10 mm and 14 mm TAC, respectively. The sites are part of the current joint research project for the HA, MPA and RBA. The sites were monitored from 2007.

TSMA31 was laid in 2001 with 14 mm TSMA using a coarse aggregate with a PSV of 63. The site was monitored from 2007.

TSMA32 was laid in July 2000 with 14 mm TSMA using a coarse aggregate with a PSV of 61. The site, which is centred around the main entrance to a small airfield, is approximately 300 m long. The site was monitored from 2007.

TSMA33 was laid in March 2002 with 14 mm TSMA using a coarse aggregate with a PSV of 65. The site is approximately 700 m long. The site was monitored from 2007.

TSMA34 was laid in August 1995 with 14 mm TSMA on the A590 at Barrow-in-Furness. The site was first reported by Nicholls (1998) but was not subsequently followed up. The site was brought to the attention of the project following the request to HA Managing Agents for examples of sites with extreme performance (Chapter 4.5). This site was put forward as an example of extremely long serviceability. The site was monitored from 2007.

The two carriageways of a section of motorway, TSMA35 and TSMA36, that was opened at the end of 2008 were added to the list of sites in order to identify what performance had been achieved. The sites were constructed in 14 mm TSMA and only monitored in 2009.

Following the technical visit to Bavaria (see Appendix K), trial sections of TSMA were laid in an urban location with high binder content (6.6 %), low air voids content and both polymer-modified binder and fibres. Two sites were added as TSMA46 and TSMA47 to observe how successful such mixtures might be in the UK and monitored in 2009.

The laying of a trial site with two sections of surface dressing (6 mm and 6 mm double and 6 mm single) and one 6 mm MS on a single-carriageway trunk road, MSD5, MSD6 and MS4, was being monitored by TRL under a separate project, Consultant Advice on Surface Dressing Trials. It was decided to incorporate these sections into this project for visual condition with the results to be available to both projects. The trial was laid in July 2008 using aggregate from Bardon quarry with a claimed PSV of 65 and with polymer-modified binder for all sections. The sites were monitored from 2008.

Appendix E: Results from third set of three years' monitoring

Table E.1 MSSC results

Section			*Inv. level**	*2007*			*2008*			*2009*		
Site	*Lane*	*Laid*		*No.*	*MSSC*	*Mean*	*No.*	*MSSC*	*Mean*	*No.*	*MSSC*	*Mean*
PLSD10	North 1	1995	0.40	3	0.47	0.48	3	0.52	0.51	3	0.45	0.45
	North 2			3	0.47		3	0.51		3	0.44	
TAC2	North 1	1995	0.40	3	0.54	0.52	3	0.57	0.56	3	0.53	0.51
	North 2			2	0.51		3	0.54		3	0.49	
TAC19	North 1	2001	0.40	3	0.61	0.56	3	0.57	0.56	3	0.55	0.55
	North 2			3	0.56		3	0.56		3	0.57	
	South 1			3	0.55		3	0.55		3	0.54	
	South 2			3	0.54		3	0.56		3	0.54	
TAC28	North	2003	0.40	3	0.55	0.55	3	0.55	0.56	3	0.50	0.50
TAC38	North	2005	–	3	0.51	0.51	3	0.55	0.54	3	0.50	0.50
TAC39	North	2005	–	3	0.49	0.49	3	0.61	0.61	3	0.55	0.55
TAC40	North	2005	–	3	0.52	0.52	3	0.58	0.57	3	0.53	0.53
TSMA5	South	1995	0.40	3	0.57	0.57	3	0.53	0.54	3	0.54	0.54
TSMA8	North 1		0.40	3	0.43	0.43	3	0.46	0.45	3	0.41	0.41
	North 2	1995		3	0.43		3	0.45		3	0.41	
TSMA10	East 1	1996	0.50	3	0.49	0.48	3	0.46	0.46	3	0.47	0.46
	East 2			3	0.48		3	0.45		3	0.46	
TSMA13	North	1997	0.35	3	0.62	0.62	3	0.62	0.62	3	0.62	0.62
TSMA15	North	1998	0.40	3	0.61	0.61	3	0.61	0.61	3	0.59	0.59
TSMA17	West	1998	–	3	0.51	0.51	3	0.47	0.47	3	0.46	0.46
TSMA29	North	2005	–	3	0.49	0.49	3	0.47	0.47	3	0.46	0.46
TSMA30	North	2005	–	3	0.52	0.52	3	0.49	0.49	3	0.49	0.49
MSD1	North	1995	0.45	3	0.48	0.45	3	0.43	0.41	3	0.50	0.49
	South	1996		3	0.42		3	0.39		3	0.47	
MS2	East 1	2000	0.45	3	0.50	0.61	3	0.63	0.57	3	0.59	0.60
	East 2			3	0.62							
	West 1			3	0.76		3	0.50		3	0.60	
	West 2			3	0.57							

* Inv. level = Investigatory level for the site.

Table E.2 Results of sand patch texture depth tests

Site	*Year laid*	*Texture depth (mm)*		
		2007	*2008*	*2009*
PLSD10	1995	–	1.43	2.44
TAC2	1995	–	1.03	1.26
TAC41	2006	–	–	1.60
TAC42	2006	–	–	1.86
TSMA5	1995	1.09	1.19	1.12
TSMA8	1995	–	1.52	1.15
TSMA10	1996	1.28	–	1.77
TSMA15	1998	1.02	–	–
TSMA17	1998	–	1.82	–
MSD1	1995	0.53	0.41	0.66
MS1	1999	0.51	0.55	0.88
MS2	2000	1.36	1.42	–

– No texture measurement taken.

Table E.3 SCRIMtex texture results

Section			*2007*			*2008*			*2009*		
Site	*Lane*	*Laid*	*No.*	*Texture (mm)*	*Mean (mm)*	*No.*	*Texture (mm)*	*Mean (mm)*	*No.*	*Texture (mm)*	*Mean (mm)*
PLSD10	North 1	1995	3	1.27	1.22	3	1.31	1.26	2	1.32	1.27
	North 2		3	1.16		3	1.21		2	1.22	
TAC2	North 1	1995	3	1.00	0.97	3	1.01	0.99	2	1.00	0.99
	North 2		3	0.94		3	0.97		2	0.99	
TAC19	North 1	2001	1	0.73	0.70	2	0.77	0.74	1	0.92	0.77
	North 2		1	0.68		2	0.73		1	0.75	
	South 1		1	0.69		2	0.74		1	0.71	
	South 2		1	0.68		2	0.74		1	0.71	
TAC28	North	2003	2	0.87	0.87	2	0.86	0.87	2	0.86	0.86
TAC38	14 mm	2005	3	1.16	1.16	2	1.19	1.19	2	1.11	1.11
TAC39	6 mm	2005	3	0.60	0.60	2	0.65	0.65	2	0.60	0.60
TAC40	10 mm	2005	2	0.90	0.90	2	0.95	0.95	2	0.89	0.89
TSMA5	South	1995	1	0.69	0.69	3	0.70	0.70	3	0.68	0.68
TSMA8	North 1	1995	3	1.14	1.03	3	1.13	1.03	2	1.14	1.04
	North 2		3	0.92		3	0.94		2	0.94	
TSMA10	East 1	1996	2	1.30	1.14	2	1.24	1.09	2	1.28	1.12
	East 2		2	0.99		2	0.95		2	0.96	
TSMA13	North	1997	2	0.54	1.08	3	1.04	1.04	3	1.03	1.03
TSMA15	North	1998	3	1.13	1.13	3	0.87	0.87	3	0.89	0.89
TSMA17	West	1998	1	1.41	1.41	3	1.43	1.43	3	1.40	1.40
TSMA29	10 mm	2005	1	1.12	1.12	3	1.11	1.11	3	1.15	1.15
TSMA30	14 mm	2005	1	0.73	0.73	3	0.70	0.70	3	0.71	0.71
MSD1	North	1995	2	0.61	0.57	3	0.50	0.43	1	0.44	0.35
	South	1996	2	0.55		3	0.35		1	0.26	
MS2	East 1	2000	1	1.51	1.51	3	0.92	1.01	3	0.80	0.86
	East 2		1	0.77		3	0.95		3	0.00	
	West 1		1	0.91		3	1.41		3	0.85	
	West 2		1	2.24		0			0		

Table E.4 Visual condition results

Site	*Laid*	*Panel mark 2007*	*Panel mark 2008*	*Panel mark 2009*
PLSD7b	1992	P –, v	Surface dressed	Not inspected
PLSD10	1995	$P/S_{-,d,s}$ [$P/B_{-,d,s}$]#	$A_{-,c,t,v}$ [$A/S_{-,c,d,v}$]	$A_{-,c,d,v}$ [$S/P_{-,c,d,s,t}$]
PLSD14	2003	$A_{-,c}$	$A/S_{-,c,d}$	$S_{-,c,v}$
PLSD15	1997	$A_{-,c,t}$	$P_{-,c,d,v}$	Replaced
PLSD16	2002	Not inspected	G	G/M_{-}
PLSD17	2004	Not inspected	G/M	$G/M_{-,c}$
TAC1a	1992	$A/S_{-,c,v}$	Surface dressed	Not inspected
TAC1b	1992	$A_{-,c}$	Surface dressed	Not inspected
TAC2	1995	A_{-} [$S_{-,c}$]#	$S_{-,c,d,t,v}$ [$P_{-,c,d,t,v}$]	$S_{-,c,d,s,t}$ [$P_{-,c,d,s,t}$]
TAC4b	1997	M_{-}	M_{-}	$M/A_{-,d,v}$
TAC7	1996	$M/A_{-,c,t,v}$	$M_{-,c,v}$	$A_{-,c,d,v}$
TAC9	1997	$M_{-,c}$	$A/S_{-,c}$	$A/S_{-,c,t,v}$
TAC11	2002	$M_{-,+,v}$	$M_{-,+,v}$	$M_{-,v}$
TAC12	1993	$A_{-,c}$	$A/S_{-,c,v}$	$S_{-,c,s}$
TAC13	1998	$M_{-,c}$	$M_{-,c}$	Replaced
TAC14	1997	$P_{-,d,v}$	Replaced	Not inspected
TAC15	2000	$A/S_{-,v}$	$S/P_{-,c,d,t}$	Replaced
TAC17	1994	$A/S_{-,c,v}$	Replaced	Not inspected
TAC18	1996	M_{-}*	Not inspected	Not inspected
TAC19	2001	$M_{-,c}$	M –	$A_{-,c,t}$
TAC20	2000	G/M	$M/A_{-,t}$	M_{-}
TAC21	1995	G/M_{-}	$M/A_{-,c,t}$	M/A –
TAC22	1999	G/M_{-}	M_{-}	$A/S_{-,d}$
TAC23a	1999	M	M_{-}	G/M_{-}
TAC23b	1999	M/A_{-}	A_{-}	$S/P_{-,d,t}$
TAC24	1999	M_{-}	Replaced	Not inspected
TAC25	2003	$M/A_{-,c}$	$A/S_{-,c,d,v}$	$A/S_{-,c,d,v}$
TAC26	2003	G†	$M/A_{-,c}$	$M/A_{-,c}$
TAC27	2000	E/G	G	G
TAC28	2003	G/M_{-}	G	G/M_{-}
TAC29	2004	G/M	G/M_{-}	$G/M_{-,c}$
TAC30	1999	M/A_{-}	$M/A_{-,v}$	$A_{+,-,d,t\,v}$
TAC31	1999	$M_{-,c}$	$A_{-,v}$	$M/A_{+,-,v}$
TAC32	1999	$A_{-,d,c}$	$A/S_{-,c,d,v}$	$S_{-,c,d,v}$
TAC33	2005	E/G	Not inspected	$M/A,_{d,t}$

Markings explained in Appendix A.
Second marking [in brackets] indicates overall mark when jointed concrete substrate.
\# Unable to have closures, so monitored different sections alongside available lay-bys.
† Extensive remedial patches noted.
‡ Bypass opened between 2005 and 2006 inspection, significantly reducing traffic carried.
* Major patching after first inspection enhanced overall marking.

Table E.4 (cont'd) Visual condition results

Site	*Laid*	*Panel mark 2007*	*Panel mark 2008*	*Panel mark 2009*
TAC34	2004	*G/M*	*E/G*	$M_{-,c}$
TAC35	2004	$G/M_{-,c}$	$G/M,_{c}$	$M_{-,c,v}$
TAC36	2004	$G/M,_{c}$	*G*	$M_{-,c}$
TAC37	1998	$A_{-,d,v}$	M/A_{-}	$S_{-,c}$
TAC38	2005	*E/G*	*E/G*	*E/G*
TAC39	2005	*E/G*	*E/G*	*G*
TAC40	2005	*E*	*E/G*	G/M_{-}
TAC41	2006	*E*	*G*	*G*
TAC42	2006	*E*	*G*	*G*
TAC43	2008	Not inspected	*E*	*G*
TAC44	2003	Not inspected	Not inspected	M_{-}
TAC45	2003	Not inspected	Not inspected	M_{-}
TSMA3	1993	$A/S_{-,c,v}$	$S_{-,c,v}$	Replaced
TSMA5	1995	G/M_{-}	*G/M*	$M/A_{-,c,v}$
TSMA8	1996	M_{-} [$M/A_{-,c}$]#	$M_{-,c,t}$ [$M/A_{-,c,d,t,v}$]	$M/A_{-,c}$ [$A/S_{-,c,d,t}$]
TSMA9	1996	$A_{-,c,v}$	$S_{-,c,v}$	$P_{-,c,d,t}$
TSMA10	1996	*G*	*G*	G/M_{-}
TSMA11	1996	$M_{-,v}$	$A_{-,c,v}$	$A_{-,c,v}$
TSMA12	1997	M_{-}	$M_{-,v}$	$M_{-,v}$
TSMA13	1997	$M/A_{-,c,t}$	$A_{-,c}$	$A/S_{-,c,t}$
TSMA14	1998	$A/S_{-,c,v}$	$A/S_{-,c,v}$	Not inspected
TSMA15	1998	$A_{-,c}$	$A/S_{-,c,t}$	$A/S_{-,c,s,t}$
TSMA17	1998	M/A_{-}	$M/A_{-,t}$	$M/A_{-,v}$
TSMA18	2000	$S_{-,c,v}$	$P_{-,c,d,v}$	Replaced
TSMA20	1999	*G*	$\mathrm{G/M}_{-,+,c,v}$	$M/A_{-,c,v}$
TSMA21	1999	*G/M*	G/M_{-}	$A_{-,c}$ (being replaced)
TSMA22	2003	*E/G*	Not inspected	Not inspected
TSMA23	2003	$M_{-,c}$	G/M_{-}	M_{-}
TSMA24	1999	$M_{-,v}$‡	*G* ‡	M_{-}‡
TSMA25	2004	M/A_{-}	$A_{-,c,v}$	$A_{-,c,v}$
TSMA26	2004	$M_{-,v}$	G/M_{+}	M_{-}
TSMA27	2004	*G*	*G*	G/M_{+}
TSMA28	2005	*G*	G/M_{-}	*G*
TSMA29	2005	*E*	*E/G*	*G*
TSMA30	2005	*E/G*	*E/G*	$G/M_{-,t}$

Markings explained in Appendix A.
Second marking [in brackets] indicates overall mark when jointed concrete substrate.
Unable to have closures, so monitored different sections alongside available lay-bys.
† Extensive remedial patches noted.
‡ Bypass opened between 2005 and 2006 inspection, significantly reducing traffic carried.
* Major patching after first inspection enhanced overall marking.

Table E.4 (cont'd) Visual condition results

Site	*Laid*	*Panel mark 2007*	*Panel mark 2008*	*Panel mark 2009*
TSMA31	2001	G/M_{-}	$G/M_{-,c,v}$	$M_{-,c}$
TSMA32	2000	$M_{-,c}$	$M/A_{-,c,v}$	$A_{-,c,v}$
TSMA33	2002	*G*	*G*	*G*
TSMA34	1995	$M_{-,c,v}$	$M/A_{-,c,v}$	$M/A_{-,c}$
TSMA35	2008	Not inspected	Not inspected	*G*
TSMA36	2008	Not inspected	Not inspected	*E/G*
TSMA37	2001	Not inspected	Not inspected	$M/A_{-,v}$
TSMA38	2001	Not inspected	Not inspected	M_{-}
TSMA39	2001	Not inspected	Not inspected	$A_{-,v}$
TSMA40	2002	Not inspected	Not inspected	G/M_{-}
TSMA41	2001	Not inspected	Not inspected	$A_{-,v}$
TSMA42	2002	Not inspected	Not inspected	$M/A_{-,v}$
TSMA43	2001	Not inspected	Not inspected	M_{-}
TSMA44	2001	Not inspected	Not inspected	M/A_{-}
TSMA46	2009	Not inspected	Not inspected	*E/G*
TSMA47	2009	Not inspected	Not inspected	*E/G*
MSD1	1995	$S/P_{+,c,v}$	$P_{+,c}$	$S_{+,-,c}$
MSD5	2008	Not inspected	*G*	$M_{-,c}$
MSD6	2008	Not inspected	*G*	$M_{-,c}$
MS1	1999	$M_{-,d}$	$A_{-,c,v}$	$A/S_{-,c,d,v}$
MS2	2000	$P_{-,d,s,t,v}$	$B_{-,d,v}$	$P/B_{-,d,v}$
MS3	2003	$P_{-,d,v}$	$P_{-,c,d,v}$	$P_{-,c,d,v}$
MS4	2008	Not inspected	$M/A_{+,v}$	$M/A_{+,c,v}$

Markings explained in Appendix A.
Second marking [in brackets] indicates overall mark when jointed concrete substrate.
Unable to have closures, so monitored different sections alongside available lay-bys.
† Extensive remedial patches noted.
‡ Bypass opened between 2005 and 2006 inspection, significantly reducing traffic carried.
* Major patching after first inspection enhanced overall marking.

Table E.5 Results of tests on binder recovered from cores

Site	*Year laid*	*Penetration (1/10 mm)*				*Softening point (°C)*			
		Initial	*2007*	*2008*	*2009*	*Initial*	*2007*	*2008*	*2009*
PLSD7b	1993	100	9	Surface dressed		46	71.2	Surface dressed	
PLSD10	1995	100	27	17	13	46	61.2	67.1	66.2
TAC1a	1992	49	31	Surface dressed		56	59.8	Surface dressed	
TAC1b	1992	49	37	Surface dressed		56	57.8	Surface dressed	
TAC2	1995	49	20	6	10	56	73.2	79.3	70.8
TAC34	2004	80	56	64	Not measured	80	57.4	64.0	Not measured
TAC35	2004	80	57	58	Not measured	80	56.6	63.6	Not measured
TAC36	2004	80	48	48	Not measured	80	58.8	61.1	Not measured
TAC37	1998	50	12	13	Not measured	52.5	66.8	69.4	Not measured
TAC41	2006	50	Not measured		20.5	59.5	Not measured		67.1
TAC42	2006	50	20	21	20	59.5	70.0	71.6	69.4
TSMA5	1995	60	7	20	17.5	51	66.2	66.2	66.1
TSMA8	1995	50	10	18	10	52.5	70.2	64.3	70.3
TSMA10	1996	50	19	22	25	52.5	62.4	60.6	58.5
TSMA13	1997	60	19	13	19	51	67.0	66.8	70.6
TSMA15	1998	50	15	Not measured	18	52.5	68.8	Not measured	64.8
TSMA17	1998	50	10	11	15	52.5	70.2	63.6	64.0
TSMA25	2004	50	23	25	Not measured	50	65.4	66.6	Not measured
TSMA26	2004	50	26	28	Not measured	50	63.8	63.8	Not measured
TSMA27	2004	50	29	30	Not measured	50	63.6	64.3	Not measured
MSD1	1995	130	62	60	86	64	50.6	49.8	45.1
MS1	1999	55	22	16	23	55	69.0	65.8	61.8
MS2	2000	55	5	Not measured		55	79.8	Not measured	

Appendix F: Results for individual sites

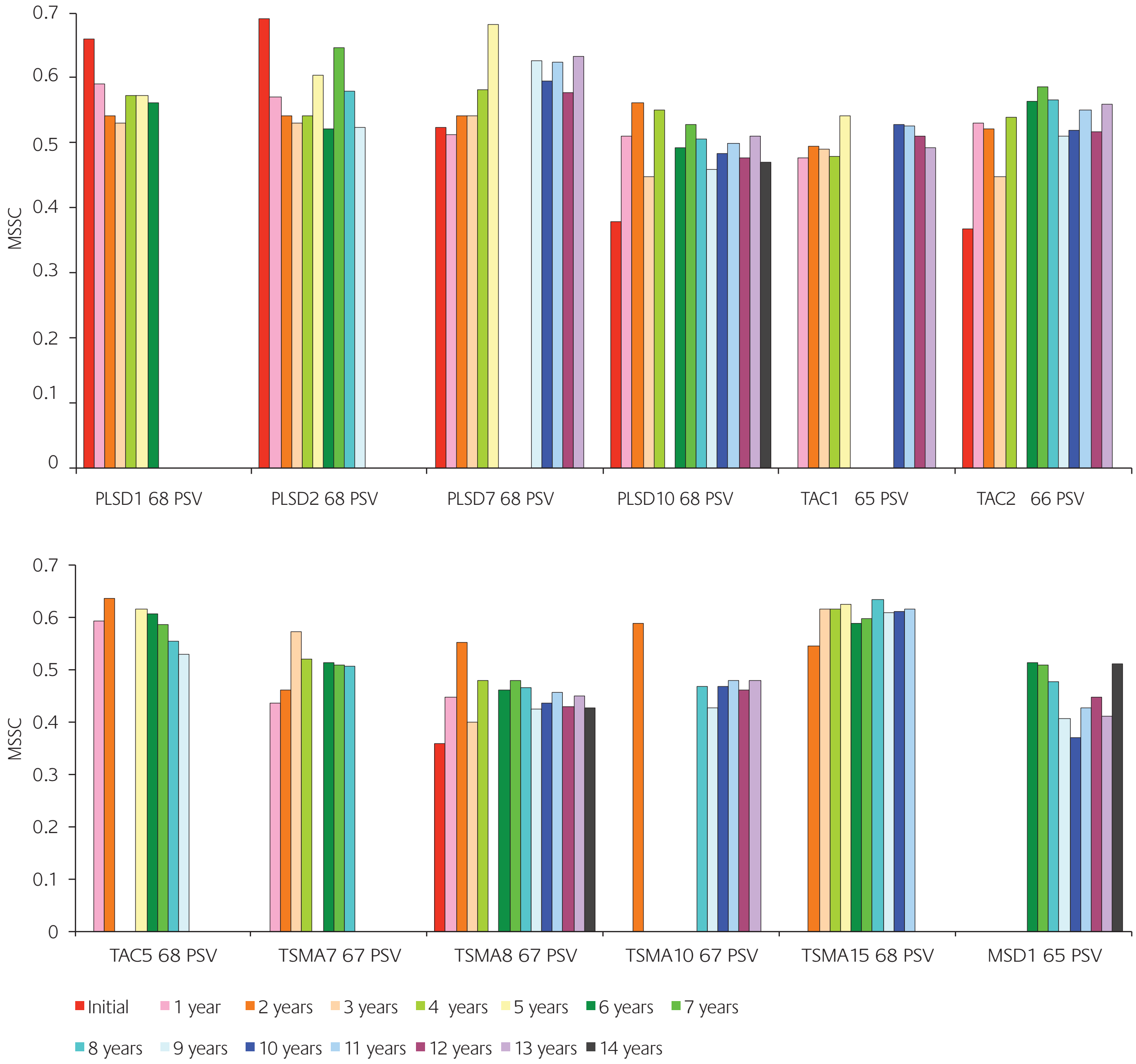

Figure F.1 Adjusted MSSC results from sites with at least seven years' data

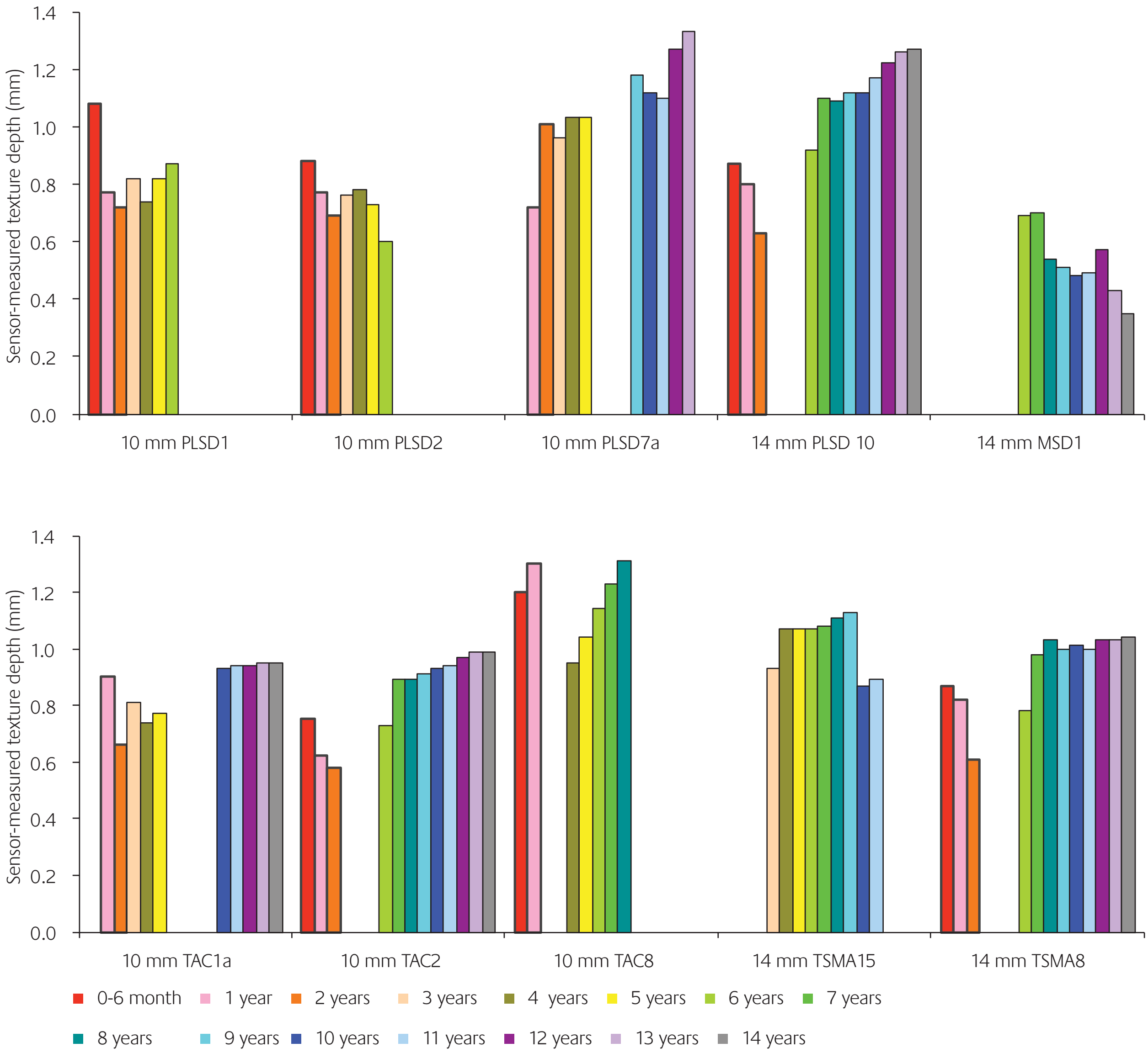

Figure F.2 SMTD results from sites with at least seven years' data

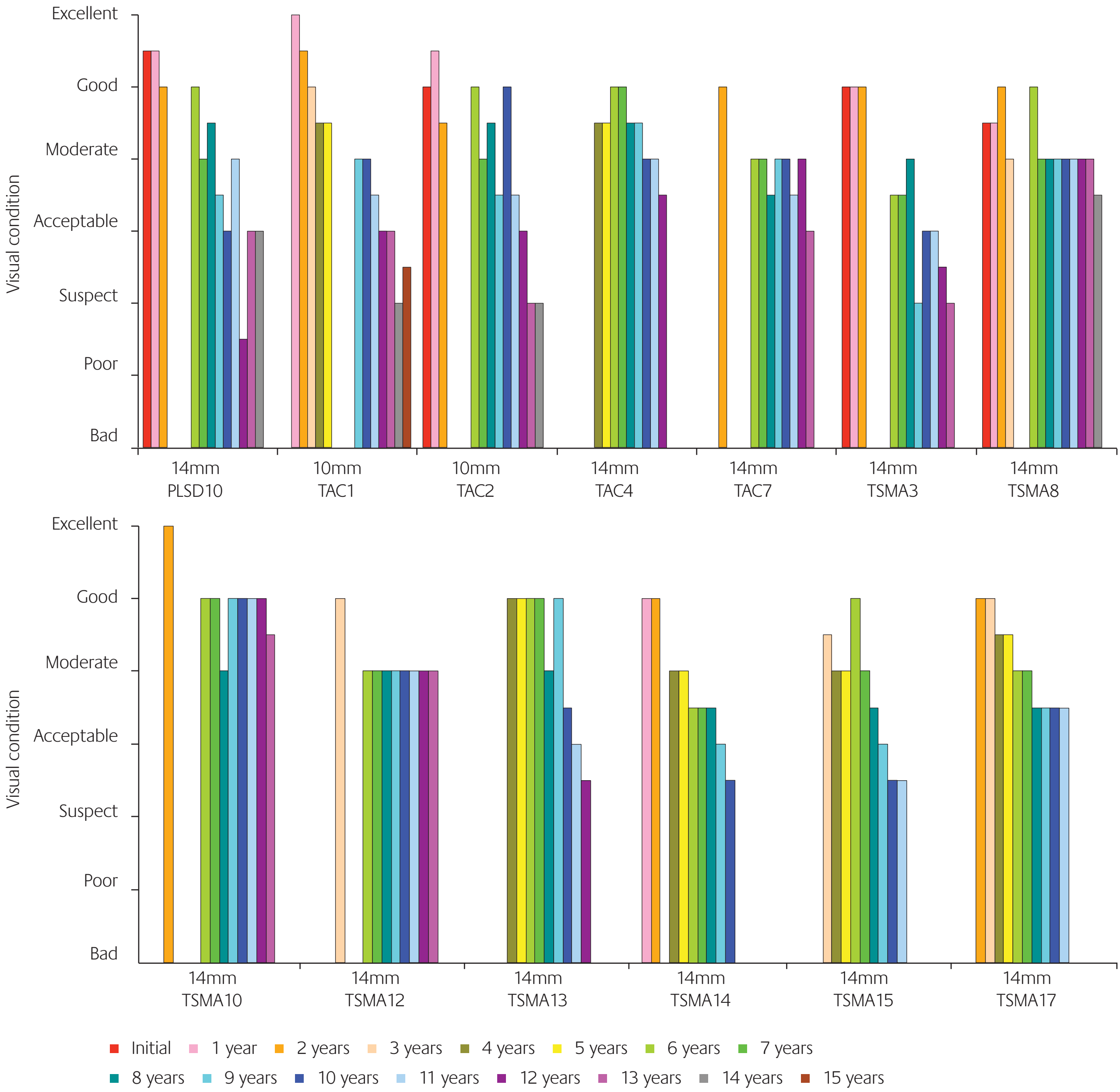

Figure F.3 Visual condition results from sites with at least nine years' data

Appendix G: Statistical analysis of skid resistance data

G.1 Skid resistance data

The Sideway-force Coefficient Routine Investigation Machine (SCRIM) is the standard equipment used for measuring skid resistance in the UK (Hosking, 1996). Measurements to obtain SCRIM coefficients were taken three times during the summer measuring season to allow for seasonal variations during each year. The average of the three SCRIM coefficients measured during the summer months gives the Mean Summer SCRIM Coefficient (MSSC). It is this measure of skid resistance that is presented, analysed and plotted in the main text. However, here it is examined in greater detail using appropriate statistical techniques in order to determine what factors may be influential as the surfaces age.

G.2 Correlation between MSSC and other measures

Table G.1 shows the correlation between MSSC and other measures. It indicates that the level of MSSC varies by age of the surface, the aggregate size and binder content. Generally, the older the surface the smaller the MSSC value, that is the values are negatively correlated. The higher the aggregate size or higher binder content then the lower MSSC value, again all negatively correlated. As expected, binder content and aggregate size are also positively correlated.

PSV values were grouped and the relationship between MSSC and the age, aggregate and binder factors considered within each PSV group:

- Group 1: PSV <63 (sample of 23)
- Group 2: PSV 63 – 67 (sample of 118)
- Group 3: PSV ≥68 (sample of 123)

Table G.2 shows the correlations of MSSC with age, aggregate and binder for each PSV group; those correlations that are statistically significant are shown in bold type. The PSV <63 group only has a few data points (n = 23) and, hence, does not have any significant correlations other than with age. The other two groups have more values and, in particular, the middle PSV group contributes to the statistically significant correlations.

Table G.1 Correlation of MSSC and other measures – all PSV values

Property	*Statistic*	*Age of surface*	*Aggregate size*	*Binder content*	*MSSC normalised*
Age of surface	Pearson Correlation (r)	1	-0.058	-0.021	-0.179
	Significance (2-tailed)		ns	ns	<0.01
	Number	797	797	610	275
Aggregate size	Pearson Correlation (r)	-0.058	1	0.243	-0.279
	Significance (2-tailed)	ns		<0.001	<0.001
	Number	797	797	610	275
Binder content	Pearson Correlation (r)	-0.021	0.243	1	-0.154
	Significance (2-tailed)	ns	<0.001		<0.001
	Number	610	610	610	242
MSSC normalised	Pearson Correlation (r)	-0.179	-0.279	-0.154	1
	Significance (2-tailed)	<0.01	<0.001	<0.05	
	Number	275	275	242	275

ns = Not significant.

Table G.2 Correlation between MSSC and other measures for PSV groups

PSV	*Age of surface*	*Aggregate size*	*Binder content*
<63	**-0.441**	0.099	0.265
63 – 67	**-0.308**	**-0.479**	**-0.333**
≥68	-0.098	**-0.224**	-0.013

Statistically significant values are in bold type.

G.3 MSSC and PSV

There were 264 MSSC measurements that also had data on PSV. The sites from which the measurements were taken include a range of road types and surfacing types and, when combined, illustrate that generally higher values of PSV lead to a higher normalised MSSC value, as shown in Figure G.1.

An analysis of variance (ANOVA) was conducted with normalised MSSC as the dependent variable and age of surface and PSV as factors (initially binder content was also included in the ANOVA but it was found to be not statistically significant). The analysis shows that there were no overall statistically significant differences between MSSC values by age of the surface with an F-test value of $F_{14,247} = 1.48$ (p = not significant). However, the PSV is important with an F-test value of $F_{2,247} = 7.61$ ($p < 0.005$), that is the differences between MSSC values that are attributable to different PSVs.

PSV <63 and PSV 63 – 67 resulted in an average of 0.03 decrease in the normalised MSSC value relative to PSV ≥68, that is the MSSC value for PSV ≥68 is, on average, about 0.03 larger than the other two groups. A linear regression analysis of MSSC and PSV suggests that MSSC decreases with age of the surface, albeit at a gentle rate (parameter value for age = -0.004, $p < 0.005$ and $R^2 = 0.055$).

However, as was stated above, the sites are a mixture of different road types and thin surfacing system types and this mixture is not balanced across all years. The normalised MSSC data were analysed taking into account these additional factors.

G.4 MSSC by system type and PSV

Potentially, there are 15 combinations of system type and PSV, but in practice only four had reasonable numbers of data. These combinations are:

- PLSD surfaced sites with PSV ≥68, sample of 69
- TAC surfaced sites with PSV 63 – 67, sample of 59
- TSMA surfaced sites with PSV 63– 67, sample of 38
- TSMA surfaced sites with PSV ≥68, sample of 32

The plot of the normalised MSSC values for these four combinations of system type and PSV is shown in Figure G.2. The same general pattern of MSSC values by age is seen as for the whole set of data in Figure G.1. However, there is some variability between the different system type/PSV subsets, with TSMA PSV ≥68 varying considerably, especially when compared with TAC PSV 63 – 67.

An ANOVA was conducted with normalised MSSC as the dependent variable and age of surface and system type/PSV subgroup as factors. The analysis shows that there were no overall statistically significant differences between MSSC values by age of the surface with an F-test value of $F_{14,197} = 0.89$ (p = ns). However, the system type/PSV combination was important with an F-test value of $F_{3.197} = 14.2$ ($p < 0.001$).

Comparing the two TSMA subgroups found that the average MSSC value is about 0.08 higher for the PSV ≥68 group. Hence, the difference controlling for system type (of TSMA) results in a higher MSSC value of about 0.08 when PSV is ≥68 as compared to PSV of 63 – 67.

G.5 MSSC by road type and PSV

Potentially there are 12 combinations of road type and PSV, but in practice only four had reasonable numbers of data. These combinations are:

- Motorway sites with PSV ≥68, sample of 30
- Major A road sites with PSV 63 – 67, sample of 78
- Major A road sites with PSV ≥68, sample of 71
- Other A road sites with PSV 63 – 67, sample of 29

The plot of the normalised MSSC values for these four road type/PSV combinations is shown in Figure G.3. The same general pattern of MSSC values by age is seen as for the whole set of data in Figure G.1.

An ANOVA was conducted with normalised MSSC as the dependent variable and age of surface and road type/PSV subgroup as factors. The analysis showed that there were no statistically significant differences between MSSC values by age of the surface with an F-test value of $F_{14,190} = 1.08$ (p = ns). However, the level of road type/PSV was important with an F-test value of $F_{3,190} = 9.30$ ($p < 0.001$).

Comparing the two major A road subgroups found that the average MSSC value is about 0.026 higher for the PSV ≥68 group. Hence, the difference controlling for road type (major A road) results in a higher MSSC value of about 0.026 when PSV ≥68 compared with PSV of 63 – 67. The difference in normalised MSSC between trunk A roads and motorways (both with PSV ≥68) was 0.004, suggesting that they are very similar.

G.6 Summary

The analysis indicates that, in general, there was no statistically significant decrease of MSSC as a uniform function with age of the surfacing. There is considerable fluctuation but no regular change in MSSC normalised values, with some of this pattern in MSSC values possibly being a function of the sites included. There is evidence that PSV does influence the MSSC measured, as would be expected, and that this influence appears to be quite consistent as the thin surfacing systems age.

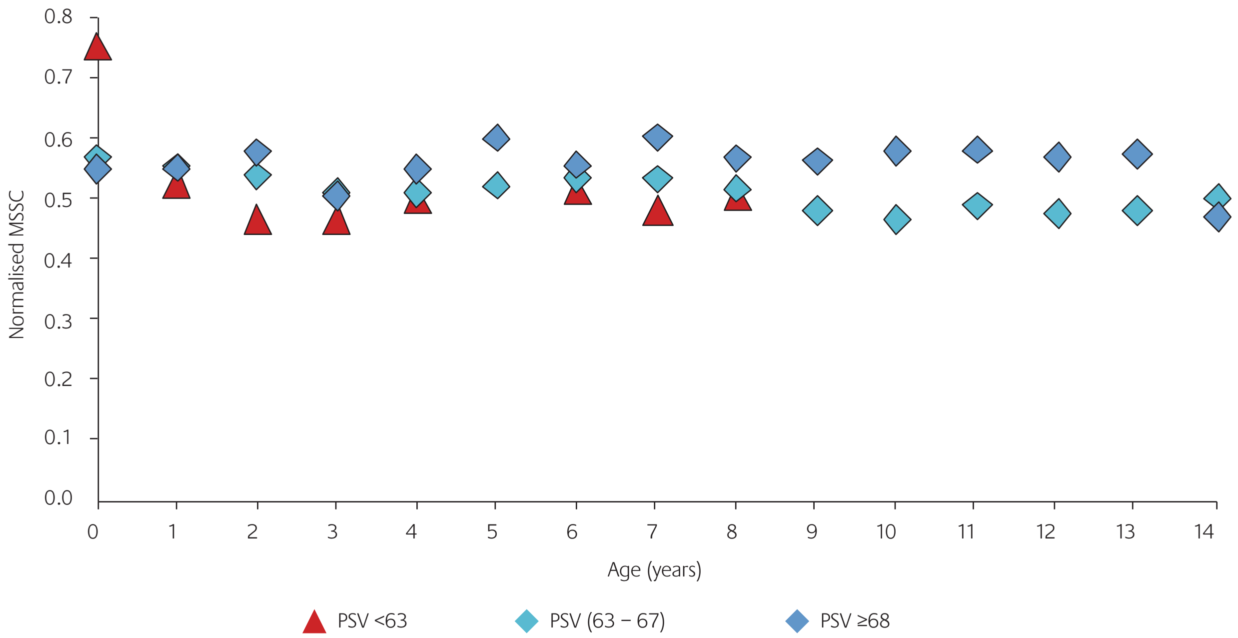

Figure G.1 Mean Summer SCRIM coefficient by PSV for all sites with data

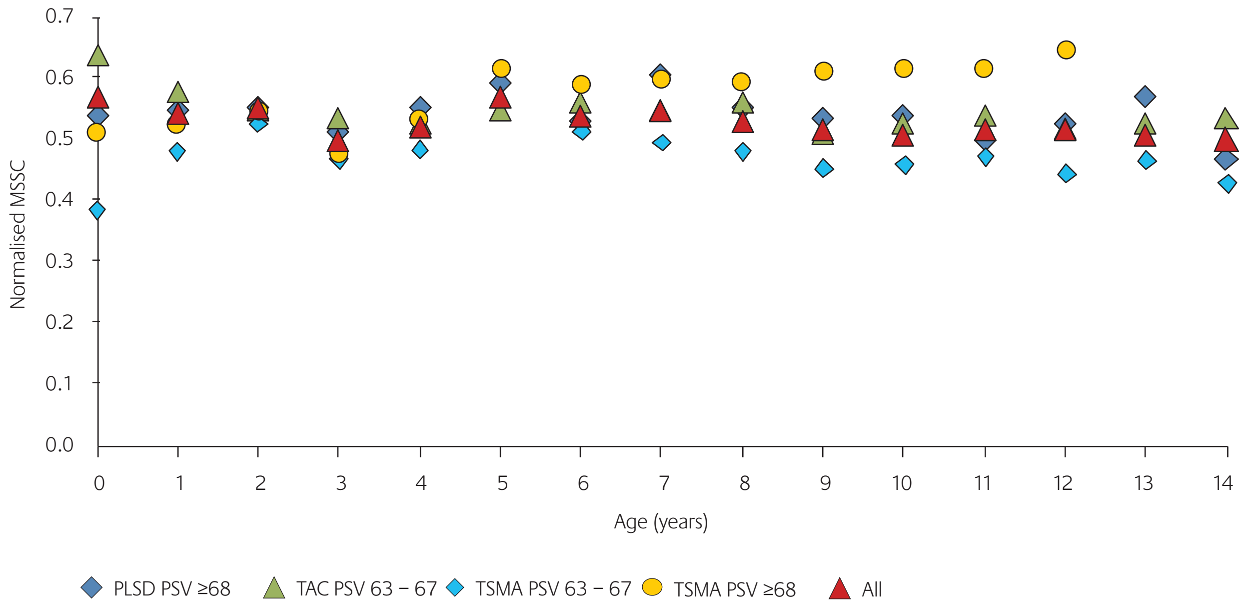

Figure G.2 Mean Summer SCRIM coefficient by PSV and system type

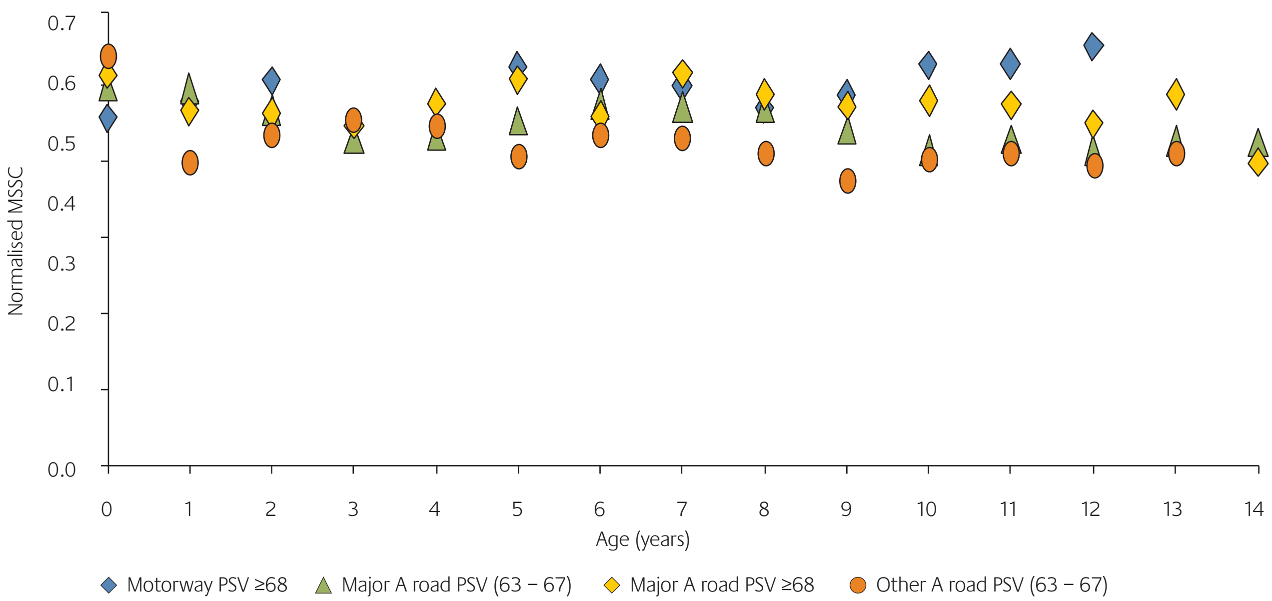

Figure G.3 Mean Summer SCRIM coefficient by PSV and road type

Appendix H: Statistical analysis of texture depth and other condition data

H.1 Texture data

The texture depth was measured on all trunk road sites by the sand patch method in accordance with BS 598-105 (BSI, 2000) prior to the road being opened to traffic. However, for in-service monitoring of trial sites, it is not practical to close sites in order to measure the texture by the sand patch method. Therefore, the texture depth (SMTD) is often monitored by laser texture-measuring equipment mounted on a vehicle such as SCRIM (SCRIMtex), which can travel at normal traffic speeds. These two measures of texture (sand patch and SMTD) are described and plotted in the main text. However, here they are examined in greater detail using appropriate statistical techniques in order to determine what factors may be influential as the surfaces age.

H.2 Texture data (sand patch and SMTD) and other measures

Figure H.1 shows the relationship between age of the surface and the two texture measures. It indicates that the texture measure levels reduce with age of the surface for the first three to five years before stabilising, which is more evident for the sand patch measure. However, this apparent stabilisation may be a result of the sites being a mixture of different road types and thin surfacing system types and this mixture is not necessarily balanced across all years.

The correlation between the texture depth measurements and other potentially influential measures is shown in Table H.1. The correlation between the sand patch measurements is statistically significant when associated with age of surface, aggregate size, binder content and particle loss, whereas for SMTD there are only statistically significant correlations with aggregate size and particle loss.

Both sand patch and SMTD measurements were only available for 66 site/age combinations and were correlated with a value 0.463, which implies they share about 21 % of common variation.

The particle loss measure is dichotomous in that particle loss is either reported or not reported in the visual condition surveys. An increasing proportion of sites seem to have particle loss as they age, as is illustrated by Figure H.2.

H.3 Sand patch and SMTD analysis of variance

An analysis of variance was conducted on both the sand patch and the SMTD measurements in order to investigate the importance of these measures and also take into account road type. The analysis included factors for the age of surface, aggregate size, road type and particle loss with binder content as a covariant. The results for the sand patch measurement suggest that aggregate size and road type were important in explaining some of the variability between the texture depth measurements but that, once these were included, particle loss was not important. This relationship presumably results from the proportion of particle loss and age being closely related. Similar results were also found for the SMTD texture measurement, albeit binder content was not statistically significant.

The results (excluding the non-significant particle loss term) for sand patch as the dependent variable in Table H.2 suggest that aggregate size and road type were important in explaining some of the variability between the texture depth values. Further analyses considered combinations of road type and aggregate size. However, only three combinations of road type and aggregate size have reasonable sample sizes of available data, as indicated by "*" in Table H.3.

The texture measures were further analysed via an ANOVA that included age and the three road type/aggregate combinations and binder as a covariant (for sand patch only). As expected, the analysis found that there is an age effect and road type/aggregate size effect. The data for these road type/aggregate size combinations is illustrated in the next two sections.

H.4 SMTD by road type and aggregate size

The change in SMTD with age is shown in Figure H.3 for three combinations of road type and aggregate size. The pattern of change in SMTD is similar to that shown in Figure H.1 for all three subsets of data. However, once the measurements have stabilised (after eight years), those sites with an aggregate size of 14 mm tend to have higher SMTD values, although an analysis of variance on these data did not find any statistically significant differences between the road type/aggregate subgroups. There are statistically significant differences in the age effect.

H.5 Sand patch by road type and aggregate size

The level of sand patch by age is shown in Figure H.4 for three combinations of road type and aggregate size. The pattern of change for sand patch measurements is similar to that shown in Figure H.1, but there is a lack of data for sites aged between four and eight years. There is considerable variation between the subgroups but, for the higher aged site data, those with aggregate size of 14 mm tend to have higher values. An analysis of variance on these data found statistically significant differences between the road type/aggregate size subgroups and there were statistical significant differences in the age effect.

On average, there is a reduction in the sand patch measurement as the surface ages; this reduction is evident (to a degree) for each of the subsets as well as over all the sites, as shown in Figure H.1.

H.6 Summary

In summary, it appears that there are initial reductions in texture depth measurements as the surfacing ages. However, after this initial reduction textures stay relatively constant with time. Understandably, the texture depth measurements are influenced by aggregate size and binder contents. Different road types tend to use different aggregate sizes and an analysis of road type/aggregate subsets found that texture measures still differ with age, suggesting that there is a reasonably consistent pattern of change (within subgroups of sites) that is not influenced by other factors such as aggregate size, binder contents or particle loss.

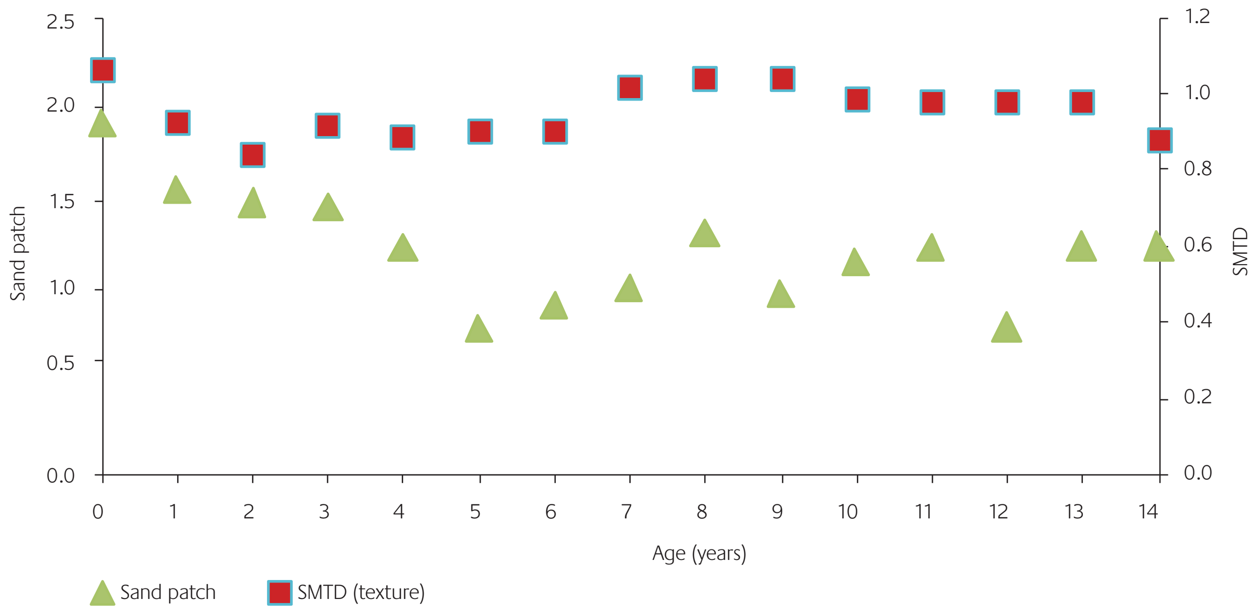

Figure H.1 Texture measures by age of surface

Table H.1 Correlation of texture measure and other measures

Parameter	*Statistic*	*Sand patch*	*SMTD*
	Pearson Correlation (r)	-0.496	0.052
Age of surface	Sig. (2-tailed)	<0.001	ns
	Number	167	230
	Pearson Correlation (r)	0.339	0.173
Aggregate size	Sig. (2-tailed)	<0.001	<0.01
	Number	167	230
	Pearson Correlation (r)	-0.332	-0.044
Binder content	Sig. (2-tailed)	< 0.001	ns
	Number	134	188
	Pearson Correlation (r)	-0.279	0.307
Particle loss	Sig. (2-tailed)	<0.02	<0.001
	Number	81	169
	Pearson Correlation (r)	1	0.463
Sand patch	Sig. (2-tailed)	–	<0.001
	Number	167	66
	Pearson Correlation (r)	0.463	1
SMTD (texture)	Sig. (2-tailed)	<0.001	–
	Number	66	230

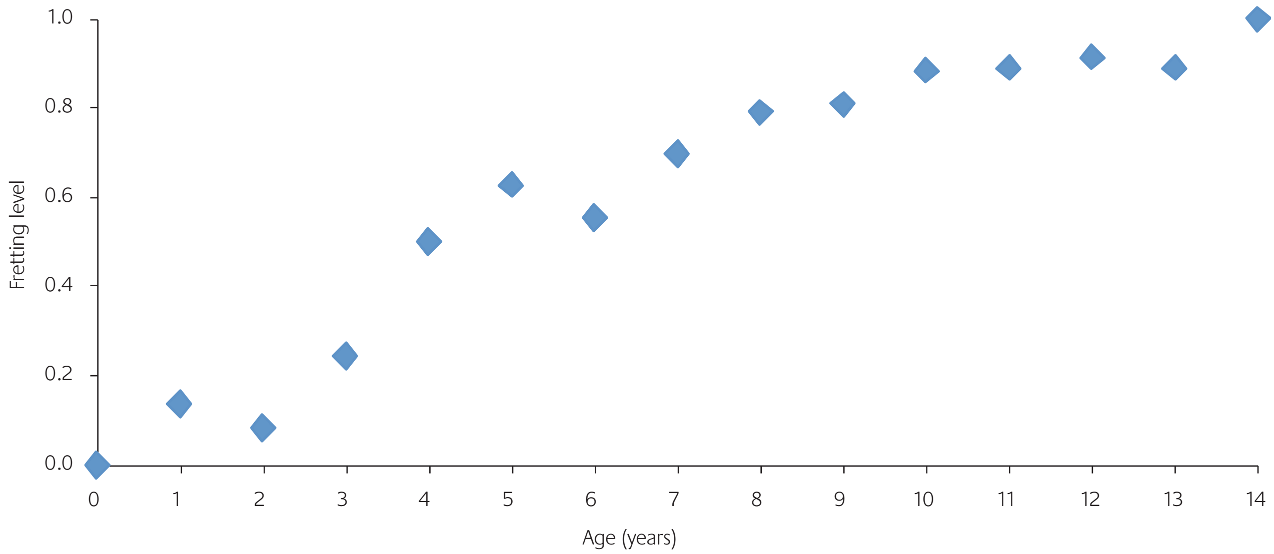

Figure H.2 Proportion with particle loss by age of surfacing

Table H.2 ANOVA results for sand patch texture measure analysis

Source	*Type IV sum of squares*	*Degrees of freedom*	*Mean square*	*F-ratio*	*Significance level*
Intercept	6.03	1	6.03	49.66	0.000
Age	10.52	12	0.88	7.22	0.000
Road type	3.87	3	1.29	10.63	0.000
Aggregate size	1.78	2	0.89	7.32	0.001
Binder content	1.77	1	1.77	14.61	0.000
Error	13.96	115	0.12		
Total	406.87	134			

Dependent variable: sand patch.
Variability explained by model: $R^2 = 0.609$ ($R^2_{adjusted} = 0.548$)

Table H.3 Road type and aggregate size combinations and sample sizes

Road type and aggregate size	*Sand patch*		*SMTD (texture)*	
	Mean	*Valid number*	*Mean*	*Valid number*
Aggregate = 6 mm and major A road	1.250	10	0.828	16
Aggregate = 6 mm and other road	0.600	6	–	0
Aggregate = 10 mm and motorway	1.992	6	1.010	10
*Aggregate = 10 mm and major A road	1.425	24	0.933	69
Aggregate = 10 mm and other A road	1.412	19	0.859	13
Aggregate = 10 mm and other road	1.468	9	–	0
Aggregate = 14 mm and motorway	2.318	16	1.124	26
*Aggregate = 14 mm and major A road	1.667	31	1.011	54
*Aggregate = 14 mm and other A road	1.552	37	0.938	33
Aggregate = 14 mm and other road	1.148	9	0.529	9

* Combinations with reasonable sample sizes.

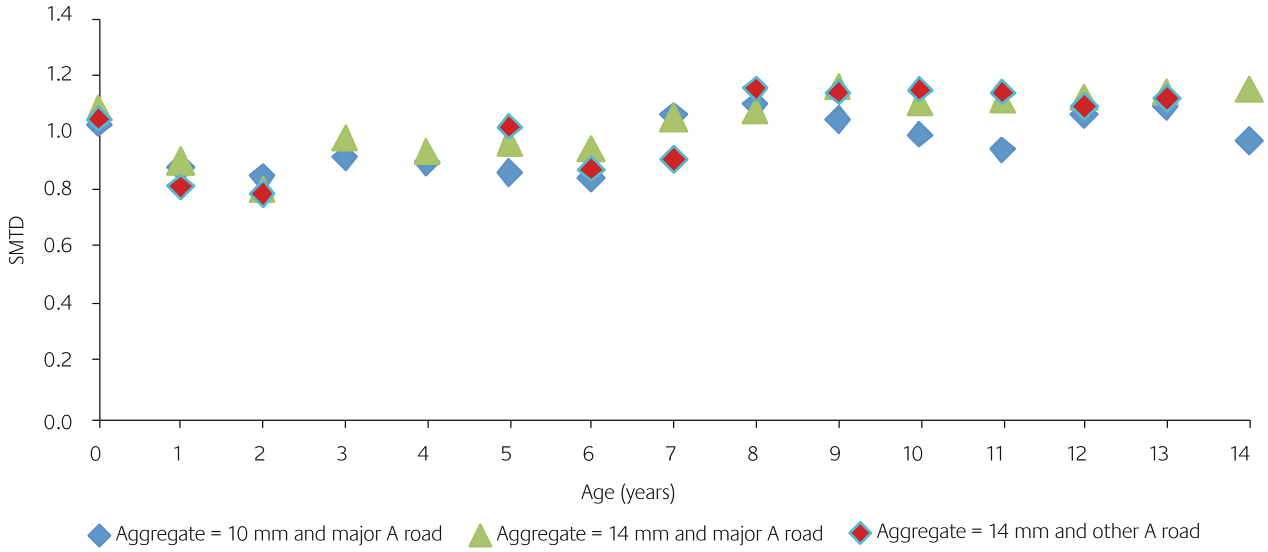

Figure H.3 Level of SMTD by age of surface and road type and aggregate

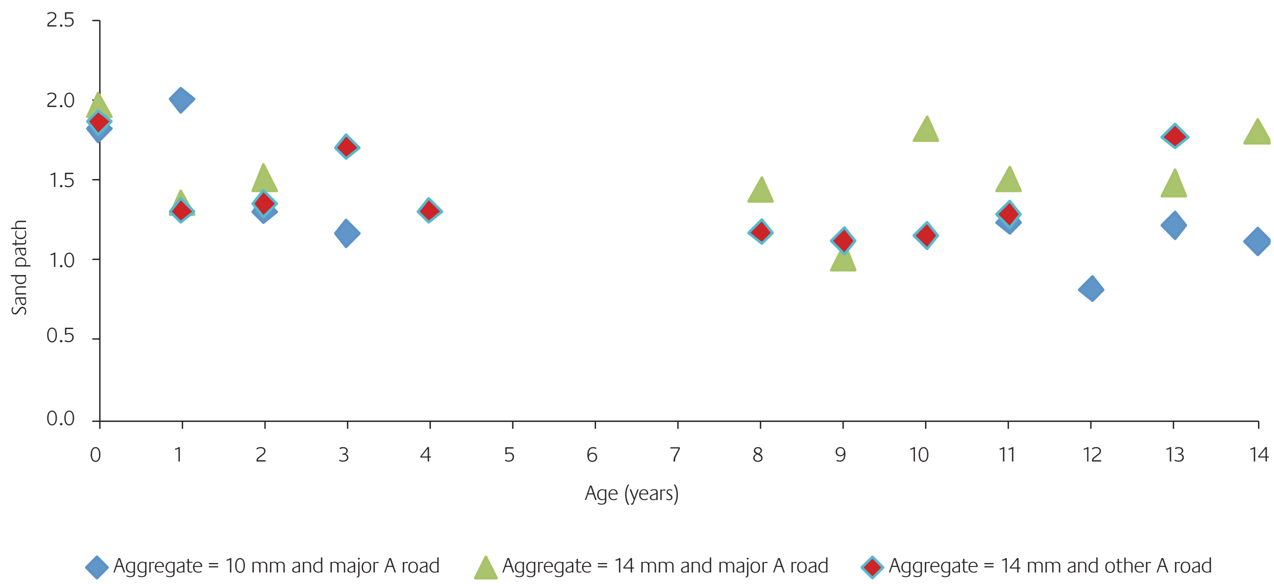

Figure H.4 Sand patch by age of surface and road type and aggregate

Appendix I: Simple analyses of visual condition

I.1 Trends for sites grouped by system type

The visual condition data in Figure 4.1 followed trends that were more consistent than those obtained for the other properties being measured. The equations for the linear trend lines (based on unweighted means for years where data existed and termed "annual means" and, as such, not statistically valid) are given in Equations I.1 to I.5. For these equations, Cond is the visual condition mark converted to a continuous variable (*Excellent* = 7, *Good* = 6, *Moderate* = 5, *Acceptable* = 4, *Suspect* = 3, *Poor* = 2 and *Bad* = 1) and *Age* is the period that the surfacing has been in service in years.

For PLSD sites (from 15 annual means):

$$Cond_{PLSD} = 6.04 - 0.202 \times Age \quad (R^2 = 0.80)$$

(Equation I.1)

For TAC sites (from 17 annual means):

$$Cond_{TAC} = 6.33 - 0.189 \times Age \quad (R^2 = 0.97)$$

(Equation I.2)

For TSMA sites (from 15 annual means):

$$Cond_{TSMA} = 6.12 - 0.133 \times Age \quad (R^2 = 0.91)$$

(Equation I.3)

For MSD sites (from 13 annual means):

$$Cond_{MSD} = 5.60 - 0.267 \times Age \quad (R^2 = 0.85)$$

(Equation I.4)

For MS sites (from 11 annual means):

$$Cond_{MS} = 4.27 - 0.129 \times Age \quad (R^2 = 0.49)$$

(Equation I.5)

The equivalent quadratic trend lines are given in Equations I.6 to I.10.

For PLSD sites (from 15 annual means):

$$Cond_{PLSD} = 6.36 - 0.370 \times Age + 0.0107 \times Age^2 \quad (R^2 = 0.83)$$

(Equation I.6)

For TAC sites (from 17 annual means):

$$Cond_{TAC} = 6.38 - 0.210 \times Age + 0.0013 \times Age^2 \quad (R^2 = 0.97)$$

(Equation I.7)

For TSMA sites (from 15 annual means):

$$Cond_{TSMA} = 6.27 - 0.204 \times Age - 0.0051 \times Age^2 \quad (R^2 = 0.93)$$

(Equation I.8)

For MSD sites (from 13 annual means):

$$Cond_{MSD} = 6.11 - 0.518 \times Age - 0.0182 \times Age^2 \quad (R^2 = 0.91)$$

(Equation I.9)

For MS sites (from 11 annual means):

$$Cond_{MS} = 4.44 - 0.245 \times Age - 0.0117 \times Age^2 \quad (R^2 = 0.52)$$

(Equation I.10)

The constants in both sets of equations imply the extrapolated value for when the surfacing is laid, which should ideally be 7.0 (*Excellent*) with good workmanship.

The values of correlation coefficients, R^2, found above together with those obtained previously from data up to 2003 (Nicholls and Carswell, 2004) and up to 2006 (Nicholls *et al*., 2007) are given in Table I.1.

In the previous reports, trend lines for MS were not included because there was an apparent improvement in the visual condition assessments with time resulting from the relationships being based on data from a limited number of sites, each over a different set of ages. There are now sufficient data for the trend lines to be consistent with those of other systems (and engineering judgement), although the correlation coefficients are significantly less than for the other system types and further data are required before they can be considered reliable.

The correlation coefficients for both linear and quadratic relationships for the asphalt systems (PLSD, TAC and TSMA) have increased since the last report with only minor changes to the equation coefficients. Therefore, the relationships for these systems can be considered to be reasonably well established. The trend lines for MSD also have reasonable correlation coefficients.

Although the quadratic trend lines have higher correlation coefficients, the limited differences from the equivalent linear trend line, particularly for TAC with 0.97 for both, indicate that there is no significant advantage with this approach and linear modelling is generally sufficient. This observation was also noted previously (Nicholls *et al*., 2007).

Table I.1 Improvement in correlation with time

System	Linear R^2 values for data to:		Quadratic R^2 values for data to:		
	2006	2009	2003	2006	2009
PLSD	0.79	0.80	0.85	0.83	0.83
TAC	0.89	0.97	0.84	0.89	0.97
TSMA	0.82	0.91	0.68	0.84	0.93
MSD	0.92	0.85	0.98	0.92	0.91
MS	–	0.49	–	–	0.52

I.2 Trends for sites grouped by system type and aggregate size

Unlike the system types based on surface treatments (MSD and MS), the asphalt systems (PLSD, TAC and TSMA) can be subdivided by maximum aggregate size, as shown in Figure 4.2. The equations for the linear trend lines for these subdivisions are given as Equations I.11 to I.18.

For 14 mm PLSD sites (from 14 annual means):

$$Cond_{14\ mm\ PLSD} = 6.06 - 0.210 \times Age \qquad (R^2 = 0.67)$$

(Equation I.11)

For 10 mm PLSD sites (from 13 annual means):

$$Cond_{10\ mm\ PLSD} = 6.15 - 0.232 \times Age \qquad (R^2 = 0.86)$$

(Equation I.12)

For 6 mm PLSD sites (from 6 annual means):

$$Cond_{6\ mm\ PLSD} = 7.03 - 0.700 \times Age \qquad (R^2 = 0.98)$$

(Equation I.13)

For 14 mm TAC sites (from 13 annual means):

$$Cond_{14\ mm\ TAC} = 6.43 - 0.157 \times Age \qquad (R^2 = 0.74)$$

(Equation I.14)

For 10 mm TAC sites (from 17 annual means):

$$Cond_{10\ mm\ TAC} = 6.40 - 0.194 \times Age \qquad (R^2 = 0.94)$$

(Equation I.15)

For 6 mm TAC sites (from 10 annual means):

$$Cond_{6\ mm\ TAC} = 5.62 - 0.169 \times Age \qquad (R^2 = 0.55)$$

(Equation I.16)

For 14 mm TSMA sites (from 15 annual means):

$$Cond_{14\ mm\ TSMA} = 6.06 - 0.135 \times Age \qquad (R^2 = 0.90)$$

(Equation I.17)

For 10 mm TSMA sites (from 15 annual means):

$$Cond_{10\ mm\ TSMA} = 6.35 - 0.097 \times Age \qquad (R^2 = 0.50)$$

(Equation I.18)

The equation for 6 mm PLSD has a significantly different slope, but the line is defined from mean values at only six ages whereas the 10 mm and 14 mm aggregate sizes for each system have mean values at between 13 and 15 ages. The other system type with a 6 mm aggregate size, TAC, has mean values at ten ages and a more similar slope to the more general pattern but a relatively low correlation coefficient. Therefore, the 6 mm aggregate size for the two asphalt systems require more data before their relationships could be considered robust.

The linear trend lines can only be considered indicative because the data that are averaged for a system type and aggregate size combination will come from a different subset of the sites for each age and require a large number of data points to avoid being biased. As a result, 14 mm PLSD and 10 mm TSMA, which have relatively few sites (as opposed to readings from sites at different ages), have significantly weaker correlations. In the case of the trend line for 10 mm TSMA, it has a gentler slope than other system type/aggregate size combinations. However, when data points at ages of 11 years and more (which are from a single, relatively good site compared with the average of three sites for previous ages) are discounted, the trend line slope becomes closer to that of the other combinations and R^2 increases to 0.64.

The trend line for 10 mm TSMA is also the only one that is above the trend line(s) for larger sizes of the same system type. Therefore, it appears that large aggregate sizes do have better durability than smaller sizes except for TSMA. However, whether the enhancement is due to the aggregate size itself or the extra thickness at which asphalt with a larger aggregate size is normally laid is not clear.

I.3 Trends for system type and aggregate size based on individual results

The individual results (as opposed to the annual mean values) for the types of thin surfacing systems (PLSD, TAC, TSMA, MSD and MS) have also been split into different aggregate sizes. They are plotted both as frequency plots for each age/visual condition value (Figures I.1 to I.10) and as simple plots (with no indication of the number of occurrences of each point) with linear trend lines (Figures I.11 to I.14). Both types are given for each system type/aggregate size combination.

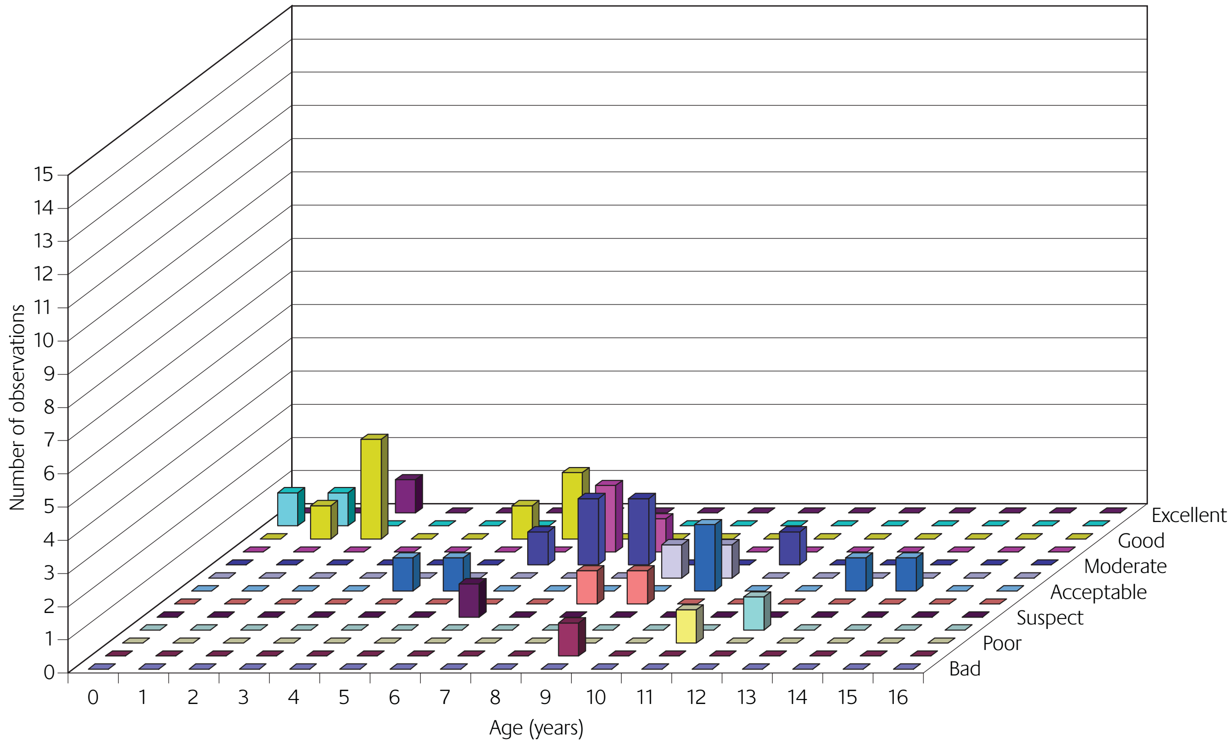

Figure I.1 Individual results for 14 mm PLSD

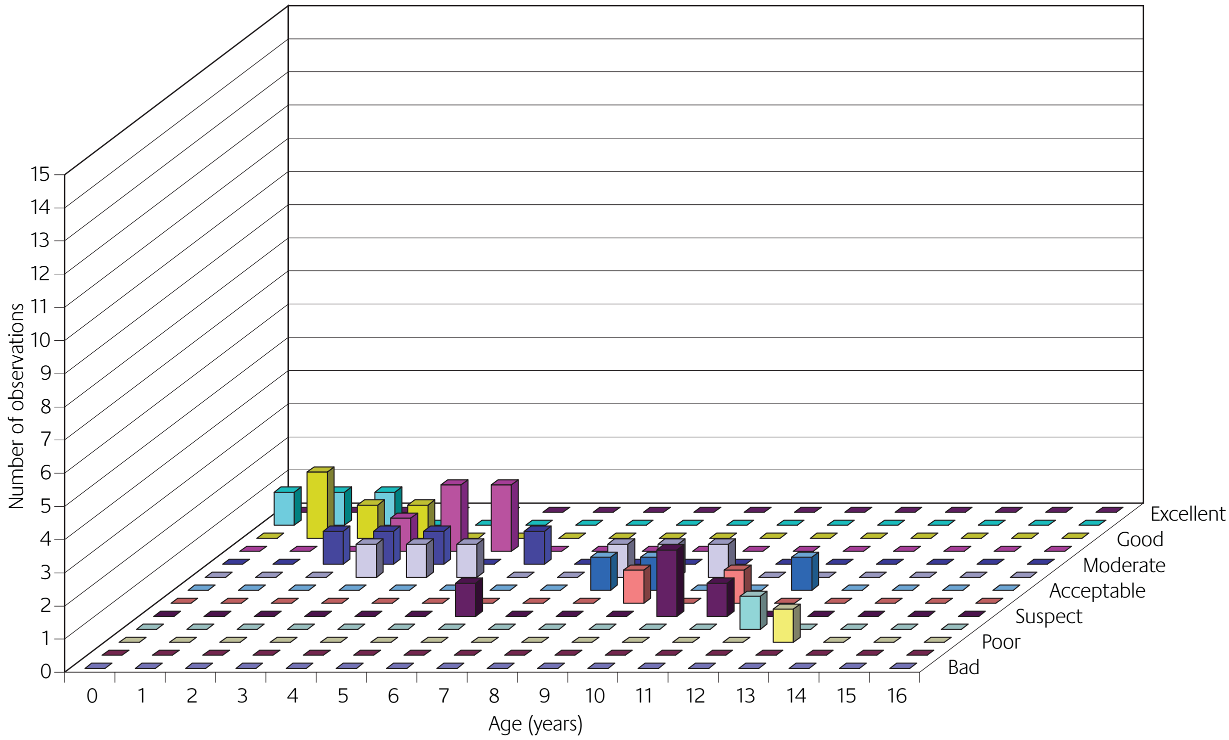

Figure I.2 Individual results for 10 mm PLSD

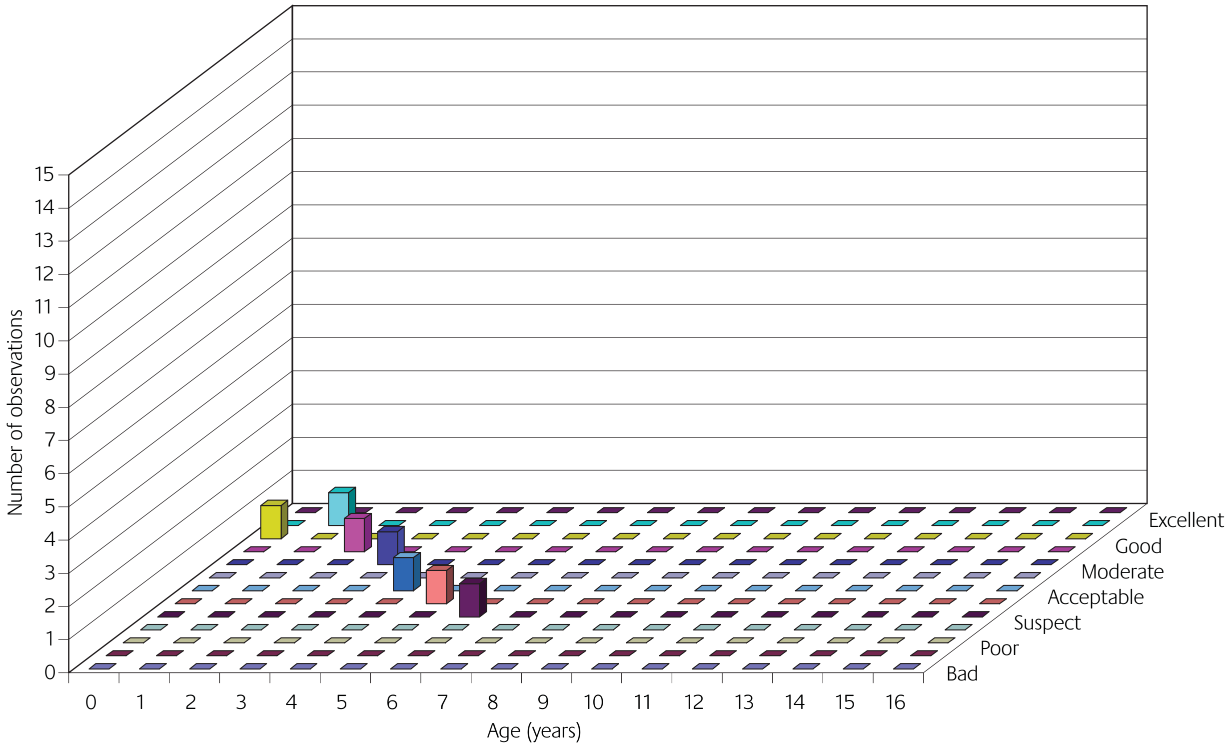

Figure I.3 Individual results for 6 mm PLSD

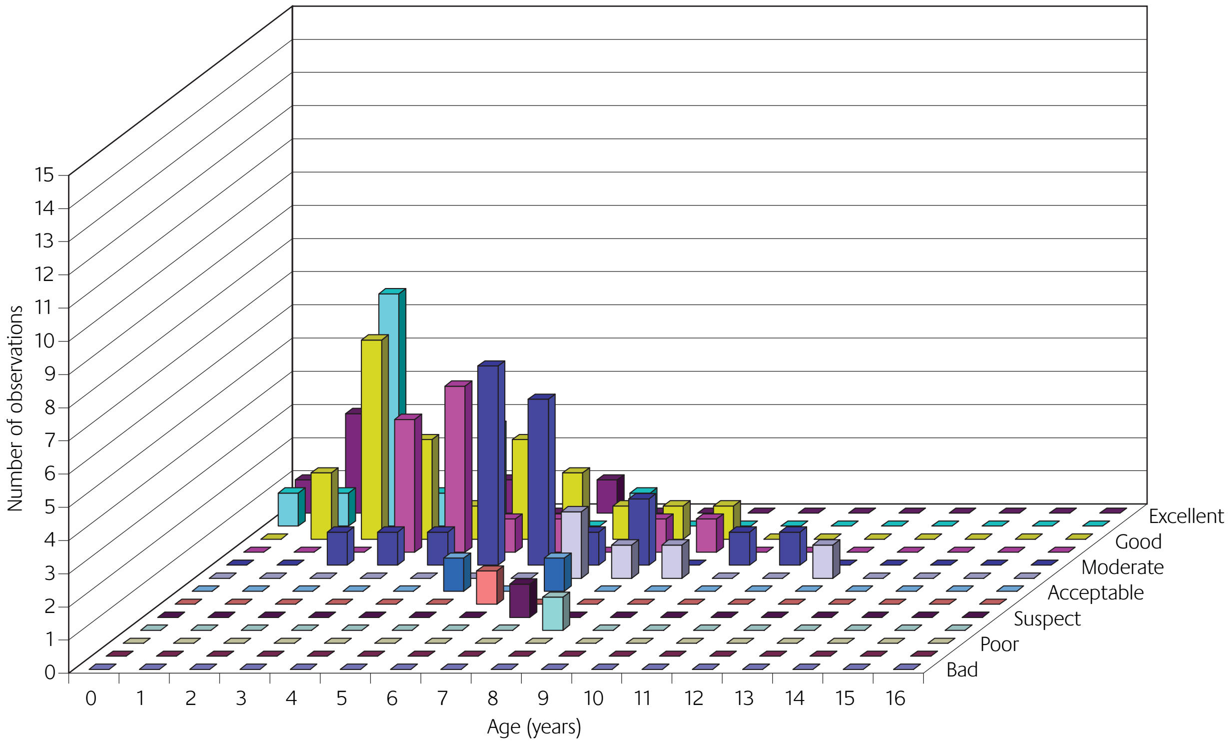

Figure I.4 Individual results for 14 mm TAC

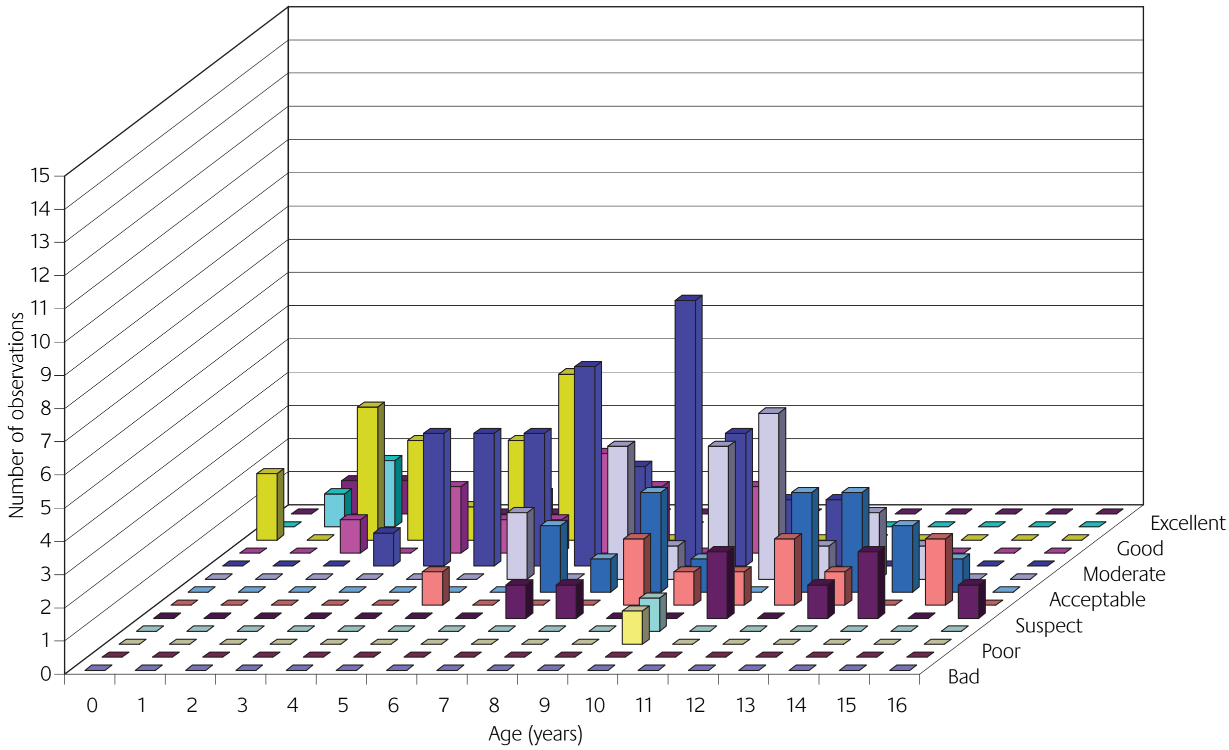

Figure I.5 Individual results for 10 mm TAC

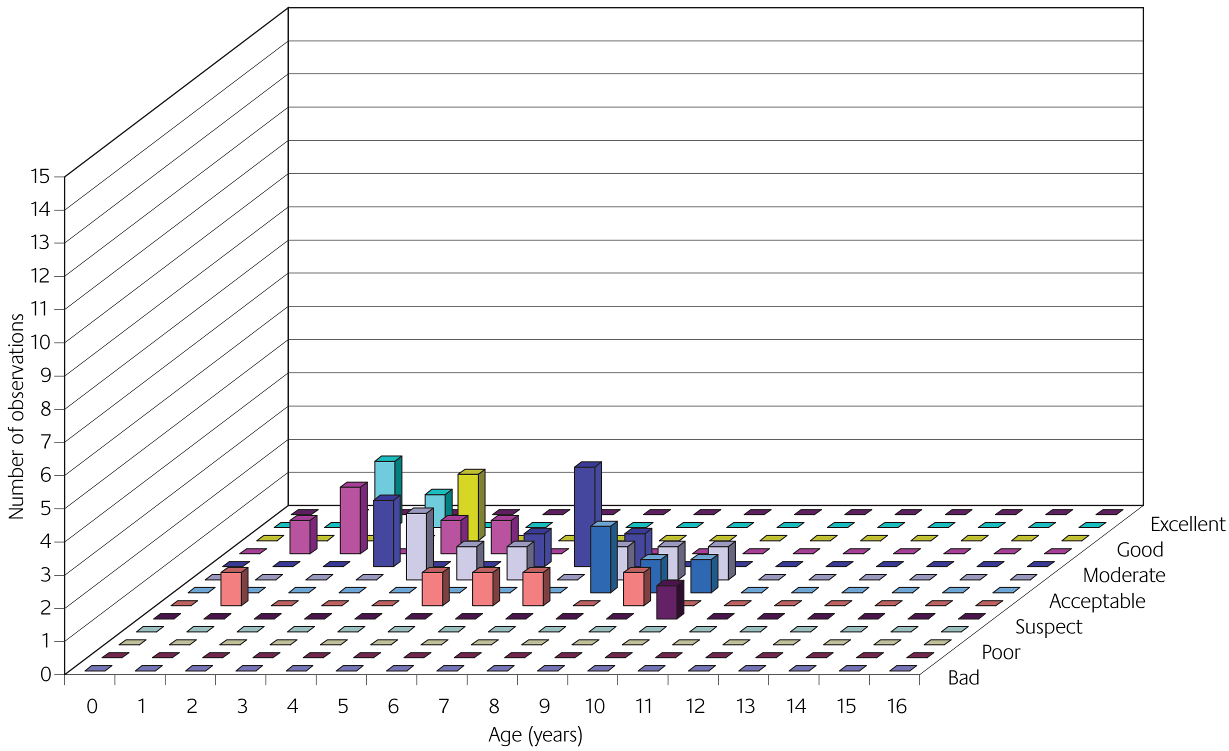

Figure I.6 Individual results for 6 mm TAC

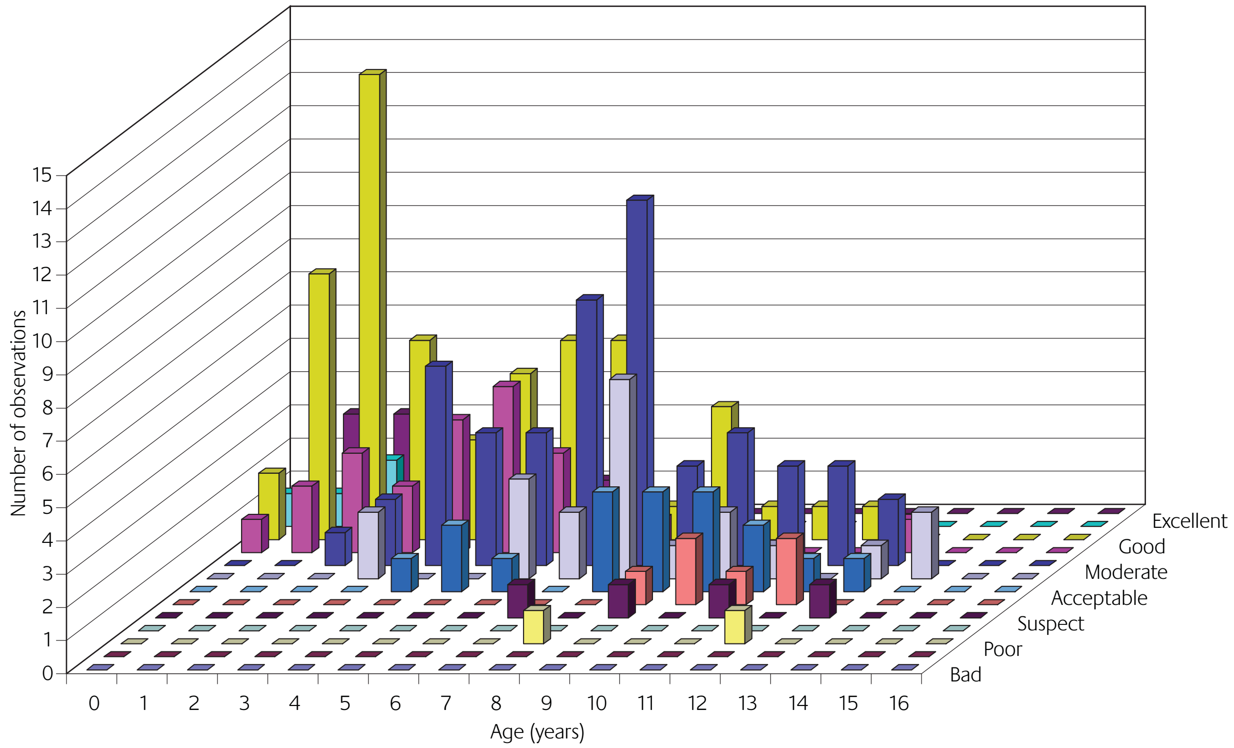

Figure I.7 Individual results for 14 mm TSMA

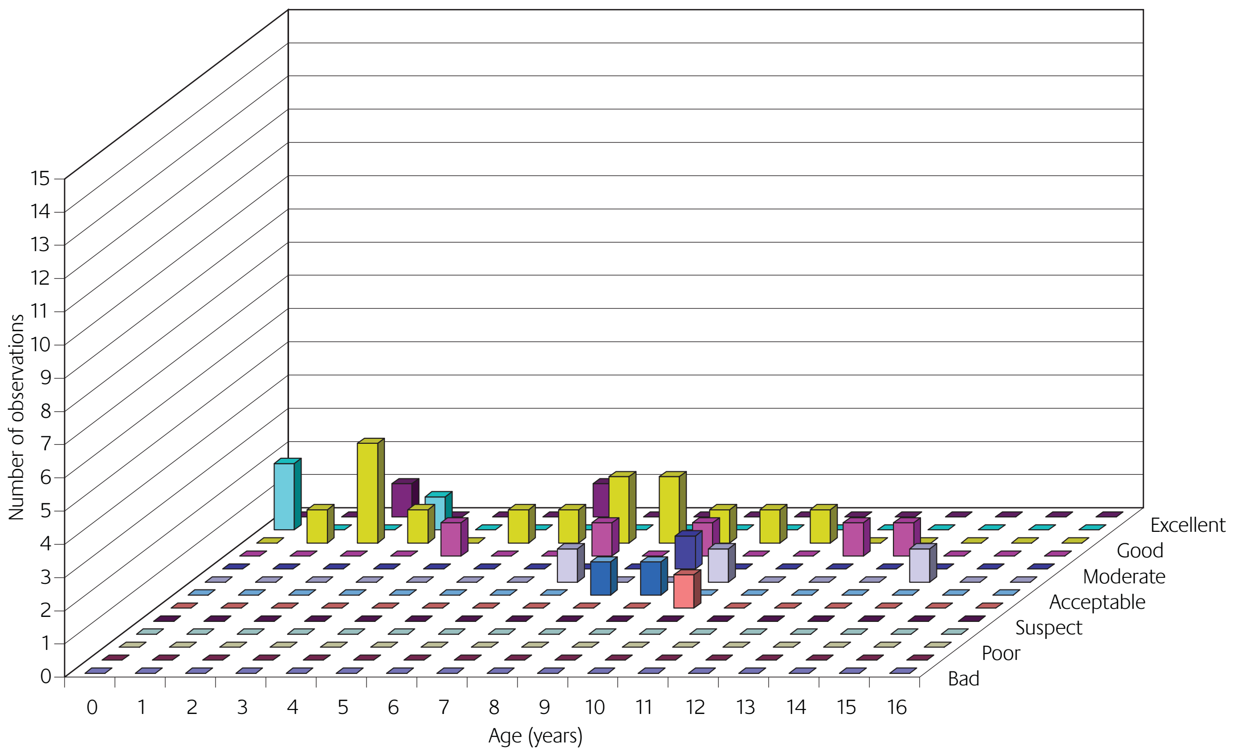

Figure I.8 Individual results for 10 mm TSMA

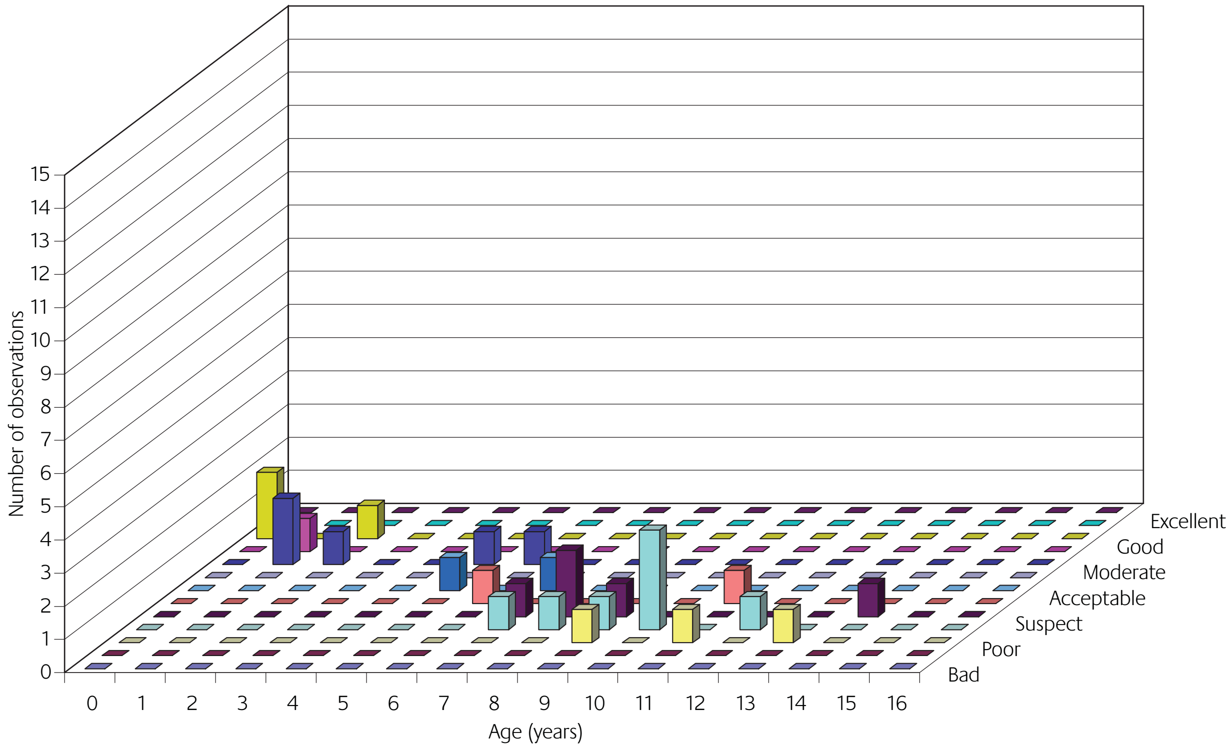

Figure I.9 Individual results for 14 mm MSD

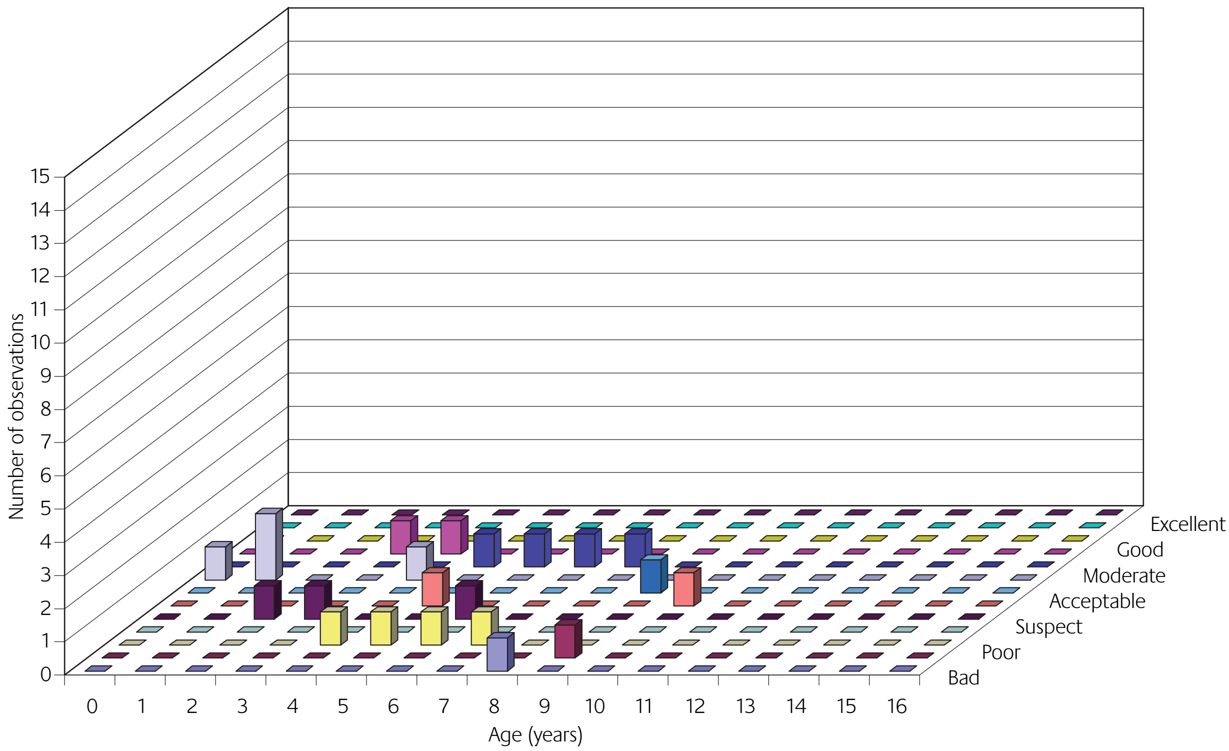

Figure I.10 Individual results for 6 mm MS

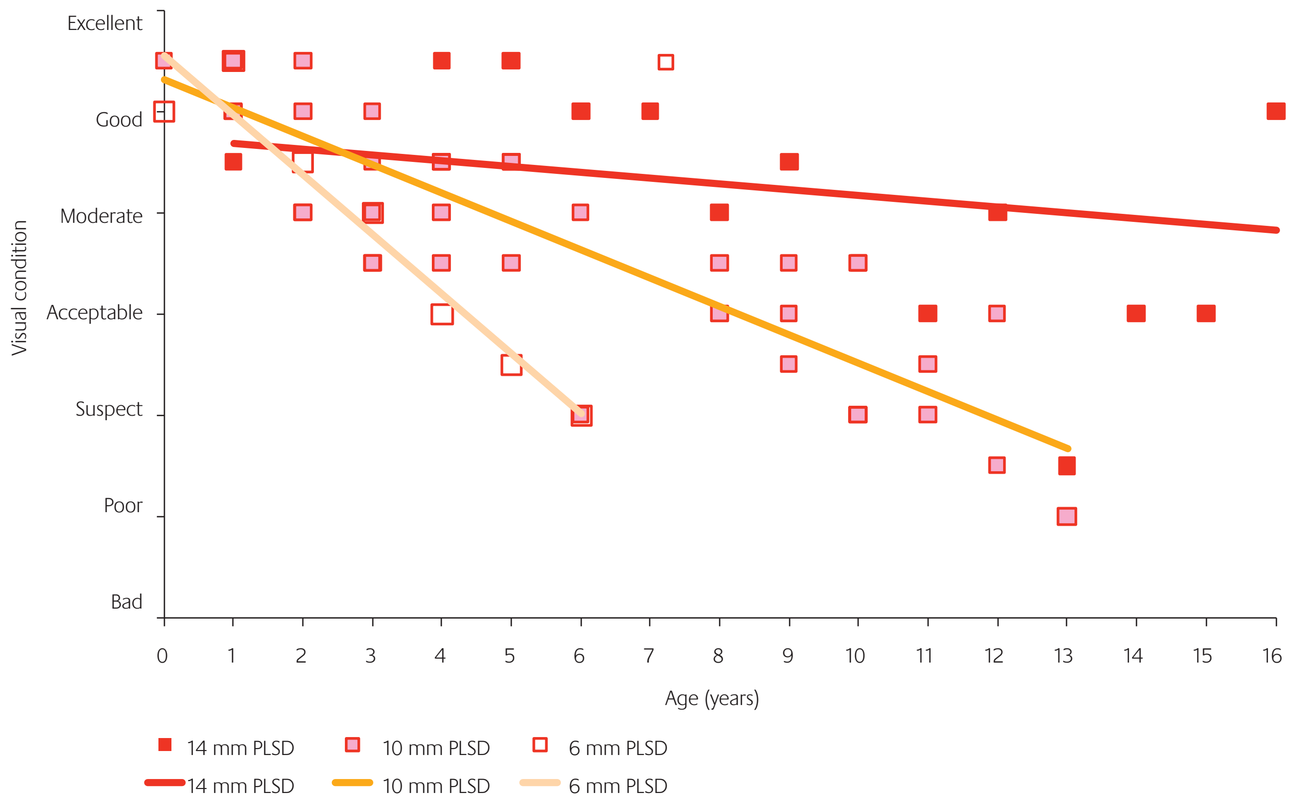

Figure I.11 Trend lines for individual results for PLSD

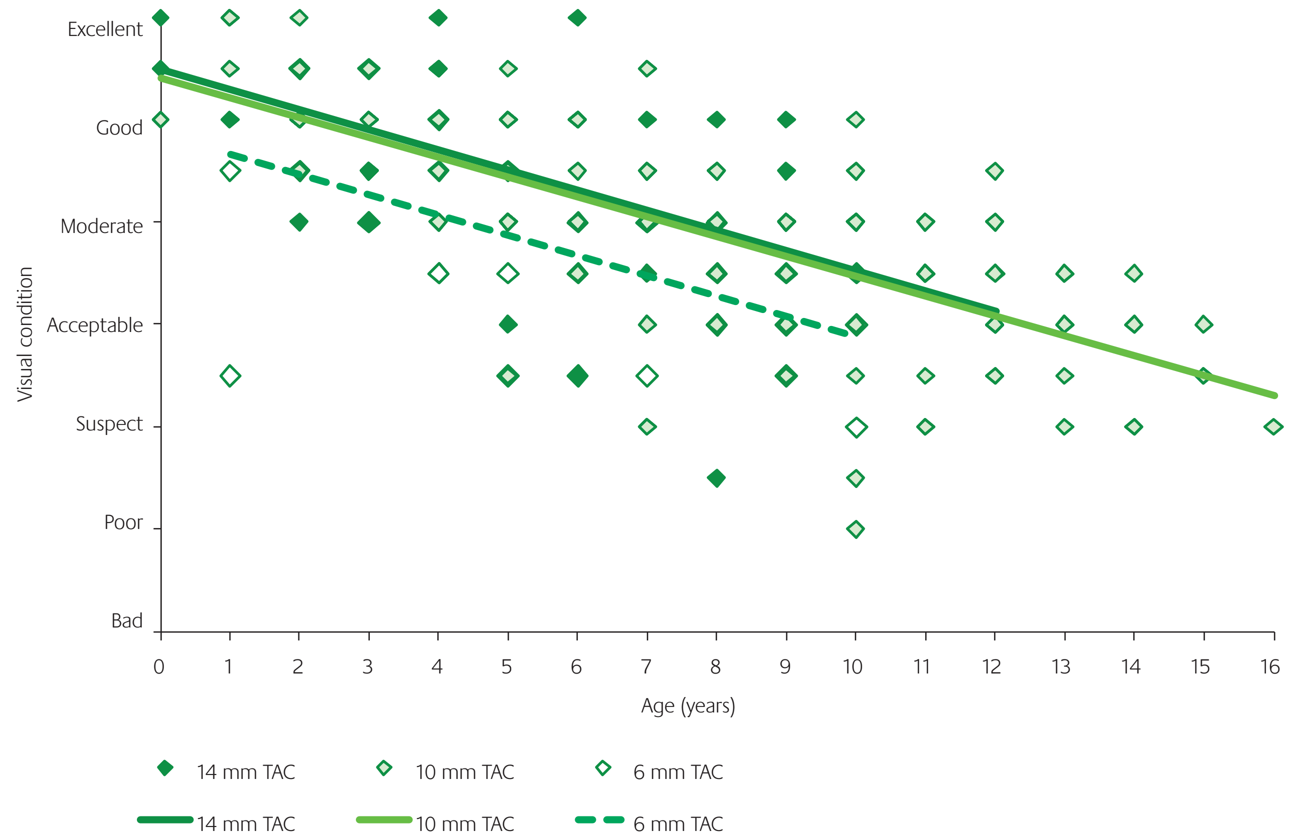

Figure I.12 Trend lines for individual results for TAC

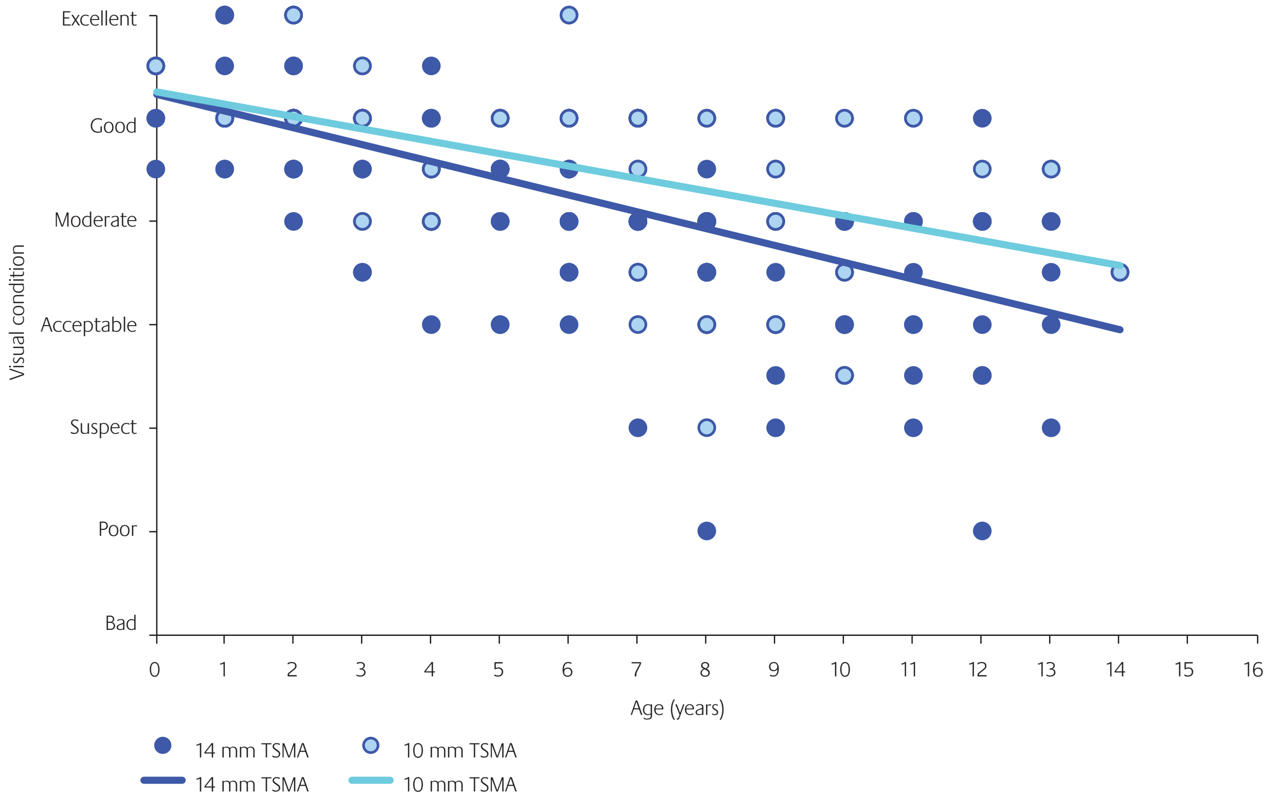

Figure I.13 Trend lines for individual results for TSMA

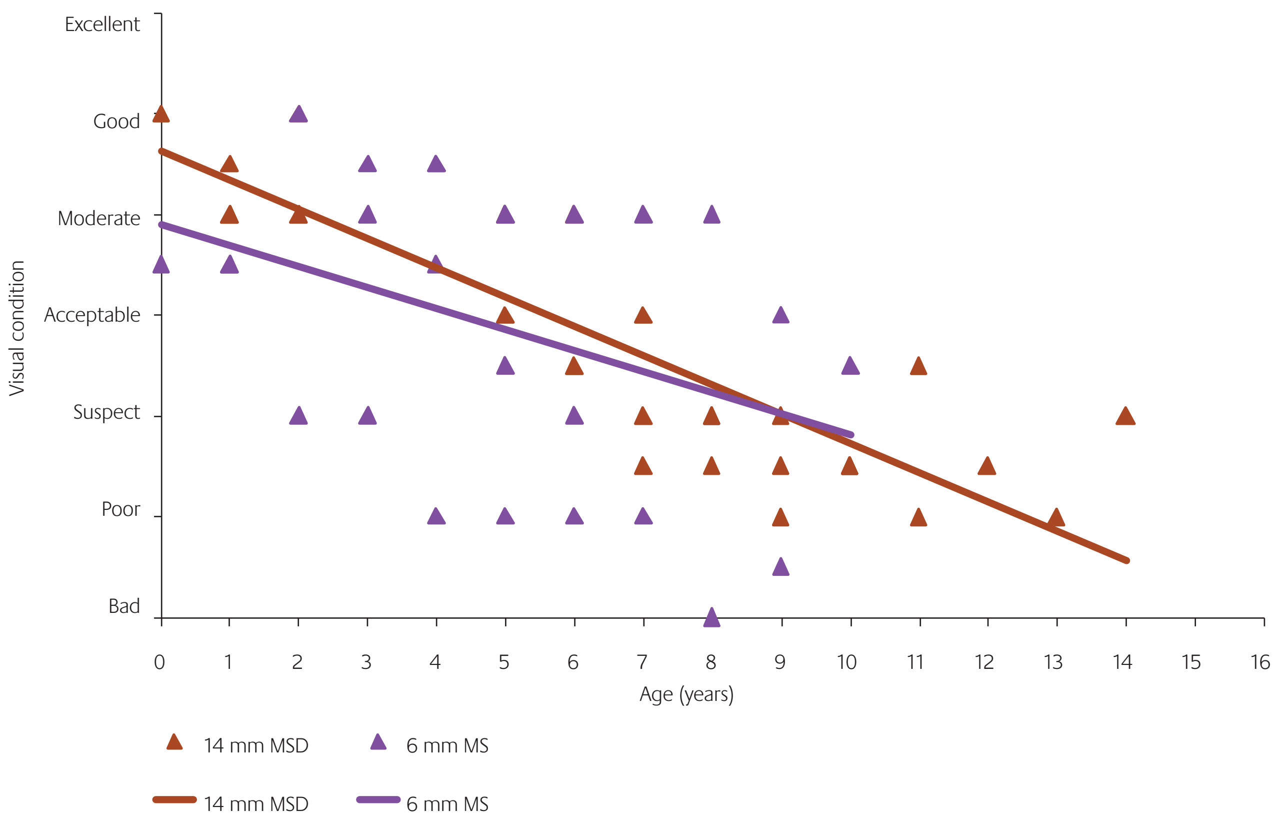

Figure I.14 Trend lines for individual results for MSD and MS

Table I.2 Properties of linear trend lines based on individual results

Type of system	*Aggregate size (mm)*	*Data points (no.)*	*Maximum age (years)*	*Corr. coeff. (R^2)*	*Slope (grade/ year)*	*Intercept with*		
						Acceptable (years)	*Suspect (years)*	*Bad (years)*
PLSD	14	33	14	0.48	-0.199	12	(17)	(22)
	10	33	13	0.76	-0.280	8	12	(15)
	6	7	6	0.93	-0.589	4	6	(8)
TAC	14	82	12	0.35	-0.202	(13)	(17)	(22)
	10	134	16	0.49	-0.189	12	(18)	(23)
	6	34	10	0.34	-0.198	9	(15)	(20)
TSMA	14	195	14	0.35	-0.158	14	(20)	(27)
	10	31	14	0.31	-0.123	(20)	(28)	(36)
MSD	14	28	14	0.77	-0.290	6	9	13
MS	6	22	10	0.10	-0.159	3	9	(15)

The properties of the trend lines (slope, intercept and correlation coefficient) obtained for each system type/ aggregate size combination in Figures I.11 to I.14 are given in Table I.2. The bracketed figures in Table I.2 are extrapolated values beyond the maximum age at which data were recorded and, therefore, should be treated with caution in case the failure mechanism accelerates (or even decelerates) as the material gets near a failure condition.

The trend line for 6 mm PLSD, with only six points from a single site, is not considered to be sufficiently robust to be included in any analysis despite its excellent correlation coefficient. Furthermore, the other correlation coefficients are also not sufficiently high to be regarded as robust. However, they would be expected to be lower than for the averaged points (Sections I.1 and I.2), where the effect of outliers can be masked.

The system types show definite trends of deterioration with the ranking for greater durability being TSMA, then TAC, then PLSD, then MSD and finally MS. With the exception of TSMA, the durability increases with the larger aggregate sizes. However, as with analysis of the averaged results, TSMA appears to be the reverse with the 10 mm size having greater durability than the 14 mm sizes.

I.4 Median for system type to reach visual condition level

The results for the types of thin surfacing system (PLSD, TAC, TSMA and MSD and MS), split into different aggregate sizes, are tabulated in terms of the proportions of the results being *Moderate*, *Acceptable* and *Suspect* after different times in Table I.3. The numbers of observations of the total of 617 observations from which each proportion is calculated are also given.

This form of presenting the data shows some apparent anomalies that result from data not being available for each site at every age. There is also an in-built bias in the system of reporting because the worst sites do not provide data for analysis once those sites are replaced. This bias is most clearly demonstrated by the increase in the proportion of sites at or above the reference grade when only one or two of the most durable sites remain – a good example is that, at 16 years, there is only one site remaining that is *Suspect*, so the proportion of at least *Suspect* value for all systems rises to 100 %.

The figures imply that, if sites can be allowed to deteriorate to a *Suspect* condition, there would be no defects on TAC and TSMA systems until eight years in service. However, the same findings would be obtained if every surfacing was replaced just before it dropped below that condition, even if several of them reach it prematurely. All the TSMA sites were still *Acceptable* or better after six years, which increased to nine years when considering just 10 mm TSMA, whilst all the TAC sites were still Acceptable or better after four years, which increased to five years when considering just 14 mm TAC. However, if a higher standard were set of *Moderate* or better, the order reverses with the same ages for the TAC sites but the combined figure for TSMA becomes only two years, although that value increases to six years when considering just 10 mm TSMA.

Because of the apparent anomalies that arise from single sites falling below the set level and then being replaced, leaving just the better sites of that classification, it is probably more logical to look for the median value, where the median is defined as the first age at which the proportion at the set condition falls to 50 % (after ignoring any explainable anomalies).

For the *Suspect* condition, the median is determined for 14 mm PLSD as five to six years, 10 mm PLSD as three to four years, MSD as eight to nine years and MS as seven years with all other types remaining above 50 % for all ages. For the *Acceptable* condition, the median is determined for more types, with 14 mm and 10 mm PLSD having the same ages, 6 mm PLSD as four to five years, 10 mm TAC as 14/15 years, MSD as six years and MS as four to five years. For the *Moderate* condition, all types are defined although not always clearly, with 50% being reached:

- for all PLSD sizes, just before four years in service;
- for TAC, after six to seven years for 14 mm, seven to eight years for 10 mm and four to five years for 6 mm;
- for both TSMA sizes, after nine/ten years;
- for MSD, after two to five years (there being no data for three and four years); and
- for MS, possibly three years but there are insufficient early data to define when the condition was better than *Moderate*.

Table I.3 Proportion of sites at or above specific condition

System type	*Size (mm)*	*Panel mark after time in service (years)*																
		0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
		Number of sites with results after time in service																
PLSD	14	1	2	4	0	1	1	9	9	4	3	3	2	1	1	1	0	0
	10	1	3	3	3	9	8	2	0	2	3	3	2	2	1	1	0	0
	6	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
TAC	14	2	6	14	9	12	11	10	7	6	2	1	1	1	0	0	0	0
	10	2	2	8	5	7	10	12	13	11	14	14	10	9	8	5	3	1
	6	0	2	4	3	5	3	3	4	4	3	3	0	0	0	0	0	0
TSMA	14	5	15	24	13	14	16	18	19	22	14	12	9	8	6	2	0	0
	10	2	1	4	2	1	1	2	4	3	3	3	1	1	1	1	0	0
MSD	14	2	3	2	0	0	2	2	3	3	3	3	2	1	1	1	0	0
MS	6	1	2	1*	2	3	3	3	2	2	2	1	0	0	0	0	0	0
All	16	37	65	38	53	56	62	61	57	47	43	27	23	18	11	3	1	
		Proportion of sites assessed as Moderate or better (%)																
PLSD	14	100	100	100	–	0	0	22	35	75	0	0	50	0	0	0	–	100
	10	100	100	100	67	24	13	50	–	0	0	0	0	0	0	0	–	100
	6	–	100	100	100	0	0	0	–	–	–	–	–	–	–	–	–	–
TAC	14	100	100	100	100	100	91	80	43	67	100	100	100	0				100
	10	100	100	100	100	100	90	83	77	45	57	43	20	33	13	0	0	100
	6	–	50	100	100	60	33	33	75	25	0	0	–	–	–	–	–	–
TSMA	14	100	100	100	85	93	88	78	84	55	57	42	44	50	50	0	–	100
	10	100	100	100	100	100	100	100	75	67	67	33	100	100	100	0	–	100
MSD	14	100	100	100	–	–	50	50	0	0	0	0	0	0	0	0	–	100
MS	6	0	0	0*	50	33	33	33	50	50	0	0	–	–	–	–	–	0
All	94	92	98	89	74	68	65	64	49	43	30	33	35	28	0	0	94	

* Single site where the surfacing was not completed.
– No sites monitored.

Table I.3 (cont'd) Proportion of sites at or above specific condition

System type	*Size (mm)*	*Panel mark after time in service (years)*																
		0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
Proportion of sites assessed as Acceptable or better (%)																		
PLSD	14	100	100	100	–	100	100	22	35	75	33	100	50	0	100	100	–	–
	10	100	100	100	100	35	27	50	–	100	67	33	50	0	100	0	–	–
	6	–	100	100	100	100	0	0	–	–	–	–	–	–	–	–	–	–
TAC	14	100	100	100	100	100	100	90	86	83	100	100	100	100	–	–	–	–
	10	100	100	100	100	100	90	100	92	91	86	79	70	78	75	60	33	0
	6	–	50	100	100	100	67	67	75	100	67	67	–	–	–	–	–	–
TSMA	14	100	100	100	100	100	100	100	95	95	86	83	78	63	83	100	–	–
	10	100	100	100	100	100	100	100	100	100	100	67	100	100	100	100	–	–
MSD	14	100	100	100	–	–	100	50	33	0	0	0	0	0	0	0	–	–
MS	6	100	100	0*	50	67	33	33	50	50	50	0	–	–	–	–	–	–
All	100	97	98	97	88	81	77	79	86	74	70	67	61	78	64	33	0	
Proportion of sites assessed as Suspect or better (%)																		
PLSD	14	100	100	100	–	100	100	33	35	100	67	100	50	0	100	100	–	–
	10	100	100	100	100	35	27	100	–	100	100	100	100	50	100	0	–	–
	6	–	100	100	100	100	100	100	–	–	–	–	–	–	–	–	–	–
TAC	14	100	100	100	100	100	100	100	100	83	100	100	100	100	–	–	–	–
	10	100	100	100	100	100	100	100	100	100	100	86	100	100	100	100	100	100
	6	–	100	100	100	100	100	100	100	100	100	100	–	–	–	–	–	–
TSMA	14	100	100	100	100	100	100	100	100	95	100	100	100	88	100	100	–	–
	10	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	–	–
MSD	14	100	100	100	–	–	100	100	67	67	33	0	50	0	0	100	–	–
MS	6	100	100	100*	100	67	67	67	50	50	50	100	–	–	–	–	–	–
All	100	100	100	100	88	88	89	88	93	91	88	93	83	94	91	100	100	

* Single site where the surfacing was not completed.
– No sites monitored.

I.5 Multiple regression for asphalt systems

The data held on the various sites include the following parameters:

- *Cond* Visual condition of the surfacing
- *Type* The type of system, from the list given above, that was applied
- *Syst* The proprietary thin surfacing system that was applied
- *Road* The road type onto which the thin surfacing system was laid
- *Agg* The nominal maximum aggregate size (in millimetres)
- *Bind* The binder content of the mixture (in percent)
- *Age* The age at which the site was monitored (in years)

Extracting the data on these parameters for the asphalt types of system (PLSD, TAC and TSMA) produces 434 complete data sets plus another 112 sets for which the binder content is not available, giving a total of 546 data sets. The following transformations of the non-numeric variables were made:

- *Cond* The visual condition markings converted to *Excellent* = 7, *Good* = 6, *Moderate* = 5, *Adequate* = 4, *Suspect* = 3, *Poor* = 2 and *Bad* = 1.
- *Type* The type of system converted to TAC = 1, PLSD = 2 and TSMA = 3*.
- *Syst* The systems ranked in descending order of average visual condition, irrespective of age or other parameter, as 1 to 23†.
- *Site* The sites categorised by the type of road with motorways = 1, other trunk roads = 2, other A roads = 3 and all other roads = 4.

Cond is the parameter that is monitored whilst *Age* is assumed to be the most important parameter because any site can be monitored through its decline from new until it becomes unserviceable, however long that takes. Multiple linear regression analyses were carried out using the SPSS 14.0 for Windows package with *Cond* as the dependent variable and *Age* plus one of the other parameters as the independent variables in order to identify the significant of those other parameters. The results are given in Table I.4.

The results show that *Bind* is the most significant parameter with *Syst* second and the others having a secondary influence, although with analysis of a slightly larger data set.

A multiple linear regression analysis was then undertaken with *Cond* as the dependent variable and all the other parameters as independent variables in order to give the relationship in Equation I.19.

$$Cond = 4.852 - 0.231 \times Type - 0.022 \times Syst + 0.001 \times Road + 0.035 \times Agg + 0.307 \times Bind - 0.186 \times Age$$
$$(R^2_{adj} = 0.539)$$

(Equation I.19)

The regression had an R^2_{adj} value of 0.539 with R of 0.739, R^2 of 0.546 and a standard error of the estimate of 0.7185. The independent variables were then extracted in turn to find the least significant as the one causing the least change to R^2_{adj}, then repeating this process to find the next least significant. The relationships at each removal are given in Equations I.20 to I.25.

Removing *Road* gives:

$$Cond = 4.849 - 0.231 \times Type - 0.022 \times Syst + 0.035 \times Agg + 0.306 \times Bind - 0.186 \times Age$$
$$(R^2_{adj} = 0.540)$$

(Equation I.20)

Removing *Agg* as well gives:

$$Cond = 5.545 - 0.177 \times Type - 0.027 \times Syst + 0.251 \times Bind - 0.185 \times Age$$
$$(R^2_{adj} = 0.538)$$

(Equation I.21)

Removing *Type* as well gives:

$$Cond = 6.435 - 0.030 \times Syst + 0.032 \times Bind - 0.182 \times Age$$
$$(R^2_{adj} = 0.526)$$

(Equation I.22)

Table I.4 Correlations with *Cond* against *Age* plus another parameter

Independent variable	*Constant*	*Coefficient for Age*	*Coefficient for other variable*	R^2_{adj}
Age and *Type*	6.126	-0.181	0.070	0.412
Age and *Syst*	6.672	-0.170	-0.037	0.462
Age and *Road*	6.199	-0.183	0.030	0.408
Age and *Agg*	5.660	-0.179	0.049	0.422
Age and *Bind*	5.085	-0.192	-0.217	0.499

* Selecting the middle system type is the critical issue because reversing the order will only result in changing the sign of the coefficient for the parameter in any regression analysis. Multiple regression analyses with all parameters order R^2_{adj} gave values of 0.522 with TAC second, 0.536 with TSMA second and 0.539 with PLSD second.

† The rankings were not constrained by type so that the two can be treated as separate independent variables.

Removing *Syst* as well gives:

$$Cond = 5.085 - 0.217 \times Bind - 0.192 \times Age$$
$$(R^2_{adj} = 0.499)$$

(Equation I.23)

Removing *Bind* as well gives:

$$Cond = 6.268 - 0.182 \times Age$$
$$(R^2_{adj} = 0.409)$$

(Equation I.24)

Starting with the last equation, the correlation increases with the addition of each parameter, as would be expected. The biggest differences occur with the addition of the first parameter, *Bind*, followed by the next parameter, *Syst*. The remaining improvements are very marginal, confirming that the parameters other than *Age*, *Bind* and possibly *Syst* are of relatively limited significance. In the case of *Road*, the correlation increased slightly with its removal, indicating that the extra degree of freedom reduced the certainty rather more than the extra parameter resolved part of the scatter.

The order of removing the independent variables implies a ranking in terms of their influence on the visual condition of surfacings as follows:

1) The age of the site, with surfacings deteriorating with increased age.
2) The amount of binder in the surfacing, with surfacings deteriorating faster with less binder.
3) The supplier of the proprietary system, with no guidance because the data have deliberately been made anonymous.
4) The type of system, with TAC surfacings being most durable, then PLSD and finally TSMA surfacings.
5) The nominal maximum aggregate size of the mixture, with surfacings deteriorating faster with smaller aggregate sizes.
6) The type of road, which has no real influence.

These rankings are unsurprising other than that the road was not significant and that TSMA appears to be the least durable of the three types of system whereas the reverse was found from the basic plots without consideration of the other parameters (Figure 4.2) where the TSMA lines were at the top. The probable reason for the anomaly is that the binder content, which is generally higher in TSMA than PLSD and TAC systems, is already taken account of in *Bind* so that any difference is due to the binder type, polymer-modified bitumen being better than straight-run bitumen and fibres. The overall marginally better performance of TSMA than TAC and, more significantly, over PLSD reflects the increased binder content being more important than the improved binder type.

The overall conclusions of this analysis are:

- The binder content is the most significant factor after age in the deterioration of thin surfacing systems.
- The system and, to a lesser extent, the binder type and the aggregate size also influence the rate of deterioration.
- The category of road does not appear to affect the deterioration, although this observation could just reflect the fact that less care is taken in construction and maintenance on minor roads which counters any extra stresses imposed on more major roads.
- After allowing for the different binder content and binder type involved, TSMA surfacings are marginally less durable than TAC or PLSD surfacings.

I.6 Predictions of serviceable life

An overall assessment of durability from the analyses is given in Table I.5.

The different analysis approaches are:

- Mean ages at which sites that no longer exist were replaced or surface dressed (Section 5.1) (different aggregate sizes not given separately).
- Estimates using quadratic regression equations for the mean at each age (Section I.1) (different aggregate sizes not given separately).
- Estimates using linear regression equations for the mean at each age (Section I.2).
- Estimates using linear regression equations for all individual results (Section I.3).
- Approximate time to reach the median value (Section I.4).

The multiple regression analysis in Section I.5 was not included because the binder content and actual system are not defined but were found to be important variables. Also, estimates of the time for a site to reach a visual condition of *Bad* was excluded because no road should be allowed to deteriorate to that level, even *Poor* being considered totally unsatisfactory.

Table I.5 Predicted time (in years) for a surfacing to reach a visual condition by different analysis approaches

Panel mark	*Analysis approach*	*Time in service (years) to reach for system type*									
		PLSD			*TAC*			*TSMA*		*MSD*	*MS*
		14 mm	*10 mm*	*6 mm*	*14 mm*	*10 mm*	*6 mm*	*14 mm*	*10 mm*	*14 mm*	*6 mm*
Mean age at replacement (years)			← 10.5 →			← 9.9 →			← 9.4 →	9.0	–
Mean age at replacement or to *Acceptable* (years)			← 9.5 →			← 9.5 →			← 9.1 →	6.0	5.7
Moderate	Quadratic of means		← 4.2 →			← 6.9 →			← 7.7 →	2.3	n.a.
	Linear of means	5.0	5.0	2.9	9.1	7.2	3.7	7.8	14.0	2.3	n.a.
	Linear of individual	6.9	4.7	2.6	7.6	7.1	4.4	7.5	11.8	2.2	n.a.
	Median	4	4	4	6 – 7	7 – 8	4 – 5	9 – 10	9 – 10	2/5	3
Acceptable	Quadratic of means		← 9.3 →			← 12.3 →			← n.a. →	4.9	2.0
	Linear of means	9.8	9.3	4.3	>12	12.4	9.6	>14	>14	6.0	2.1
	Linear of individual	12.0	8.3	4.3	>12	12.4	9.4	13.8	>14	5.6	2.7
	Median	5 – 6	3 – 4	4 – 5	n.d.	14 – 15	n.d.	>20	n.d.	6	4 – 5
Suspect	Quadratic of means		← n.a. →			← > 16 →			← n.a. →	8.6	n.a.
	Linear of means	>14	13.6	5.8	>12	>16	>10	>14	>14	9.7	9.8
	Linear of individual	>14	11.8	6.0	>12	>16	>10	>14	>14	9.1	9.0
	Median	5 – 6	3 – 4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	8 – 9	7
Poor	Quadratic of means		← n.a. →			← > 16 →			← n.a. →	n.a.	n.a.
	Linear of means	>14	>14	>6	>12	>16	>10	>14	>14	13.5	>10
	Linear of individual	>14	>14	>6	>12	>16	>10	>14	>14	>14	>10
	Median	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Maximum age of data (years)		14	14	6	12	16	10	14	14	14	10

Values with arrows (← →) are estimates for a system type without separating into aggregate sizes.
n.a. = Not applicable because the quadratic curve does not cross that value.
n.d. = Not defined because never reaches 50 %.

Appendix J: Rigorous statistical analysis of visual condition data

J.1 Visual inspection data

The sites monitored as part of this research project were assessed visually by an Inspection Panel (comprising representatives from the HA, asphalt producers, bitumen suppliers, trade bodies and TRL) and ranked in accordance with the TRL Inspection Panel methodology (Nicholls, 1997a). The assessment attributes a mark (*Excellent*, *Good*, *Moderate*, *Acceptable*, *Suspect*, *Poor*, *Bad* or midway between two adjacent marks). These marks are assigned values from 1 (*Bad*) to 7 (*Excellent*) and are assumed to be a numeric scale for analytical purposes.

J.2 Functional form

Much of the analysis presented in the main text has considered simple linear relationships between the age of the surface and measure of its condition. However, in practice a site is more likely to deteriorate following an “S” shaped curve, that is that it changes at a gradual rate for a few years, then starts to deteriorate more rapidly before reaching a low plateau of acceptability. The statistical analyses reported here assume that the site deteriorates with time following an “S” shaped curve. This type of relationship is often observed for “dose” versus “response” type models where, in this context, “dose” is time and, hence, associated with wear. The hypothetical form of the curve (for the visual condition) is shown in Figure J.1, and is intuitively attractive, albeit may not otherwise be justified.

An ANOVA investigated the “logit” of the visual condition to determine which measures may be influential. A regression of the observed data to these measures used a logit-transformed version of the visual condition, this transformation being:

$$\log_e = \left(\frac{Cond}{8 - Cond}\right)$$

The inverse of the fitted regression function was used to illustrate the predicted “life” of the system type. For visual condition, a rating of 3 would generally mean that the site is *Suspect* and the regression can be used to estimate how long it takes before this condition is reached.

J.3 Data and correlation between measures

There were a total of 797 data points available from different yearly measurements obtained from a number of different sites. There were, for example, 113 sites with data for age of zero, 72 sites with age of one year, 90 sites with age of two years; the number varying according to the ages at which each site is inspected. The data set is, thus, incomplete in terms of data on a year-to-year basis for every site in the study. It is also incomplete in terms of the measures obtained at each site inspection, as shown in Table J.1. This incompleteness is due in part to the complexity of obtaining a sample and then testing it in the laboratory for such parameters as the penetration and softening point for the recovered binder.

The degree of incompleteness varies by age of the surface, partly because some sites were not as old as others when monitoring ceased. There is only one data value for a site with a surface 16 years old, and only three for sites with surfaces 15 years old.

However, 75 % of site/age data have a value for the visual condition. Much of the following analysis is based on using the visual condition as the outcome measure.

The correlation between potentially influential variables and outcome measures gives an indication of which variables may be useful. Table J.2 shows the correlation, significance level and sample size for a number of measures.

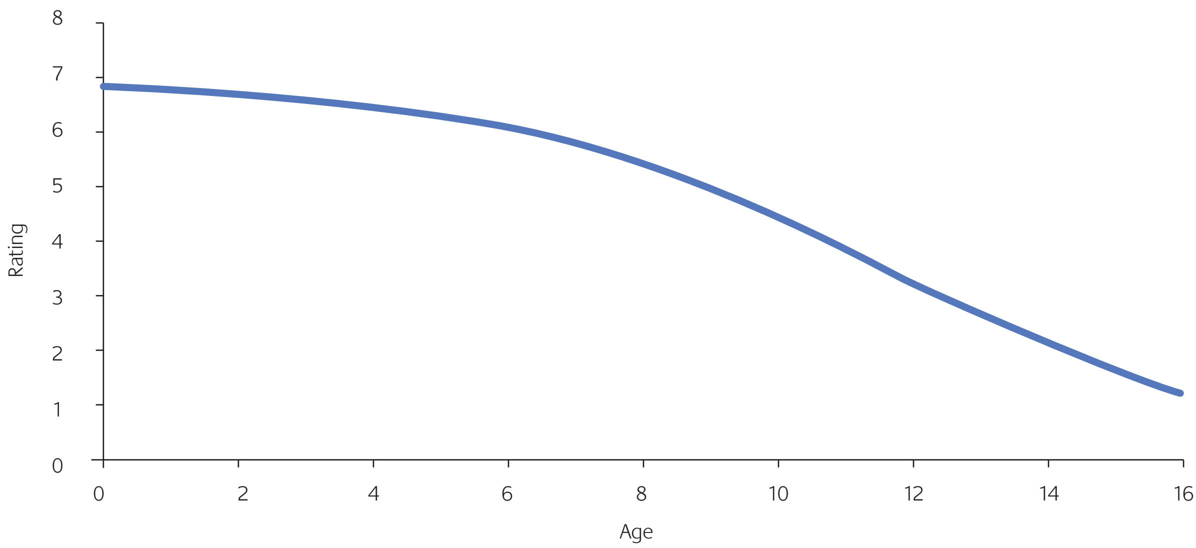

Figure J.1 Theoretical relationship between age and visual condition

Table J.1 Count of available measures in data set

Parameter	*Count*	*Proportion available (%)*
Aggregate size	797	100
Age	797	100
Type of system	797	100
PSV/PSV category	702	88
Binder content	610	77
Pavement depth	345	43
Traffic	510	64
Road type	797	100
Penetration (of recovered binder)	171	21
Softening point (of recovered binder)	171	21
Sand patch	167	21
SMTD (texture)	230	29
MSSC/normalised MSSC	275	35
Visual condition	596	75
Particle loss	592	74
Cracking	592	74

Table J.2 Correlation between outcome measures and variables

Property	*Statistic*	*Age*	*Binder content*	*Penetration*	*Softening point*	*Sand patch*
Visual condition	Correlation (r)	-0.59	0.13	0.12	-0.13	0.40
	Significance (2-tail)	<0.01	<0.01	ns	ns	<0.01
	Number	596	434	126	128	82
SMTD (texture)	Correlation (r)	0.05	-0.04	-0.45	0.42	0.46
	Significance (2-tail)	ns	ns	<0.01	<0.01	<0.01
	Number	230	188	83	84	66
MSSC normalised	Correlation (r)	-0.25	-0.23	-0.16	0.19	0.14
	Significance (2-tail)	<0.01	<0.01	ns	ns	ns
	Number	275	242	86	87	82
Penetration of recovered binder	Correlation (r)	-0.60	-0.12	1.00	-0.57	0.37
	Significance (2-tail)	<0.01	ns	–	<0.01	<0.01
	Number	171	134	–	168	61
Ring and ball softening point of recovered binder	Correlation (r)	0.34	-0.10	-0.57	1.00	-0.28
	Significance (2-tail)	<0.01	ns	<0.01	–	<0.05
	Number	171	133	168	–	62
Sand patch	Correlation (r)	-0.50	-0.33	0.37	-0.28	1.00
	Significance (2-tail)	<0.01	<0.01	<0.01	<0.05	–
	Number	167	134	61	62	–

J.4 Grouping of sites

Defining sites by grouping into five system types (asphalt systems of PLSD, TAC, TSMA and surface treatment of MSD or MS) together with the size of aggregate generates ten site types (although not every combination is used). These combinations are:

- PLSD
  - 6 mm
  - 10 mm
  - 14 mm
- TAC
  - 6 mm
  - 10 mm
  - 14 mm
- TSMA
  - 10 mm
  - 14 mm
- MSD
- MS

This grouping of sites was used for analysis purposes, albeit analysis indicated that the size of aggregate is not always a statistically significant‡ factor in the "life" of the surface.

J.5 Analysis

The approach adopted was initially to conduct an ANOVA on the outcome variable (e.g. logit version of visual condition) in order to see which variables may be explaining some of the variation in the data at statistically significant levels. The measures considered included aggregate size, road type and binder content. However, having defined 13 groups of sites, the ANOVA was restricted to looking at age, site combination (system type and aggregate) and binder content. This analysis was complicated by an incomplete set of data because not all measures were available for all sites.

The ANOVA found that, overall, some of the variability in the visual condition (transformed to a logit) is explained by the age ($p < 0.001$§), the system type and aggregate size (i.e. site grouping, $p < 0.001$) and binder content ($p < 0.013$).

Having determined that these variables are important in helping to explain some of the variability, a regression line was fitted for each site combination (as defined above). The age and the binder content were fitted as independent variables. Where the binder content is not statistically significant, the final regression only included the age effect as an explanatory variable.

J.6 Regression results – visual condition outcome measure

The results from the regression analysis found that only for the TAC 10 mm and TAC 14 mm sites is binder content statistically significant, and even then only at the $p = 0.10$ (10 %) level for TAC 14 mm sites. Binder content was not statistically significant for all other sites. However, this lack of significance may have been due to lack of data points with values for the visual condition as well as for the binder content.

This analysis is illustrated in Table J.3, which gives the regression coefficients and the sample sizes available for the visual outcome measure and with the binder content. The functional form for the regression is shown in Equation J.1:

$$\log_e = \left(\frac{Cond}{8 - Cond}\right) = a + b_1 \times Age + b_2 \times Bind \qquad \text{(Equation J.1)}$$

where a, b_1 and b_2 are coefficients to be determined. A value for b_2 is only available where binder content was included in the regression. Table J.3 gives the R^2 value associated with each equation. It is a coefficient of determination and indicates how much of the variability in the outcome measure has been explained by the regression equation. It can be seen that this varies from only 0.07 (7 %) for MS sites to 0.96 (96 %) for the 6 mm PLSD sites.

The very poor fit for the MS sites is due to some inconsistent data for $Age = 2$ and $Age = 10$, as can be seen in Figure J.2. The fit for TSMA sites is slightly better and that for MSD considerably better. (It should be noted that the average observed values in the figure for each age value are given, not the individual points on which the regressions were based.) There was no statistically significant effect due to different binder contents for TSMA, MSD or MS surfaced sites.

The 22 values on which the MS site regression line was based are shown in Figure J.3. It illustrates the variability in the individual site assessments that resulted in the poor regression fit obtained.

Table J.3 Regression results when fitting logit (visual condition)

Site type and aggregate	*a*	*b_1 (Age)*	*b_2 (Bind)*	*R_{2adj}*	*Sites with a Cond value*	*Sites with Cond and Bind values*
PLSD 6 mm	1.337	-0.334		0.96	6	6
PLSD 10 mm	1.012	-0.139		0.71	33	33
PLSD 14 mm	1.006	-0.129		0.45	32	32
TAC 6 mm	0.876	-0.097		0.33	34	16
TAC 10 mm	-2.206	-0.121	0.679	0.65	134	100
TAC 14 mm	0.452	-0.123	0.192	0.50	82	69
TSMA 10 mm	1.305	-0.070		0.29	30	16
TSMA 14 mm	1.095	-0.085		0.37	195	162
MSD	0.545	-0.143		0.76	28	
MS	0.141	-0.084		0.07	22	

‡ Statistically significant generally means that there is less than a 5 % probability that a measure or variable has no effect, that is we can be 95 % confident that it does have an effect.

§ P is the probability that the variable did not have an effect, that is $p = 0.001$ means that there is only a 0.1 % proability that the effect is not contributing.

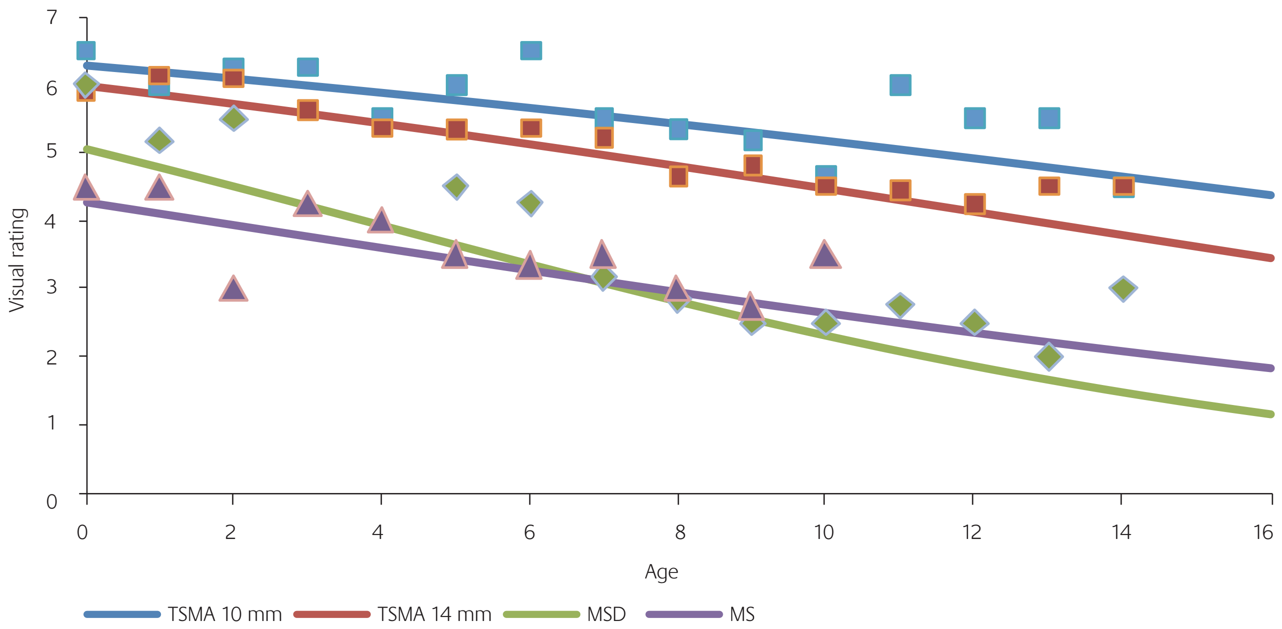

Figure J.2 Average observed and fitted values for TSMA, MSD and MS sites

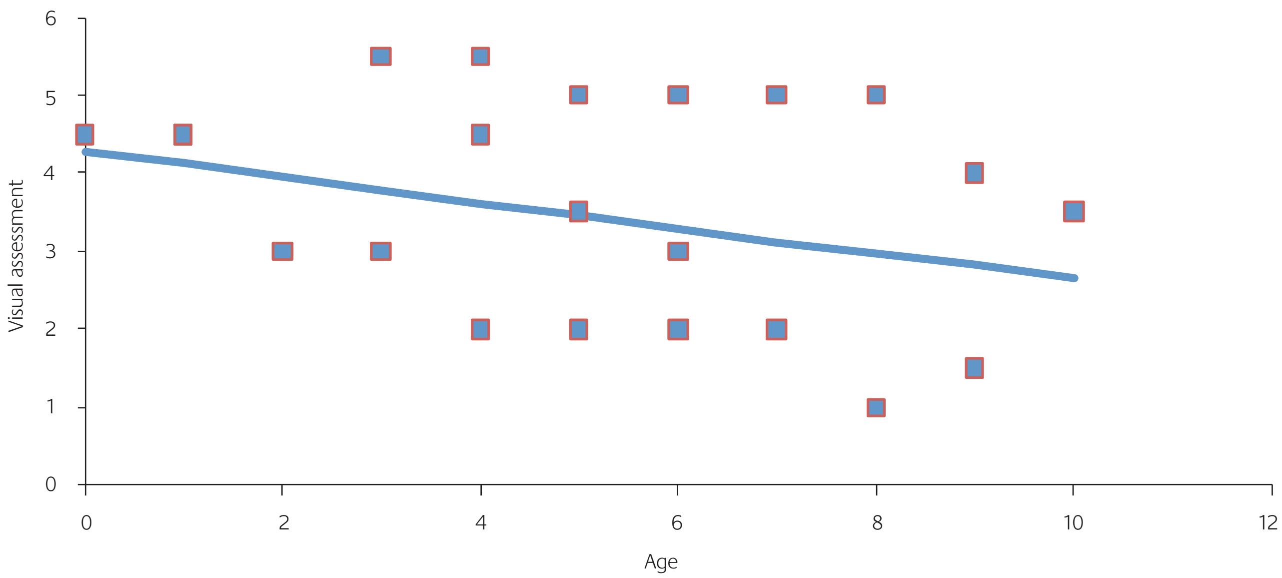

Figure J.3 Observed points and fitted line for MS site

The binder content was not statistically significant for PLSD sites. The fitted regression lines and averaged observed data values are shown in Figure J.4. The 6 mm line is only based on six data points, but is a very good fit, the 10 mm line is based on 33 points and explains 71 % of the variation in visual condition and the 14 mm line is based on 32 points and explains just 45 % of the variation. There is no difference between the 10 mm and 14 mm aggregate lines, as is illustrated by the plot, in that the effect of aggregate size for PLSD surfaced road life is not significant whether 10 mm or 14 mm is used.

The binder content was not statistically significant for the 6 mm TAC sites, but was for the 10 mm and 14 mm TAC sites. The fitted regression lines and averaged observed data values are shown in Figure J.5 for binder content of 5.5 %. The 6 mm line is based on 34 data points and explains 33 % of the variation in visual condition. The 10 mm line is based on 100 points and explains 65 % of the variation and the 14 mm line is based on 69 points and explains 50 % of the variation. There is no difference between the 10 mm and 14 mm aggregate lines, as is illustrated by the plot, with the effect of aggregate size for the PLSD serviceable life being not significant whether 10 mm or 14 mm is used. However, binder content is statistically significant for the TAC 10 mm regression line ($p < 0.001$), and approaching statistical significance for the 14 mm regression ($p < 0.100$).

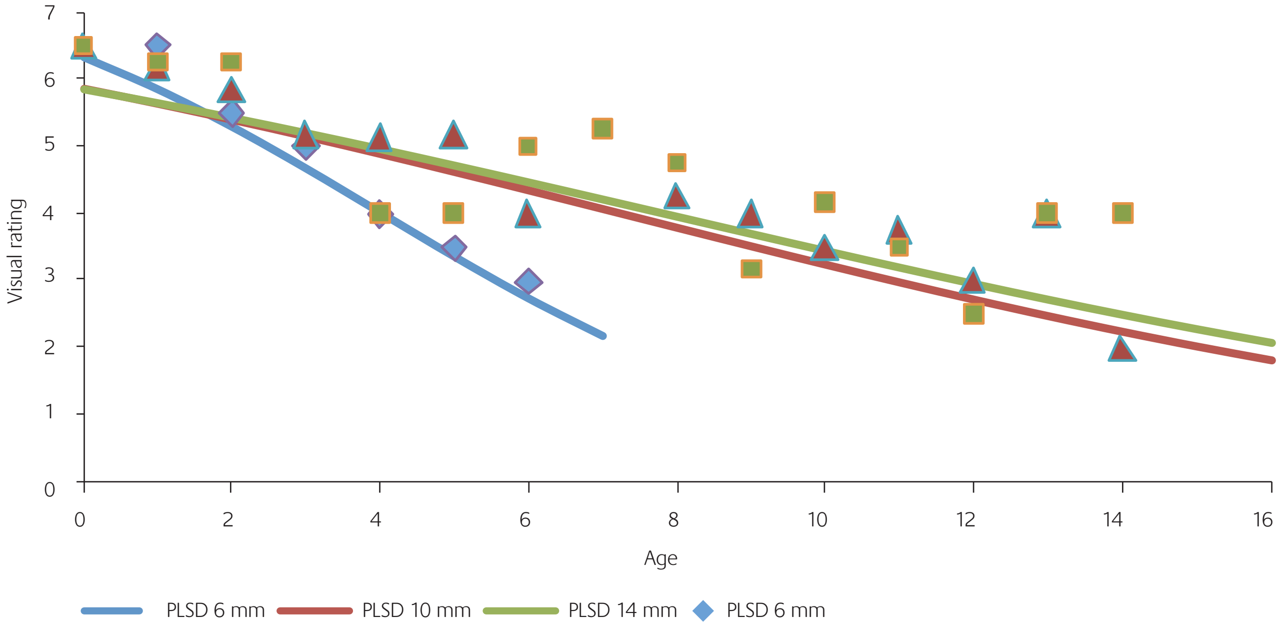

Figure J.4 Average observed and fitted values for PLSD sites

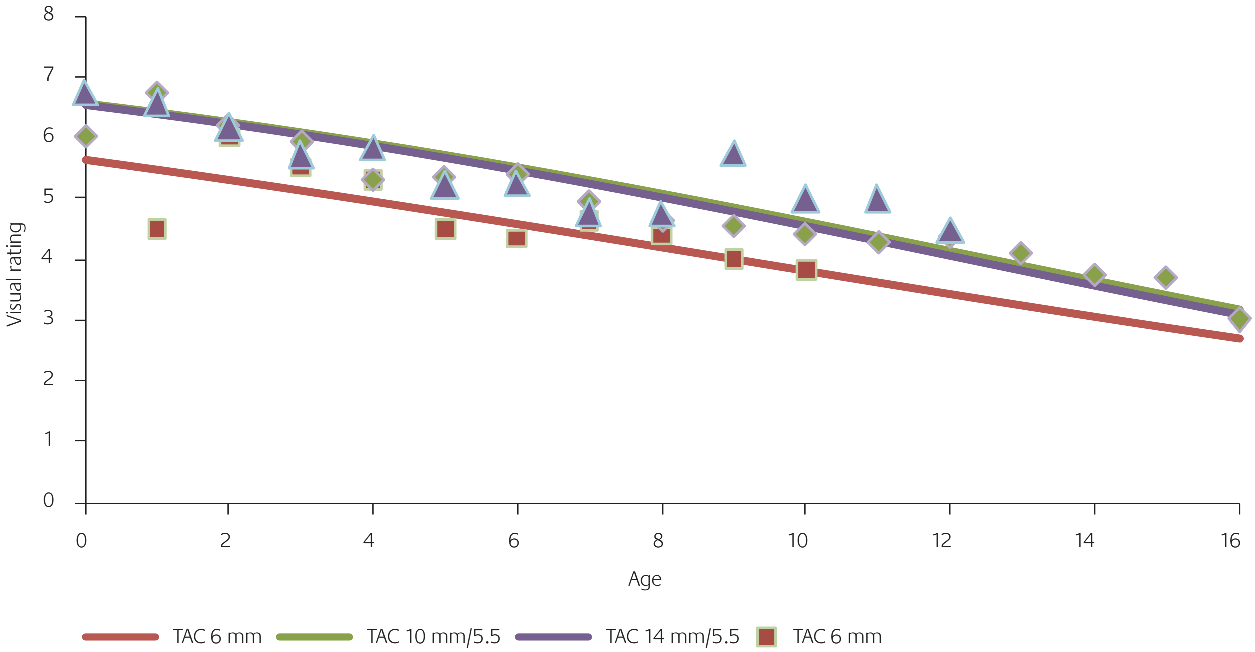

Figure J.5 Average observed and fitted values for TAC sites

Figure J.6 shows the fitted regression lines for TAC with 10 mm aggregate by age for three different binder contents. It clearly illustrates that higher binder contents result in a longer life for this system type in that a 10 mm mixture will last longer with a binder content of 6 % than with a binder content of 5 %.

Figure J.7 shows the fitted regression lines with age of surface for three different binder contents for TAC with an aggregate size of 14 mm. It shows that higher binder content results in a longer life for this system type, implying that a mixture with 14 mm aggregate and a binder content of 6 % will last longer than one with a binder content of 5 %. However, the difference in expected life of the surface is minimal in that there is a binder content effect but it is quite small.

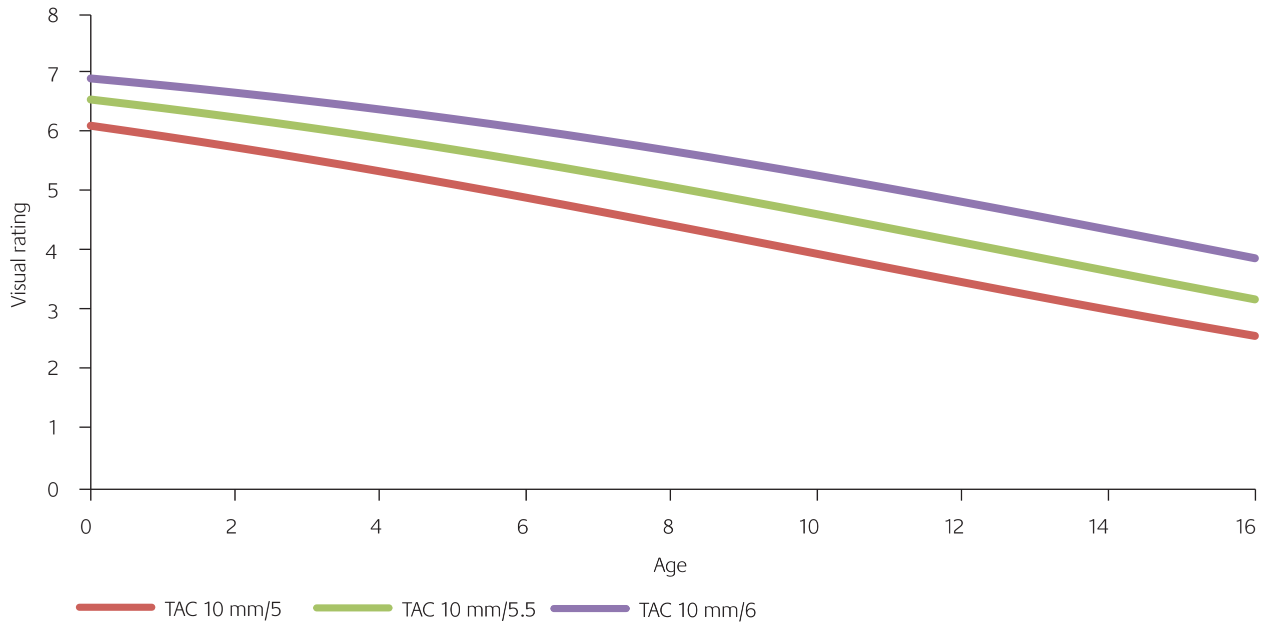

Figure J.6 Fitted regression lines for TAC 10 mm sites for different binder contents

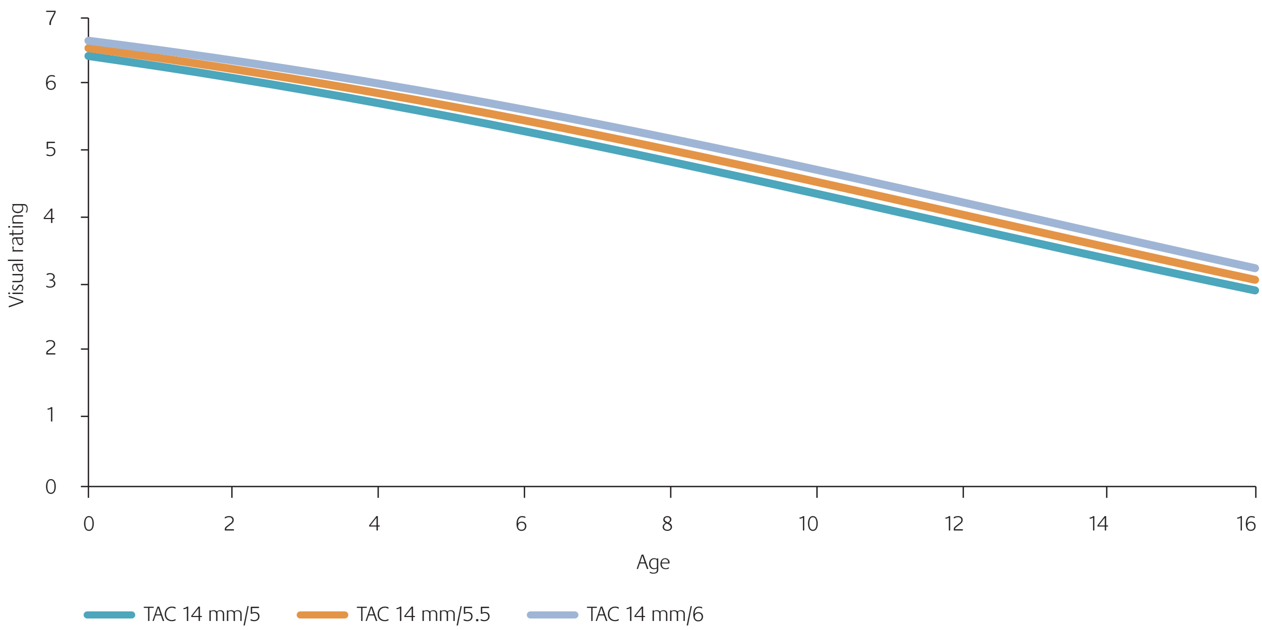

Figure J.7 Fitted regression lines for TAC 14 mm sites for different binder contents

J.7 Estimated age of thin surface systems

The fitted regression equations can be used to estimate the age of the surface when it becomes *Suspect* (reaches a visual condition level of 3). Table J.4 shows the estimated age for each of the ten surface site/aggregate combinations. Where binder content has an effect, an average value of 5.5 % has been used.

The estimated number of years, for *Suspect* condition (*Cond* = 3) is derived from Equation J.2:

$$Age = a_0 = \frac{\log_e\left(\frac{3}{8-3}\right) - a + b_2 \times Bind}{b_1} \qquad \text{(Equation J.2)}$$

where a, b_1 and b_2 are coefficients to be determined as in Equation J.1. The 95 % confidence interval for the visual

$$Cond = 3 \pm t_{0.05,\,\mathrm{df}} \times s \times \sqrt{\frac{1}{n} + \frac{(a_0 - a)^2}{(\sum(a_1 - a))^2}} \qquad \text{(Equation J.3)}$$

condition value of 3 is derived from Equation J.3:
where a_0 is the estimated number of years, s is the residual error from the regression based on a sample size of n and $t_{0.05,\,\mathrm{df}}$ is the "t" value for the 95 % confidence interval based on the appropriate degrees of freedom. The 95 % confidence interval for a0 is then based on using the 95 % confidence interval values of visual condition derived from Equation J.3 in Equation J.2.

The figures in Table J.4 suggest that TSMA systems with 10 mm aggregate should last longest before becoming *Suspect*. However, this regression is based on just 30 data points and only 29 % of the variation has been explained, so that there are wide confidence intervals on the 25.9-year estimate (which is also beyond the data range used to determine the regression). The 95 % confidence interval for the 10 mm TSMA range from 15.9 years to 38.3 years, which is a considerably wider interval than for the TSMA 14 mm sites with a range from 16.5 years to 21.4 years. The TSMA 14 mm estimate is based on 195 data points and 37 % of the variability in the visual condition was explained (Table J.4).

The estimated ages and associated confidence intervals should be used with care when the estimate exceeds the data range used to derive the regression equations, with there being no data for sites older than 16 years (and most for somewhat less) so that predicting a life greater than 16 years is extrapolating beyond the data.

Figure J.8 shows the estimated surface age, with the 95 % confidence interval, for a visual condition of *Suspect*. It clearly indicates the wide confidence interval associated with poorly based regression fits, due to not much of the variability being explained and/or the analysis being based on small sample sizes.

J.8 Recovered binder properties and visual condition

The properties of recovered binder may change as the surfaces age. Further, they may be closely associated with the visual condition measure. However, there were only 126 data points that had values for the penetration and softening point of the recovered binder together with a visual condition. Averaging these by age of the surface gives Table J.5.

Table J.5 shows that there were only one or two data points for some surface ages, which may result in not very good estimates. As a result, *Age* = 1 year and *Age* = 15 year values have not been used in Figure J.9, which shows the relationship of visual condition with two properties of the recovered binder.

The correlation between visual condition and recovered binder properties is shown in Table J.6. It indicates that, overall, 52 % of the variability between visual condition and penetration in the measures is shared, so that the coefficient of determination is 52 %.

Interestingly, the correlation between the penetration and the softening point is quite high (as would be expected) over all ages, and for ages zero to five years and five to ten years. However, it is almost non-existent for surfaces aged ten to 15 years. This lack of correlation may simply be due to very few data values or perhaps a divergence between these measures once the binder has reached a certain age.

The relationship between the visual condition and either recovered binder property is reasonably consistent within age groups except for surface age between five and ten years. This may simply be a result of little change within these measures during the mid-life period for the thin surfacing systems. However, the inter-correlations are not very strong and so it may not be sensible to replace either of the recovered binder properties by using visual condition as a proxy.

J.9 Summary

This Appendix has reported on a relatively rigorous statistical analysis of the available visual condition data. The analysis found that it was important to consider aggregate size and system type when analysing change in the assessment as the surface ages. Further, for some combinations the binder content was also important. The use of a logistic transform of the visual condition was used in the regression equations in order to estimate the expected life before a visual condition of *Suspect* was reached. The estimated serviceable life varied between five years (PLSD with 6 mm aggregate) and 26 years (TSMA with 10 mm aggregate) depending on the system type and aggregate size. The size of the confidence interval on the estimated serviceable life varied considerably, reflecting the sample size used for the regression calculation. The relationship between the visual condition and either recovered binder property is reasonably consistent but the correlations are not exceptionally strong and so it may not be sensible to consider replacing either of the recovered binder properties by using the visual condition as a proxy.

Table J.4 Predicted life of surface until *Suspect* is reached

Site type and aggregate	*Predicted age in years for visual condition = 3 (Suspect) and 95 % confidence interval*		
	Estimate	*Lower 95 %*	*Upper 95 %*
PLSD 6 mm	5.5	4.7	6.5
PLSD 10 mm	11.0	9.5	12.5
PLSD 14 mm	11.8	9.1	14.7
TAC 6 mm	14.3	9.6	19.6
TAC 10 mm, binder = 5.5 %	16.9	15.7	18.1
TAC 14 mm, binder = 5.5 %	16.4	14.1	19.0
TSMA 10 mm	25.9	15.9	38.3
TSMA 14 mm	18.9	16.5	21.4
MSD	7.4	6.3	8.5
MS	7.8	2.8	13.3

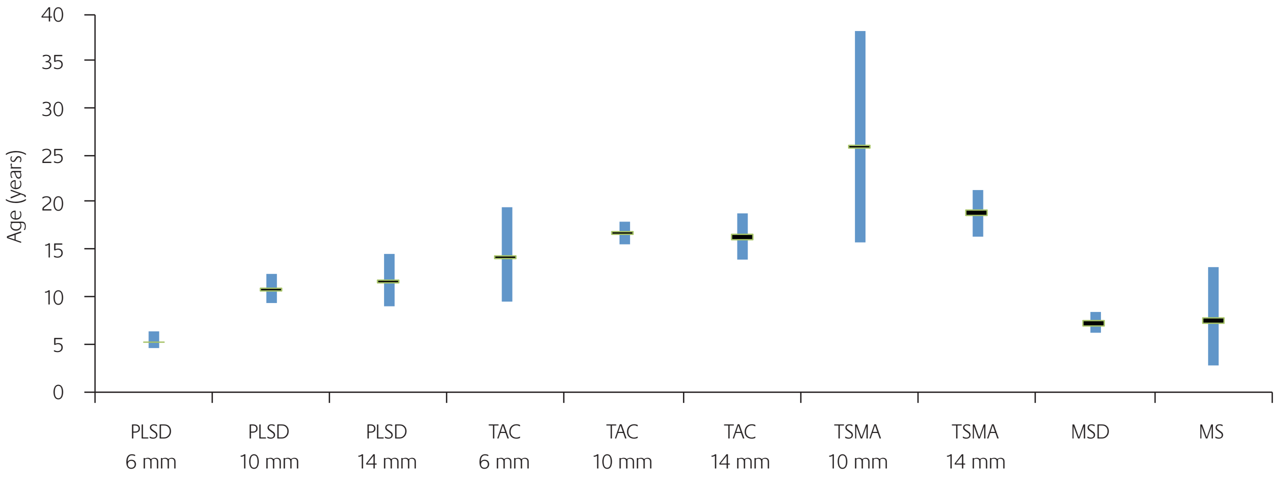

Figure J.8 Estimated age for *Suspect* with 95 % confidence interval

Table J.5 Averaged measures within age for recovered binder properties and visual conditions

Age	*Visual condition*	*Penetration*	*Softening point*	*Sample*
0	6.13	74.75	50.13	4
1	7.00	20.00	70.00	1
2	5.79	41.00	64.09	7
3	5.50	33.50	63.08	9
4	5.38	36.00	64.95	8
5	4.83	34.33	61.53	3
6	5.56	25.00	63.39	9
7	4.35	25.35	64.04	10
8	4.69	26.69	62.18	13
9	4.46	25.42	63.80	12
10	4.78	19.44	65.82	9
11	4.63	22.33	64.72	12
12	4.10	23.10	66.30	10
13	4.17	22.22	65.53	9
14	3.50	21.69	66.46	8
15	3.75	34.00	58.80	2

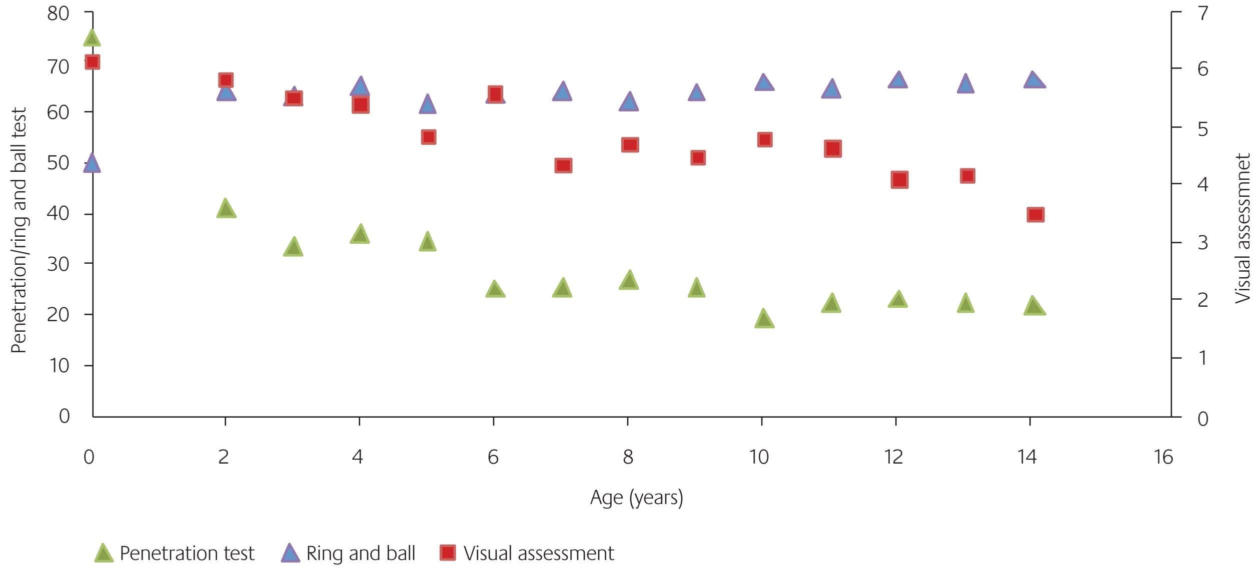

Figure J.9 Relationship of visual condition with recovered binder properties by age of surface

Table J.6 Correlation and coefficient of variation between visual condition and recovered binder properties

Age range	*Statistic*	*Cond vs. softening point*	*Cond vs. penetration*	*Penetration vs. softening point*
0 to 5	Correlation	-0.57	0.77	-0.95
	Coefficient of determination	33 %	59 %	90 %
5 to 10	Correlation	-0.13	0.01	-0.91
	Coefficient of determination	2 %	0 %	83 %
10 to 15	Correlation	-0.68	-0.43	-0.05
	Coefficient of determination	46 %	18 %	0 %
All	Correlation	-0.62	0.72	-0.91
	Coefficient of determination	39 %	52 %	84 %

Appendix K: Inspection Panel visit to Germany

K.1 Preliminary visit

A preliminary visit was made in 2007 by TRL to contacts in Munich in order to make the necessary arrangements for an Inspection Panel visit in 2008. The object of the visit was to assess the affect of using SMA with lower texture, as is used on the continent. Visits to a series of sites of varying ages on three Autobahns around Munich had been arranged that provided an opportunity to assess the sites with an ad hoc panel. A description of the sites and the results from this visit are given in Table K.1.

K.2 Visual monitoring

The main visit took place in September 2008 when a series of sites of varying ages on three Autobahns around Munich were inspected. Some, but not all, were sites visited in the preliminary visit.

Table K.1 Results from visit to Germany

Road	*Site location*	*Lanes*	*Site no.*		*Constructed*	*Mixture*	*Panel mark*	
			2007	*2008*			*2007*	*2008*
A96, Munich to Lindau	AS Sendling – AS Laim	all	1	1	2001	35 mm thick 8 mm SMA, 7.5 % PmB 45 (22 mm B/C)	*E/G*	*G*
A96	Not recorded	all	2	–	2000	8 mm SMA, 50/70 pen	*G/M* $_{c}$	–
A96	Not recorded	all	3	–	1998	8 mm SMA, PmB 45	*M* $_{-, t, v}$	–
A96	Not recorded	all	4	–	1997	8 mm SMA	*M* $_{-, c}$	–
A96	AS Oberpfaffenhofen – AS Wörthsee	HS and L2	5a	2a	1989	40 mm thick 11 mm SMA, 6.6 % PmB (Olexobit S)	*G/M* $_{+}$	*G/M*
		L1	5b	2b	2005	5 mm HRA	*G*	*E/G*
A96	Not recorded	all	6	–	1998	8 mm SMA, PmB 45, 7.0 % bitumen, 3.5 % voids	*G/M* $_{t}$	–
A96	AS Wörthsee – AS Inning	all	7	3	1996	35 mm thick 8 mm SMA, PmB 65, 7.1 % bitumen, 3.5 % voids	*M* $_{-, c}$	*M* $_{-, c}$
A96	AS Landsberg – AS Schöffelding	all	–	4	2003	35 mm thick 8 mm SMA, 7.3 % PmB 45A	–	*E/G*
A96	AS Bad Wörishofen – AS Mindeleim	all	–	5	1994	30 mm thick 8 mm SMA, 7.3 % 70/100 pen + 0.9 % NAF (5:1 TLA:fibre), 3.1 % voids	–	*M/A* $_{-, c}$
A96	AS Memmingen Nord – AS Holzgünz	all	–	6	2008	35 mm thick 8 mm SMA, 7.3 % PmB 45A	–	*E*
A99, Munich orbital	Not recorded	all	8	–	2006	8 mm SMA, PmB 45A, 7.5 % bitumen, 3.5 % voids	*E/G*	–
A99	Not recorded	L1	9a	–	1994	8 mm SMA	*M/A* $_{c}$	–
		L2 and L3	9b	–	pre 1994	8 mm SMA	*G/M*	–
A99	Not recorded	HS and L1	10	–	2003	8 mm SMA, PmB Olexobit + wax, 7.0 % bitumen, 3.8 % voids	*E/G*	–
A99	500 m before Haar exit	all	11	–	2005	5 mm SMA, PmB 65 + wax	*E/G*	–
A9, Munich to Ingolstadt	Not recorded	all	12	7	2005	Twin lay: 1) 5/8 mm PA, high PmB, 0.4 % fibres; 2) 11/16 mm PA, high PmB, 0.4 % fibres	*E/G*	*G/M* $_{-}$

Weather: 2007 – Overcast, damp, some heavy showers.
2008 – Overcast but dry.

K.3 Discussion

The results for both inspections are plotted together with the averaged UK results in Figure K.1.

All the points from the Bavarian sites are on or above the trend line derived from the UK TSMA systems, with one site being *Good* to *Moderate* after 19 years in service on a busy Autobahn. These sites show the advantage of low air voids contents in the durability of SMA mixtures. However, it is appreciated that the relatively high texture depths specified on high-speed trunk roads in the UK preclude the use of mixtures with the sort of low air voids contents specified for German Autobahns. Nevertheless, the consensus of the UK delegation on the technical visit was that it would be appropriate to review the current balance between safety (with better skid resistance and spray reduction from high texture) and sustainability (from enhanced durability and noise reduction from low texture) with greater emphasis on the latter.

It is recognised that SCRIM-type testing may not provide an accurate indication of high-speed friction. Therefore, there is some merit in monitoring a range of German SMAs with the Pavement Friction Testing machine belonging to the HA in order to provide information on the high-speed skid resistance on SMAs with low texture and low PSV. A range of material ages could easily be covered from newly laid, one year, two years, five years, ten years and 15 years; the results would provide guidance on the likely outcome of the potential introduction of these types of surfacing in the UK.

K.4 Technical exchanges

In addition to the site visits, the opportunity was taken to have a technical exchange. The Germany delegation was organised by Dipl-Ing Siegfried Scheuer of Oberste Baubehörde im Bayerischen Staatsministerium des Innern (OBB), the Bavarian state government. The people present were:

German delegates

- Karl Wiebel (Head of Highway and Bridges Department, OBB)
- Siegfried Scheuer (OBB)
- Gernot Rodehack (OBB)
- Klaus Graf (Prof Schellenberger Laboratory)
- Rupert Schmerbeck (Highway Agency Southern Bavaria)
- Horst Erdlen (J Rettenmaier & Söhne)
- Kevin Taylor (Rettenmaier UK Limited)

UK delegates

- Cliff Nicholls (TRL Limited)
- Ian Carswell (TRL Limited)
- Martin Ashfield (CEMEX UK)
- John Bradshaw-Bullock (Technical Asphalt and Aggregate Solutions)
- Paul Collins (Aggregate Industries Limited)
- Mike Gibb (Atkins Highways and Transportation)
- Arthur Hannah (Consultant)
- Alistair Jack (Road Surface Treatments Association)
- Jukka Laitinen (Nynas UK AB)
- Bob Noakes (Norfolk County Council)
- Bob Overett (Lafarge Aggregates Limited)
- Malcolm Simms (Mineral Products Association)

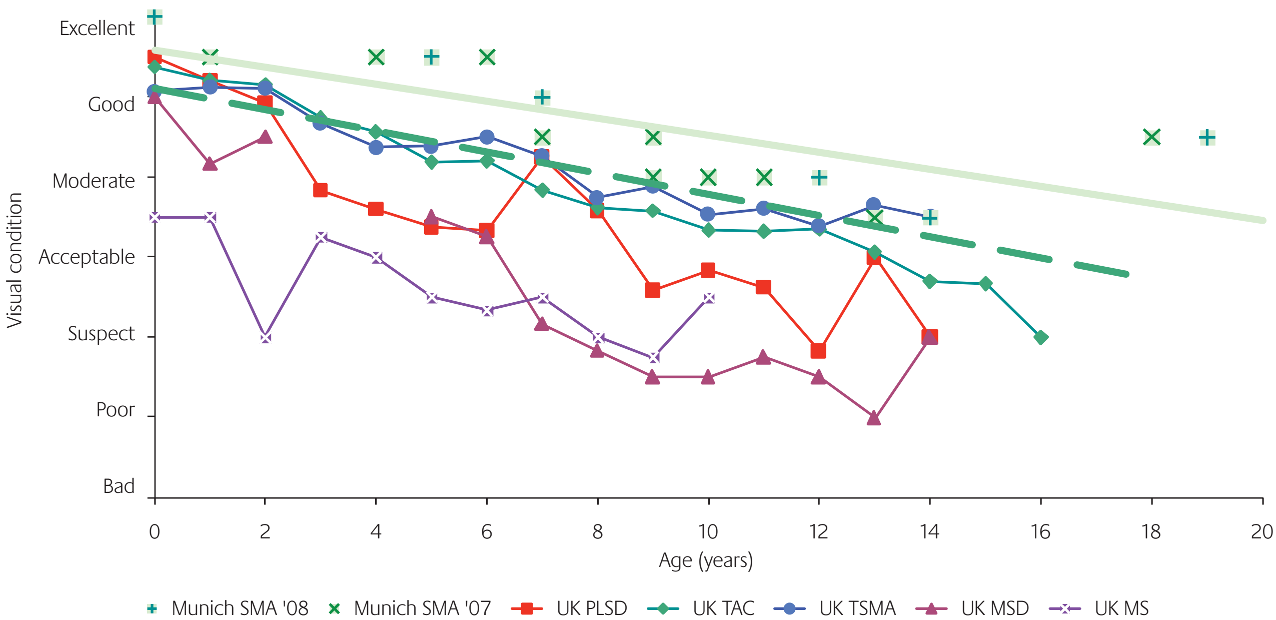

Figure K.1 Results from Bavaria compared with average visual condition rankings for different surfacing types

The technical exchange took place as general discussions based around presentations lead by different delegates. The overall agenda was intended to cover the following subject areas:

- Specification of SMA in the UK and Germany – pre and post EN 13108-5
- Production of SMA in the UK and Germany – texture and durability
- Monitoring of SMA properties in the UK and Germany – including the UK HAPAS scheme
- Public perception of SMA and use of SMA in the UK and Germany – including noise reduction and early life skid resistance
- Application and use of SMA in Germany and the UK

The most important aspect discussed from the UK perspective was the design of SMA. Whereas SMA has to be designed to provide high levels of micro- and macro-texture in the UK in order to optimise the safety of our road users, the design in Bavaria is more towards high binder contents and low air voids content in order to optimise the durability of the surfacing. The success of the Bavarian approach was demonstrated in the visual monitoring of sites on local Autobahns whilst they do not report any particular concerns about lack of skid resistance for the road users. Their design criteria to produce durable SMA include air voids contents of between 3.0 % and 4.0 % for 11 mm and 8 mm SMA, and between 2.0 % and 4.0 % for 5 mm SMA in the design and not greater than 5.0 % in the layer. Corresponding minimum binder contents (generally polymer-modified binder with fibres) are 6.6 % for 11 mm SMA, 7.2 % for 8 mm SMA and 7.4 % for 5 mm SMA.

As a result of this technical exchange, Norfolk County Council and Lafarge Aggregates Limited co-operated on some trials of SMA designed using the principles observed in Bavaria. Two sites with these mixtures were monitored in 2009 as part of the national inspections, but they were still very new at that time.

There is a widely-held belief in the UK that part of the reason that Germany can have lower texture in the road is because they have a higher requirement for tread depth in the tyre. However, the legal minimum tyre tread depth for ordinary cars (excluding slow vehicles, public transport vehicles, trucks, etc.) is the same as in the UK at 1.6 mm according to §36 Strassenverkehrszulassungsordnung (STVZO) with a fine of €100 being applied for tyre depths below this limit. ADAC (German Association of Automobilists) and others advise changing tyres with profile depths of lower than 3.0 mm in the summer and 4.0 mm in the winter whilst insurance companies can request further investigations in cases of accidents with profile depths slightly above 1.6 mm. No data are available on the extent to which tyres are changed at tread depths of around 3.0 mm or 4.0 mm in Germany rather than at around 2.0 mm as in the UK. If German motorists do generally change at around 2 mm, the accident rates on German roads will not have benefited from the higher minimum tread depth. Furthermore, the German specification demands that surfaces are gritted at the time of laying to remove the surface binder film and increase the initial skid resistance. They also have a requirement to undertake a SCRIM-equivalent type test at four weeks and annually thereafter. Maintenance is then carried out when SCRIM-equivalent values fall below specified limits.

Appendix L: Examples of sites with extreme performance

L.1 Approach

Extreme examples of thin surfacing system sites are defined for this purpose as those sites where the surfacing has either failed within five years (based on the recently introduced five-year warranty period) or has survived for more than 12 years (the systems having only been introduced into the UK in 1991). In order to identify some examples, an email request was sent to representatives of the HA Area Agents and relevant HA staff in 2007. The addressees were people identified as being involved in Value Management Workshops, although some of the emails were returned as being undeliverable. Nevertheless, eight responses were received.

Although it was intended to establish why some sites are particularly long- or short-lived, the information was not incorporated into the general database (unless already there) because it will theoretically bias the findings by the selection criteria. Despite the reports of considerable numbers of early failures of thin surfacing systems, very few examples were forthcoming and only three examples, one good and two bad, were followed up and are reported in this Appendix.

L.2 Example of good durability

AmeyMouchel, in HA Area 13, reported a site with extended durability. A recipe mixture of 14 mm TSMA had been laid on the A590 in Park Road, Barrow-in-Furness, in late August 1995 with a short length of HRA as a control. The site was de-trunked in July 2007. Limited details of the site were already known (Nicholls, 1998) so the site was added to the northern Inspection Panel route, when it was assessed as being *Moderate* in 2007 with loss of aggregate, cracking and random variability defects (Figure L.1). This condition is considered to be good for a 12-year-old surfacing.

Figure L.1 A590 at Barrow-in-Furness in 2007

Figure L.2 Widespread particle loss on A5

Figure L.3 Development of potholes on A5

L.3 Examples of poor durability

L.3.1 A5, Shotatton

AmeyMouchel, in HA Area 9, reported a case of extreme particle loss that started after less than five years in service. The site, located on the A5 at Shotatton near Shrewsbury, was laid with a TAC surfacing in April 2000 for a length of approximately 3.5 km of a two-lane single carriageway. The site started to deteriorate noticeably in early 2004 with major particle loss that had developed into potholes (Figures L.2 and L.3) by 2005. There had been no issues with the binder course. The maintaining agent had spent in the region of £100,000 during 2006/2007 on patching works to keep the road safe, treating the worse areas only. The remainder of the surfacing was to be replaced in September 2007.

The site was visited on 24 July 2007 when the overall condition was assessed as being *Poor* with defect suffixes for loss of aggregate, delamination from substrate and random variability. The primary defect was that the surfacing was losing particles badly in places to an extent that waJust prior to the visit, cores had been taken and tested for recovered penetration and water sensitivity by Pavement Testing Services Limited. The penetration of the binder, recovered in accordance with BS EN 12697-3 (CEN, 2005), was determined in accordance with BS EN 1426 (CEN, 2000) as 9 x 1/10 mm, 10 x 1/10 mm and 10 x 1/10 mm. The results of the HAPAS sensitivity to water test (BBA, 2008) at 20 ºC are given in Table L.1.

Table L.1 Results of HAPAS sensitivity to water test

Property		*Specimen no.*					
		1	*2*	*3*	*4*	*5*	*6*
Unconditioned stiffness (MPa)		1,685	3,210	2,039	2,516	1,930	4,046
Cycle 1	Conditioned stiffness (MPa)	Failed	1,985	Failed	Failed	Failed	1,308
	Stiffness ratio	0.00	0.62	0.00	0.00	0.00	0.32
Cycle 2	Conditioned stiffness (MPa)	–	1,350	–	–	–	Failed
	Stiffness ratio	–	0.42	–	–	–	0.00
Cycle 3	Conditioned stiffness (MPa)	–	1,436	–	–	–	–
	Stiffness ratio	–	0.44	–	–	–	–

The test results are consistent with the poor appearance because:

- A penetration value of ten is lower than would be expected for a site after about five years (Daines, 1991), although values from polymer-modified binders are often somewhat unusual.
- The inability of the cores to retain any stiffness after one cycle in the HAPAS water sensitivity test indicates poor adhesion. However, it does not actually indicate sensitivity to water because laboratory samples are normally used for the test rather than aged cores with the resulting cut faces allowing water easier access below the binder film than would occur normally.

The results from both tests merely demonstrate that the surfacing is failing rather than giving the cause of its failure – the low recovered penetration and the poor water sensitivity could have caused the particle loss or the particle loss could have caused the penetration to drop and the cores to effectively collapse. Possible alternatives to poor water sensitivity as the cause of the particle loss are inadequate compaction, although this defect was not obvious from the visual inspection, and a failure to adequately dry the stone when the asphalt was mixed. It has been suggested that the primary reason for premature failure of their thin surfacing systems in the early years (i.e. two to five years) was the inability to dry the stone adequately in winter conditions or at other times when their stockpiles were saturated.

L.3.2 Area 7 roundabouts

AMScott in HA Area 7 reported low friction readings obtained on roundabouts from thin surfacing systems, with particular reference to the A52/A6011 Gamston Island roundabout by Nottingham airport and the A5111/A6 Raynesway Park roundabout in Derby. Accidents had occurred at both these sites.

Although the number of accidents indicated a problem, it was an early-life skidding problem rather than a durability problem. Furthermore, the skidding problem on roundabouts is influenced by the choice of aggregate at least as much as, if not more than, by the type of material. Therefore, the information was passed to the team investigating early-life skidding for further study.

L.3.3 Thin surfacing systems in Cumbria

Capita Symonds reported that it had carried out a review of thin surfacing systems in Cumbria for Cumbria Highways. The need for a review came from anecdotal evidence, which suggested that there may be problems with systems in the county although it was not known how extensive these were.

Seventy sites with thin surfacing systems from four separate HAPAS-certified systems of varying age throughout Cumbria were assessed by site inspections backed up by routine survey data extracted from the Pavement Management System. The observations from these assessments were compared with the requirements in the Specification for Highway Works, enabling conclusions to be drawn about compliance.

Their observations demonstrated that the installed systems were generally performing satisfactorily but that there were problems identified with a number of common factors. These related to initial treatment selection for the site, the designer's assessment of the site, selection of systems and workmanship. All these factors contributed to some degree at each of the problem sites. SCANNER surveys showed that eight of the sites which were still within their guarantee period had low texture depths and were expected to fail to meet the specified value.

The report made the following recommendations:

- Scheme selection processes should ensure that any existing structural problems have been identified and addressed within the proposed scheme in order to maximise the serviceable life of the new installation.
- Scheme compilers must provide sufficient information in Appendix 7/1 for the designer to select the appropriate system for the site.
- The design process should be reviewed to ensure that there is a clear selection process for the thin surfacing system to be applied that considers site parameters such as stress level (BBA, 2008) and any retained texture requirements. This process should also include the need to visit the site and consult with the system supplier.
- Installation techniques need to be reviewed with the supplier, particularly the location and treatment of joints, sealing edges against ironwork, kerbs, etc. The location of joints should be agreed prior to the works to ensure compliance with clause 901.23 of the *Specification for Highway Works.*
- There should be a formal inspection of the installation towards the end of its guarantee period and the results recorded and fed back to the designer.

- Texture depth measurements to determine compliance should be undertaken on all of the eight sites with lower than specified values that were still within their guarantee period. These measurements should be compared with those taken immediately after installation.

This approach could be usefully followed on the HA and other road networks.

L.3.4 References

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Nicholls, J C (1998). Road trials of stone mastic asphalt and other thin surfacings. TRL Report TRL314. Crowthorne: Transport Research Laboratory.

Appendix M: Actual lives found

Site	*Year laid*	*End year*	*Year to "S"*	*Mark prior to maintenance*	*Life (years) to*	
					Maintenance	*Suspect*
PLSD1	1991	2000	–	n/m	9	–
PLSD2	1991	2000	–	n/m	9	–
PLSD3	1992	n/k	n/k	–	n/a	–
PLSD4	1993	n/k	n/k	–	n/a	–
PLSD5	1991	2001	1997	n/m	10	6
PLSD6	1991	2004	2000	$S/P_{-, c, d, v}$	13	9
PLSD7a	1993	2003	–	$A_{-, c, d}$	10	–
PLSD7b	1993	2007	2004	$P_{-, v}$	14	12
PLSD8	1993	2004	2002	$S_{-, d, v}$ ($S/P_{-, c, d, t, v}$)	11	9
PLSD9	1994	2004	–	$M/A_{-, t}$	10	–
PLSD10	1995	2009	2007	$A_{-, c, d, v}$ ($S/P_{-, c, d, s, t}$)	14	12
PLSD11	1995	2003	–	$M_{c, t, v}$	8	–
PLSD12	1997	2003	2003	$S_{-, c, d, v}$	6	6
PLSD13	1995	2005	–	$P/B_{-, d}$	10	–
PLSD15	1997	2009	2005	$P_{-, c, d, t}$	12	8
PLSD14	2003	–	2008	–	–	5
TAC1a	1992	2007	2006	$A/S_{-, c, v}$	15	14
TAC1b	1992	2007	–	$A_{-, c}$	15	–
TAC2	1995	2009	2008	$S_{-, c, d, s, t}$ ($P_{-, c, d, s, t}$)	14	13
TAC3	1995	2003	2003	$M_{-, c}$	8	8
TAC4	1997	2001	–	n/m	4	–
TAC5	1997	2005	–	$M/A_{-, t}$	8	–
TAC6	1996	2005	2005	$A/S_{-, d, v}$	9	9
TAC8	1997	2005	–	$S_{-, c, t}$	8	–
TAC9	1997	–	2008	–	–	11
TAC10a	1998	2005	–	$S_{-, c, d, v}$	7	–
TAC10b	1998	2005	–	$A_{-, c, v}$	7	–
TAC12	1993	–	2008	–	–	15
TAC13	1998	2008	–	$M/A_{-, c}$	10	–
TAC14	1997	2007	2006	$P_{-, d, v}$	10	9
TAC15	2000	2008	2006	$S/P_{-, d, s, t}$	8	6
TAC16	1993	2006	–	M_{-}	13	–
TAC17	1994	2006	–	A/S_{-}	12	–
TAC18	1996	2007	2006	$M/A_{-, c, t}$	11	10
TAC22	1999	–	2009	–	–	10

Year laid = Year when thin surfacing system was laid on the site.
End year = Year when thin surfacing system was replaced or overlain on the site.
Year to "S" = Year when the thin surfacing system was first assessed as *Suspect* or worse.
n/m = Site not inspected in year of or year preceding maintenance.
n/k = Date of resurfacing or replacement not known.

Site	*Year laid*	*End year*	*Year to "S"*	*Mark prior to maintenance*	*Life (years) to*	
					Maintenance	*Suspect*
TAC23	1999	–	2009	–	–	10
TAC24	1999	2008	–	M_{-}	9	–
TAC25	2003	–	2008	–	–	5
TAC32	1999	–	2006	–	–	7
TAC37	1998	–	2009	–	–	11
TSMA1	1995	n/k	–	–	n/k	–
TSMA2	1998	n/k	–	–	n/k	–
TSMA3	1995	2008	2004	$S_{-, c, v}$	13	9
TSMA5	1995	2004	–	*G*	9	–
TSMA6	1995	2003	–	*G*	8	–
TSMA7	1995	–	2005	–	–	10
TSMA8	1995	2009	–	$M/A_{-, c}$ ($A/S_{-, c, d, t}$)	14	–
TSMA9	1997	–	2006	–	–	9
TSMA13	1997	–	2009	–	–	12
TSMA14	1997	2008	2007	$A/S_{-, c, v}$	11	10
TSMA15	1998	–	2008	–	–	10
TSMA16	1998	2004	–	$M_{-, c}$	6	–
TSMA18	2000	2009	2007	$P_{-, c, d, v}$	9	7
TSMA19	2002	2004	–	*G*	2	–
TSMA21	1999	2009	–	$A_{-, c}$	10	–
MSD1	1995	–	2001	–	–	6
MSD2	1995	2007	2001	$P_{-, c, d, t, v}$	12	6
MSD3	1996	2006	–	$S/P_{-, c, d, v}$	10	–
MSD4	1996	2001	–	$M_{-, t}$	5	–
MS1	1999	–	2009	–	–	10
MS2	2000	–	2005	–	–	5
MS3	2003	–	2005	–	–	2

Year laid = Year when thin surfacing system was laid on the site.
End year = Year when thin surfacing system was replaced or overlain on the site.
Year to "S" = Year when the thin surfacing system was first assessed as *Suspect* or worse.
n/m = Site not inspected in year of or year preceding maintenance.
n/k = Date of resurfacing or replacement not known.

Appendix N: Tables of observed defects

Table N.1 Number of observations

	Age (years)	*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
PLSD	All	2	6	7	4	6	5	7	4	6	6	6	4	3	2	2	0	0
	14 mm	1	2	3	0	1	1	4	4	4	3	3	2	1	1	1	0	0
	10 mm	1	3	3	3	4	3	2	0	2	3	3	2	2	1	1	0	0
	6 mm	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
TAC	All	4	10	26	17	24	24	25	24	21	19	18	11	10	8	5	3	1
	14 mm	2	6	14	9	12	11	10	7	6	2	1	1	1	0	0	0	0
	10 mm	2	2	8	5	7	10	12	13	11	14	14	10	9	8	5	3	1
	6 mm	0	2	4	3	5	3	3	4	4	3	3	0	0	0	0	0	0
TSMA	All	7	16	25	14	15	17	20	23	25	17	15	10	9	7	3	0	0
	14 mm	5	15	22	12	14	16	18	20	22	14	12	9	8	6	2	0	0
	10 mm	2	1	3	2	1	1	2	3	3	3	3	1	1	1	1	0	0
MSD	14 mm	2	3	2	0	0	2	2	3	3	3	3	2	1	1	1	0	0
MS	6 mm	1	2	1	2	3	3	3	2	2	2	1	0	0	0	0	0	0
All	All	16	37	61	37	48	51	57	56	57	47	43	27	23	18	11	3	1

Table N.2 Average number of types of defect per site

Age (years)		*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
PLSD	All	0.00	0.00	0.29	0.75	1.50	2.00	1.57	1.75	2.33	3.00	2.33	2.75	3.33	3.50	3.00	–	–
	14 mm	0.00	0.00	0.00	–	2.00	3.00	1.25	1.75	2.25	2.67	2.33	3.00	3.00	4.00	4.00	–	–
	10 mm	0.00	0.00	0.33	0.33	1.25	1.33	1.50	–	2.50	3.33	2.33	2.50	3.50	3.00	2.00	–	–
	6 mm	–	0.00	1.00	2.00	2.00	3.00	3.00	–	–	–	–	–	–	–	–	–	–
TAC	All	0.00	0.25	0.14	0.53	0.88	1.38	1.16	1.42	1.61	1.67	2.30	2.00	1.67	2.30	2.00	1.60	1.00
	14 mm	0.00	0.00	0.13	0.45	0.57	1.31	0.90	1.11	1.38	0.25	0.33	0.33	1.00	–	–	–	–
	10 mm	0.00	0.00	0.25	0.40	1.43	1.20	1.00	1.54	1.55	1.86	2.36	2.50	1.89	2.88	2.80	2.67	3.00
	6 mm	–	1.50	0.00	1.00	1.00	2.33	2.67	1.75	2.25	2.67	4.00	–	–	–	–	–	–
TSMA	All	0.07	0.21	0.09	0.23	0.57	0.76	0.71	1.35	1.52	1.08	1.39	0.89	1.18	1.00	0.64	–	–
	14 mm	0.08	0.22	0.10	0.25	0.59	0.79	0.77	1.45	1.64	0.91	1.30	0.94	1.19	1.07	0.40	–	–
	10 mm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.67	2.33	2.00	0.00	1.00	0.00	3.00	–	–
MSD	14 mm	0.00	2.00	1.00	–	–	3.00	4.00	3.67	4.00	4.33	3.67	4.00	3.00	2.00	3.00	–	–
MS	6 mm	2.00	2.00	3.00	1.00	1.67	2.00	2.67	3.00	2.50	3.00	4.00	–	–	–	–	–	–
All	All	0.12	0.38	0.20	0.43	0.86	1.26	1.17	1.59	1.80	1.74	2.02	1.65	1.61	1.68	1.43	0.62	0.27

Table N.3 Proportion of sites with fatting up (%)

Age (years)		*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
PLSD	All	0	0	0	0	0	0	0	25	0	0	0	0	0	0	0	–	–
	14 mm	0	0	0	–	0	0	0	25	0	0	0	0	0	0	0	–	–
	10 mm	0	0	0	0	0	0	0	–	0	0	0	0	0	0	0	–	–
	6 mm	–	0	0	0	0	0	0	–	–	–	–	–	–	–	–	–	–
TAC	All	0	0	4	6	13	4	8	0	0	5	17	9	0	0	0	0	0
	14 mm	0	0	7	11	8	9	20	0	0	50	0	0	0	–	–	–	–
	10 mm	0	0	0	0	29	0	0	0	0	0	7	10	0	0	0	0	0
	6 mm	–	0	0	0	0	0	0	0	0	0	67	–	–	–	–	–	–
TSMA	All	0	13	0	0	7	6	5	0	4	12	7	0	0	0	0	–	–
	14 mm	0	13	0	0	7	6	6	0	5	7	8	0	0	0	0	–	–
	10 mm	0	0	0	0	0	0	0	0	0	33	0	0	0	0	0	–	–
MSD	14 mm	0	0	0	–	–	50	50	67	67	100	33	50	100	100	100	–	–
MS	6 mm	100	50	0	0	0	0	0	0	0	0	0	–	–	–	–	–	–
All	All	6	8	2	3	8	6	7	5	5	13	12	7	4	6	9	0	0

Table N.4 Proportion of sites with particle loss (%)

Age (years)		*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
PLSD	All	0	0	14	50	67	80	43	100	83	100	100	100	100	100	100	–	–
	14 mm	0	0	0	–	100	100	25	100	75	100	100	100	100	100	100	–	–
	10 mm	0	0	0	33	50	67	50	–	100	100	100	100	100	100	100	–	–
	6 mm	–	0	100	100	100	100	100	–	–	–	–	–	–	–	–	–	–
TAC	All	0	10	0	18	42	71	60	75	86	84	94	100	100	100	100	100	100
	14 mm	0	0	0	11	33	73	60	71	83	0	100	100	100	–	–	–	–
	10 mm	0	0	0	20	57	60	50	69	82	93	93	100	100	100	100	100	100
	6 mm	–	50	0	33	40	100	100	100	100	100	100	–	–	–	–	–	–
TSMA	All	0	0	8	21	53	41	40	57	72	71	80	80	89	86	100	–	–
	14 mm	0	0	9	25	57	44	44	60	77	71	83	89	88	100	100	–	–
	10 mm	0	0	0	0	0	0	0	33	33	67	67	0	100	0	100	–	–
MSD	14 mm	0	100	50	–	–	100	100	67	67	67	67	50	0	0	100	–	–
MS	6 mm	0	50	100	50	67	67	100	100	100	100	100	–	–	–	–	–	–
All	All	0	14	8	24	50	63	54	70	79	81	88	89	91	89	100	100	100

Table N.5 Proportion of sites with cracking (%)

Age (years)		*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
PLSD	All	0	0	0	25	50	60	43	25	33	67	33	75	67	100	50	–	–
	14 mm	0	0	0	–	100	100	25	25	50	67	33	100	0	100	100	–	–
	10 mm	0	0	0	0	25	33	50	–	0	67	33	50	100	100	0	–	–
	6 mm	–	0	0	100	100	100	100	–	–	–	–	–	–	–	–	–	–
TAC	All	0	0	4	29	21	38	20	38	38	26	50	73	40	88	60	100	100
	14 mm	0	0	0	22	17	36	0	14	33	0	0	0	0	–	–	–	–
	10 mm	0	0	13	20	29	30	17	46	27	29	57	80	44	88	60	100	100
	6 mm	–	0	0	67	20	67	100	50	75	33	33	–	–	–	–	–	–
TSMA	All	0	0	0	0	13	24	20	35	24	41	53	40	56	57	100	–	–
	14 mm	0	0	0	0	14	25	22	35	23	36	50	44	63	67	100	–	–
	10 mm	0	0	0	0	0	0	0	33	33	67	67	0	0	0	100	–	–
MSD	14 mm	0	67	0	–	–	0	50	33	67	67	67	100	100	100	100	–	–
MS	6 mm	0	50	0	0	0	33	33	0	0	50	100	–	–	–	–	–	–
All	All	0	8	2	16	21	33	25	34	32	40	51	63	52	78	73	100	100

Table N.6 Proportion of sites with delamination (%)

Age (years)		*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
PLSD	All	0	0	0	0	0	20	14	0	33	67	17	50	67	0	50	–	–
	14 mm	0	0	0	–	0	0	25	0	25	67	0	50	100	0	100	–	–
	10 mm	0	0	0	0	0	0	0	–	50	67	33	50	50	0	0	–	–
	6 mm	–	0	0	0	0	100	0	–	–	–	–	–	–	–	–	–	–
TAC	All	0	10	0	0	4	8	8	8	14	21	33	9	10	25	60	0	0
	14 mm	0	0	0	0	0	0	0	14	17	0	0	0	100	–	–	–	–
	10 mm	0	0	0	0	0	10	8	8	9	21	29	10	0	25	60	0	0
	6 mm	–	50	0	0	20	33	33	0	25	33	67	–	–	–	–	–	–
TSMA	All	0	0	0	0	0	0	0	0	4	0	0	0	11	0	0	–	–
	14 mm	0	0	0	0	0	0	0	0	5	0	0	0	13	0	0	–	–
	10 mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	–	–
MSD	14 mm	0	0	0	–	–	0	0	67	67	67	67	50	0	0	0	–	–
MS	6 mm	0	0	100	50	33	33	67	50	100	50	100	–	–	–	–	–	–
All	All	0	3	2	3	4	8	9	9	18	23	23	15	17	11	36	0	0

Table N.7 Proportion of sites with stripping (%)

Age (years)		*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
PLSD	All	0	0	0	0	0	0	0	0	0	0	0	0	33	0	0	–	–
	14 mm	0	0	0	–	0	0	0	0	0	0	0	0	100	0	0	–	–
	10 mm	0	0	0	0	0	0	0	–	0	0	0	0	0	0	0	–	–
	6 mm	–	0	0	0	0	0	0	–	–	–	–	–	–	–	–	–	–
TAC	All	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	100
	14 mm	0	0	0	0	0	0	0	0	17	0	0	0	0	–	–	–	–
	10 mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
	6 mm	–	0	0	0	0	0	0	0	0	0	0	–	–	–	–	–	–
TSMA	All	0	0	0	0	0	0	0	0	0	0	7	10	0	0	0	–	–
	14 mm	0	0	0	0	0	0	0	0	0	0	8	11	0	0	0	–	–
	10 mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	–	–
MSD	14 mm	0	0	0	–	–	0	50	33	33	33	33	0	0	0	0	–	–
MS	6 mm	0	0	0	0	0	0	0	50	0	0	0	–	–	–	–	–	–

Table N.8 Proportion of sites with variation from traffic intensity (%)

Age (years)		*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
PLSD	All	0	0	0	0	0	0	0	0	50	50	50	25	0	50	0	–	–
	14 mm	0	0	0	–	0	0	0	0	50	33	100	50	0	100	0	–	–
	10 mm	0	0	0	0	0	0	0	–	50	67	0	0	0	0	0	–	–
	6 mm	–	0	0	0	0	0	0	–	–	–	–	–	–	–	–	–	–
TAC	All	0	0	4	0	4	4	4	4	29	0	28	18	10	25	0	0	0
	14 mm	0	0	7	0	0	9	10	14	33	0	0	0	0	–	–	–	–
	10 mm	0	0	0	0	0	0	0	0	27	0	29	20	11	25	0	0	0
	6 mm	–	0	0	0	20	0	0	0	25	0	33	–	–	–	–	–	–
TSMA	All	14	19	0	7	7	24	20	13	12	6	27	10	22	14	0	–	–
	14 mm	20	20	0	8	7	25	22	15	14	0	33	11	25	17	0	–	–
	10 mm	0	0	0	0	0	0	0	0	0	33	0	0	0	0	0	–	–
MSD	14 mm	0	0	0	–	–	100	50	0	0	33	0	100	0	0	0	–	–
MS	6 mm	0	0	0	0	33	0	0	50	0	0	0	–	–	–	–	–	–
All	All	6	8	2	3	6	14	11	9	21	11	28	22	13	22	0	0	0

Table N.9 Proportion of sites with random variations (%)

Age years)		*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
PLSD	All	0	0	14	0	33	40	57	25	50	17	33	25	67	100	100	–	–
	14 mm	0	0	0	–	0	100	50	25	50	0	0	0	0	100	100	–	–
	10 mm	0	0	33	0	50	33	50	–	50	33	67	50	100	100	100	–	–
	6 mm	–	0	0	0	0	0	100	–	–	–	–	–	–	–	–	–	–
TAC	All	0	10	4	6	13	25	24	29	5	47	33	27	40	50	60	67	0
	14 mm	0	0	0	11	8	27	20	29	0	0	0	0	100	–	–	–	–
	10 mm	0	0	13	0	29	20	25	31	9	43	21	30	33	50	60	67	0
	6 mm	–	50	0	0	0	33	33	25	0	100	100	–	–	–	–	–	–
TSMA	All	0	0	4	7	7	18	15	30	36	29	40	20	44	57	33	–	–
	14 mm	0	0	5	8	7	19	17	35	41	29	33	22	50	67	0	–	–
	10 mm	0	0	0	0	0	0	0	0	0	33	67	0	0	0	100	–	–
MSD	14 mm	0	33	50	–	–	50	100	100	100	67	100	50	100	0	0	–	–
MS	6 mm	100	50	100	0	33	67	67	50	50	100	100	–	–	–	–	–	–
All	All	6	8	8	5	15	27	30	34	30	40	42	26	48	56	55	67	0

Table N.10 Proportion of sites with either form of variability (%)

Age (years)		*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
PLSD	All	0	0	14	0	33	40	57	25	67	50	83	50	67	100	100	–	–
	14 mm	0	0	0	–	0	100	50	25	50	33	100	50	0	100	100	–	–
	10 mm	0	0	33	0	50	33	50	–	100	67	67	50	100	100	100	–	–
	6 mm	–	0	0	0	0	0	100	–	–	–	–	–	–	–	–	–	–
TAC	All	0	10	8	6	17	29	28	33	33	47	50	36	40	63	60	67	0
	14 mm	0	0	7	11	8	36	30	43	33	0	0	0	100	–	–	–	–
	10 mm	0	0	13	0	29	20	25	31	36	43	43	40	33	63	60	67	0
	6 mm	–	50	0	0	20	33	33	25	25	100	100	–	–	–	–	–	–
TSMA	All	14	19	4	14	13	29	30	43	48	29	67	30	67	71	33	–	–
	14 mm	20	20	5	17	14	31	33	50	55	29	67	33	75	83	0	–	–
	10 mm	0	0	0	0	0	0	0	0	0	33	67	0	0	0	100	–	–
MSD	14 mm	0	33	50	–	–	100	100	100	100	100	100	100	100	0	0	–	–
MS	6 mm	100	50	100	0	67	67	67	50	50	100	100	–	–	–	–	–	–
All	All	13	16	10	8	21	35	37	41	47	47	65	41	57	67	55	67	0

Appendix O: Analysis of recovered binder properties

O.1 Recovered penetration

The penetration results for each site are plotted in Figure O.1, with hatched lines joining the values obtained from particular sites. The "initial" penetration values do not include a factor for the immediate ageing that occurs during mixing and placement, which is generally assumed to be a loss of about 30 % for unmodified binders in batch mixers and half that for drum mixers (Read and Whiteoak, 2003).

The results show a general decrease with time, as would be expected, although there are some apparent increases due, presumably, to local variability (including from any lubricant or fuel spillage) and/or testing errors. However, the rate of loss of penetration is unclear. To try to clarify the situation, the recovered penetration for each year in service was divided by the initial penetration and the mean value of these relative penetrations for each system type and age in service were plotted in Figure O.2. The trend lines are based on unweighted means and, as such, are not statistically valid.

Although the correlations of the trend lines are not particularly good (R^2 = 0.24 to 0.75), they all imply an initial relative penetration (at age = 0) of about 0.7, consistent with the expected ageing during construction.

For comparison, the linear trend lines can be changed to quadratic trend lines to give Figure O.3.

There is no discernible difference for the trend in Figure O.2 for the surface treatment systems (MSD and MS) whereas the asphalt system types (PLSD, TAC and TSMA) show a reduced rate of loss of penetration with time. However, they start to indicate an increase in penetration with extended ageing, particularly TAC after about nine years, which cannot be correct unless the material has been contaminated with lubricants or fuel. Therefore, there appears to be no justification for using quadratic trend lines.

From the trend lines in Figure O.2, a rough ranking can be generated in terms of the rate of hardening of the binder. This ranking, with the coefficients of correlation for both the linear and quadratic trend lines, is:

1	MSD	$R_{linear}^2 = 0.24$	($R_{quadratic}^2 = 0.24$)
2	TAC	$R_{linear}^2 = 0.29$	($R_{quadratic}^2 = 0.76$)
3=	TSMA	$R_{linear}^2 = 0.75$	($R_{quadratic}^2 = 0.85$)
3=	PLSD	$R_{linear}^2 = 0.70$	($R_{quadratic}^2 = 0.94$)
5	MS	$R_{linear}^2 = 0.42$	($R_{quadratic}^2 = 0.34$)

The correlation coeffwicients are very poor except for PLSD and TSMA, which have reasonable values for both their linear and quadratic trend lines, as does TAC provided the quadratic trend line is used. However, even the better correlations imply that the relationships are only indicative rather than definitive. The relatively poor correlation for TAC with a linear trend line is assumed to be the result of different polymers which affect the ageing differently. Nevertheless, despite the poor correlation coefficient, the results do indicate that the polymer-modified binders used in TAC systems appear to age more slowly.

Although Figures O.2 and O.3 show a trend with age, they give limited indication of a consistent relationship between recovered penetration and the condition of the surfacing system. In order to try to link the surfacing performance with the binder properties, the recovered penetration as a proportion of initial value was plotted against the visual condition of the site from which the binder was recovered at the same age and is shown in Figure O.4.

The linear trend lines give the expected relationship of the visual condition getting worse with reducing relative penetration with the exception of MSD which appeared to marginally improve with reduced penetration. The correlation coefficients were low, R^2 varying from 0.001 (for MSD) to 0.54 (for MS) with a weighted average of 0.18. Similar findings were made when comparing the penetration values directly with the visual condition. Therefore, no estimate can be made of the visual condition of a surfacing from its recovered penetration.

O.2 Recovered softening point

The softening point results for each site are plotted in Figure O.5 with different hatched lines joining the values obtained from a particular site. As for penetration, the "initial" softening point values do not include a factor for the immediate ageing that occurs during mixing and placement, which is generally assumed to be an increase of between about 3 °C and 5 °C.

A similar analysis was carried out as for penetration, but with even less correlation found. The mean recovered softening point as a proportion of initial value is plotted in Figure O.6 against time in service and against visual condition in Figure O.7. The main point of interest is the apparent reduction in softening point with age for the multiple surface dressing systems, which implies that the initial softening point was over-estimated, possibly due to the interaction with the binder in the substrate layer for this type of system.

O.3 Penetration Index

The Penetration Index (PI) of binders was developed as a measure of its temperature susceptibility but it has also been used as a surrogate for other properties. The value for unmodified bitumens can be calculated from the penetration (pen) and softening point (SP) using Equation O.1 (Read and Whiteoak, 2003).

$$PI = \frac{1952 - 500\log(pen) - 20\,SP}{50\log(pen) - SP - 120} \qquad \text{(Equation O.1)}$$

The values of PI from the recovered binders, including modified binders, are plotted against the visual condition of the sites at the same age in Figure O.8.

The graph shows no obvious relationships between the PI of the recovered binders and the visual condition of the thin surfacing systems with the linear trend lines going in all directions (negative for PLSD, neutral for TSMA and positive for TAC, MSD and, most strongly, MS).

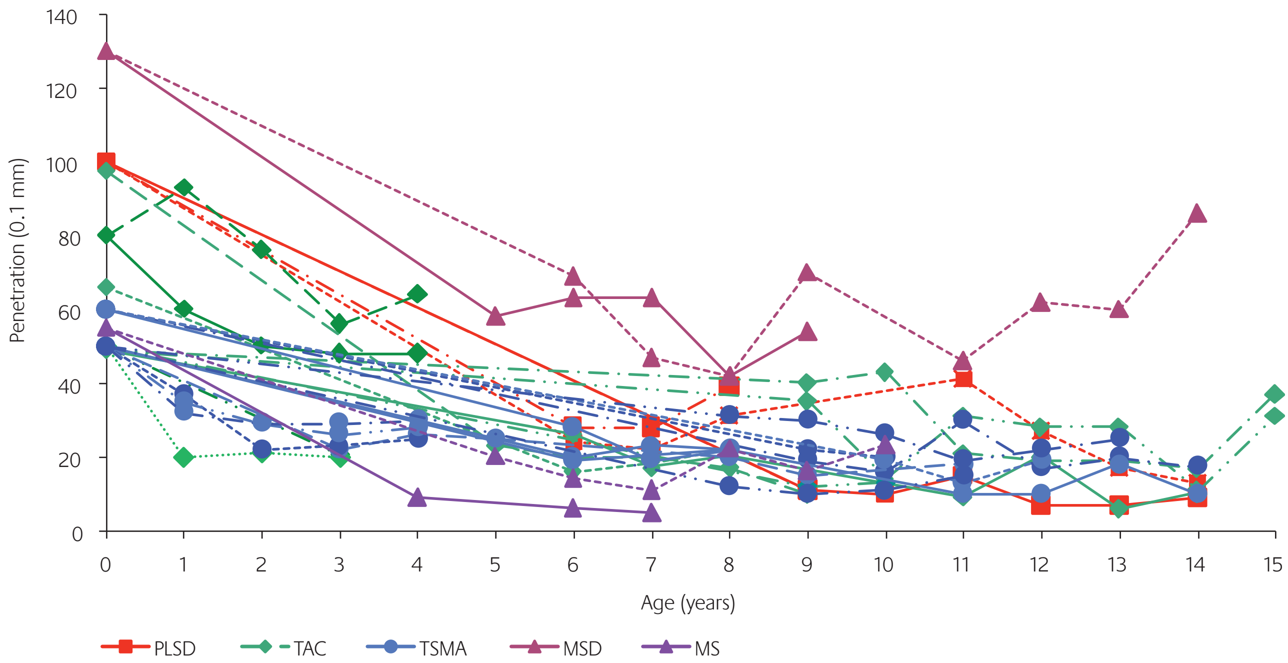

Figure O.1 Recovered penetration values for each site

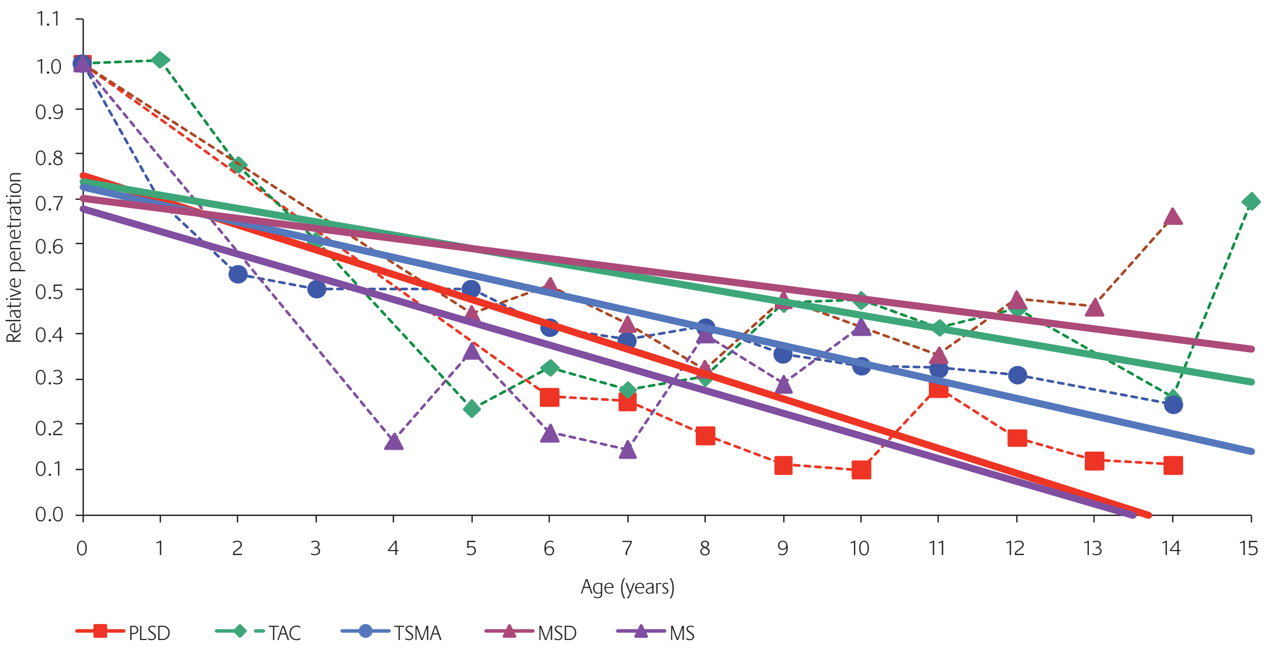

Figure O.2 Change in mean recovered penetration relative to initial value with time

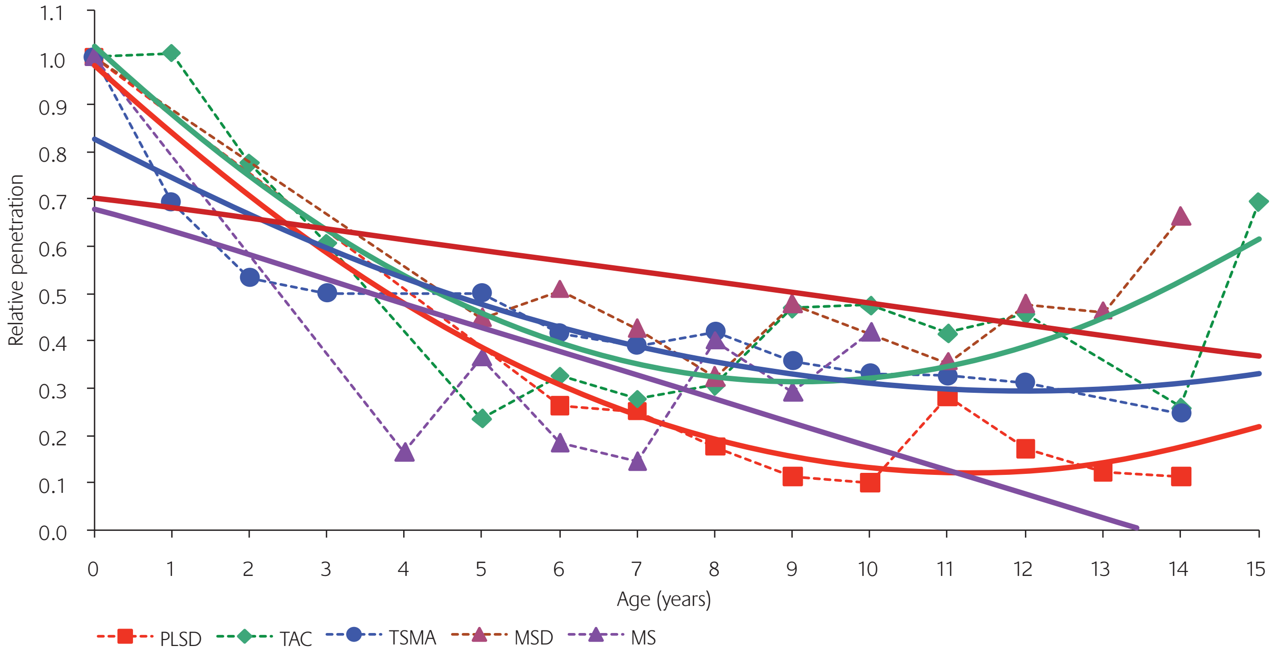

Figure O.3 Mean recovered penetration as a proportion of initial value with quadratic trend lines

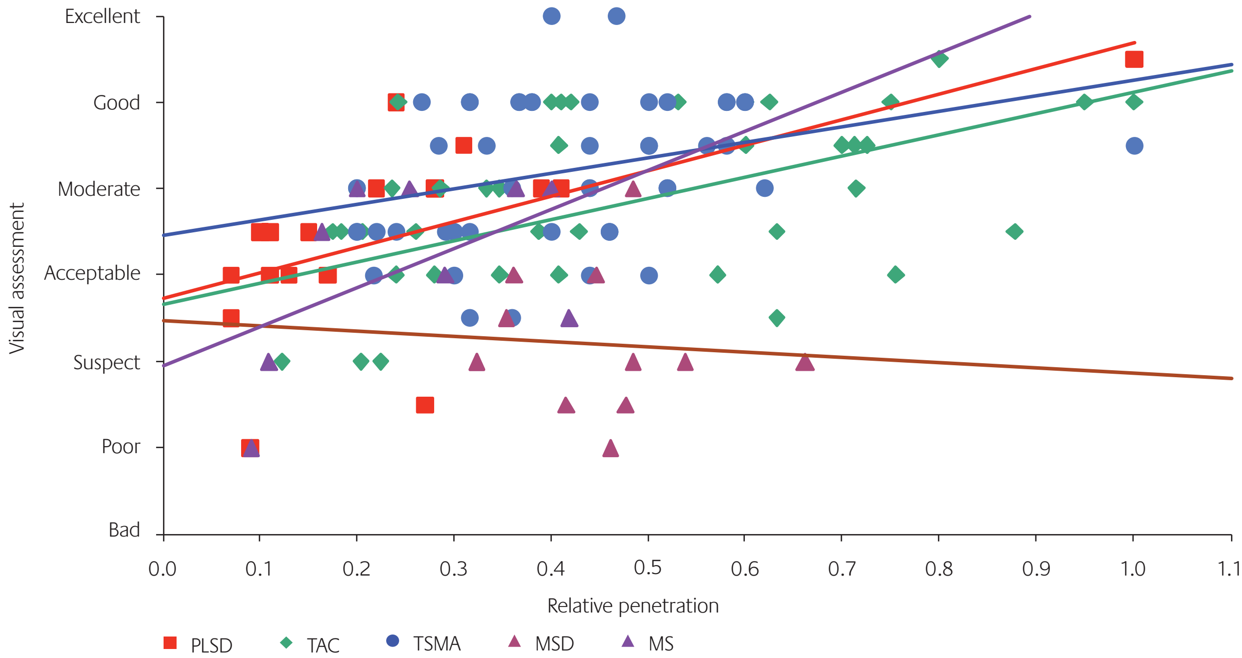

Figure O.4 Mean recovered penetration as a proportion of initial value against visual condition

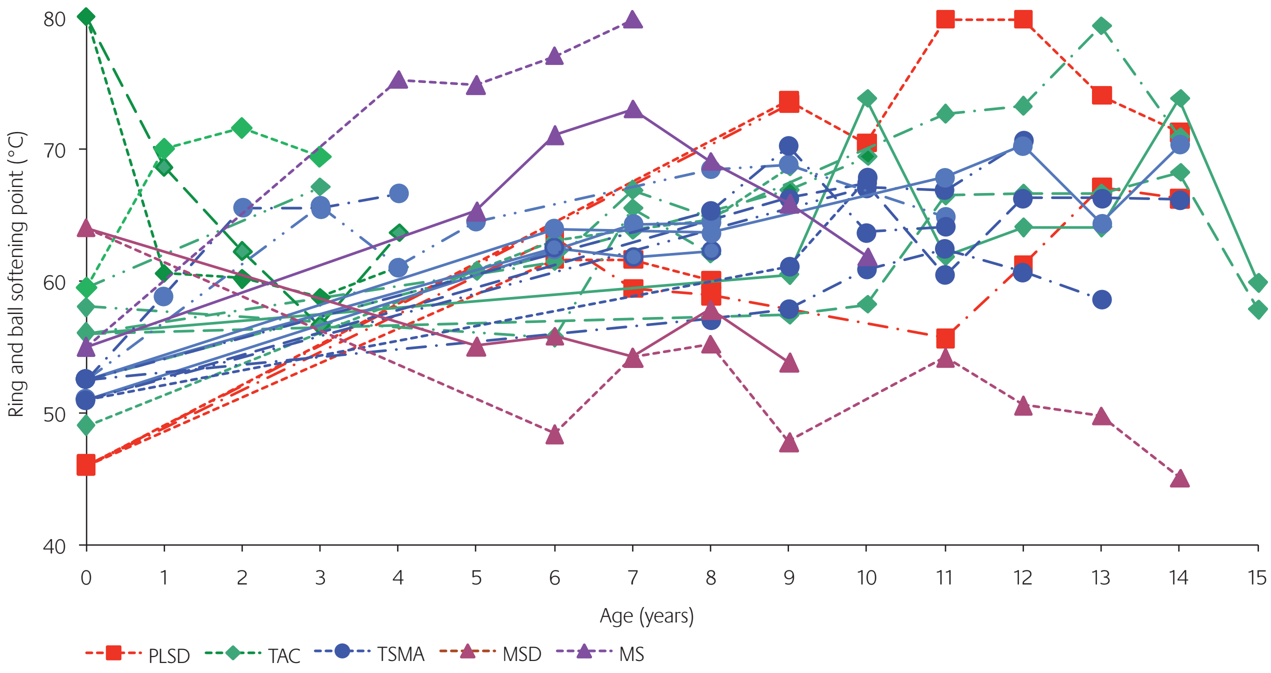

Figure O.5 Recovered softening point values for each site

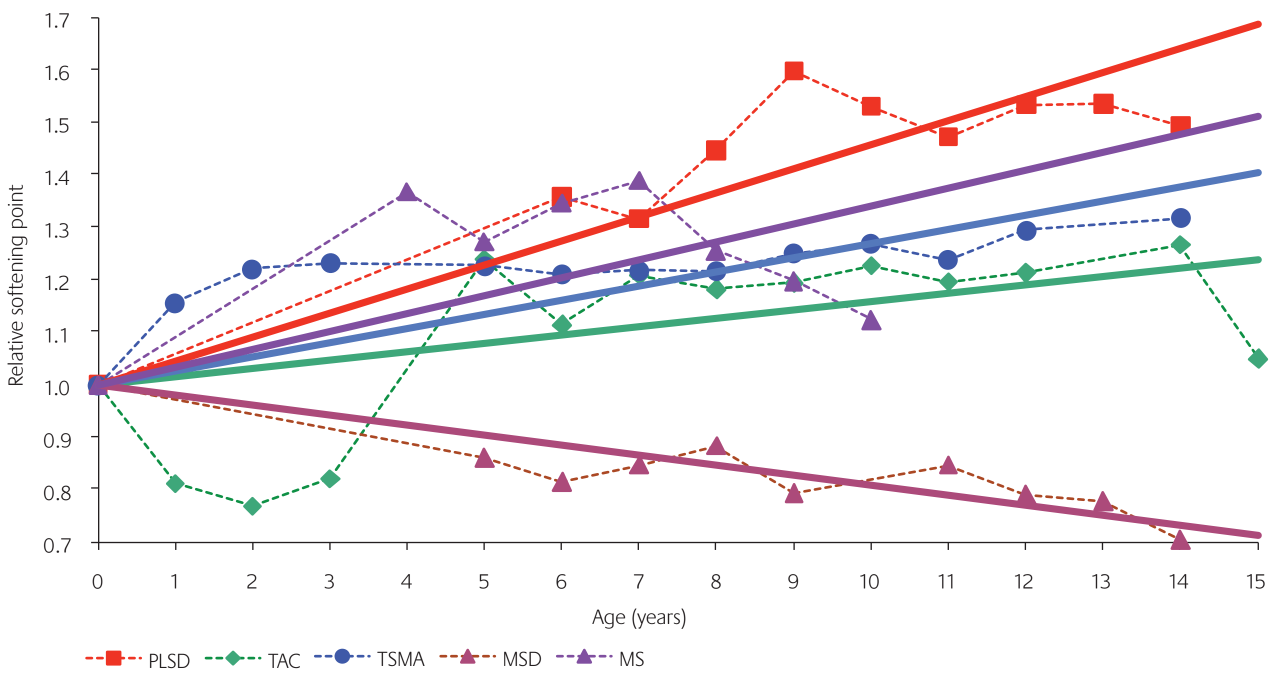

Figure O.6 Change in mean recovered softening point relative to initial value with time

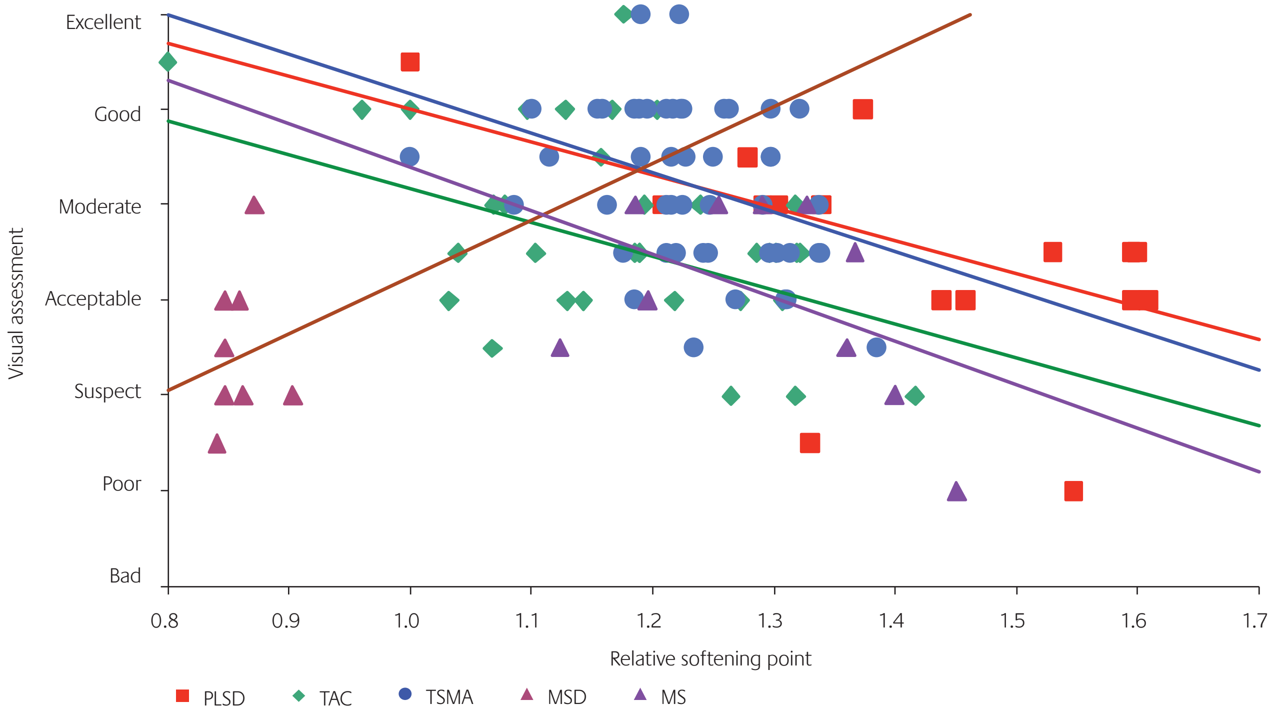

Figure O.7 Mean recovered softening point as a proportion of initial value against visual condition

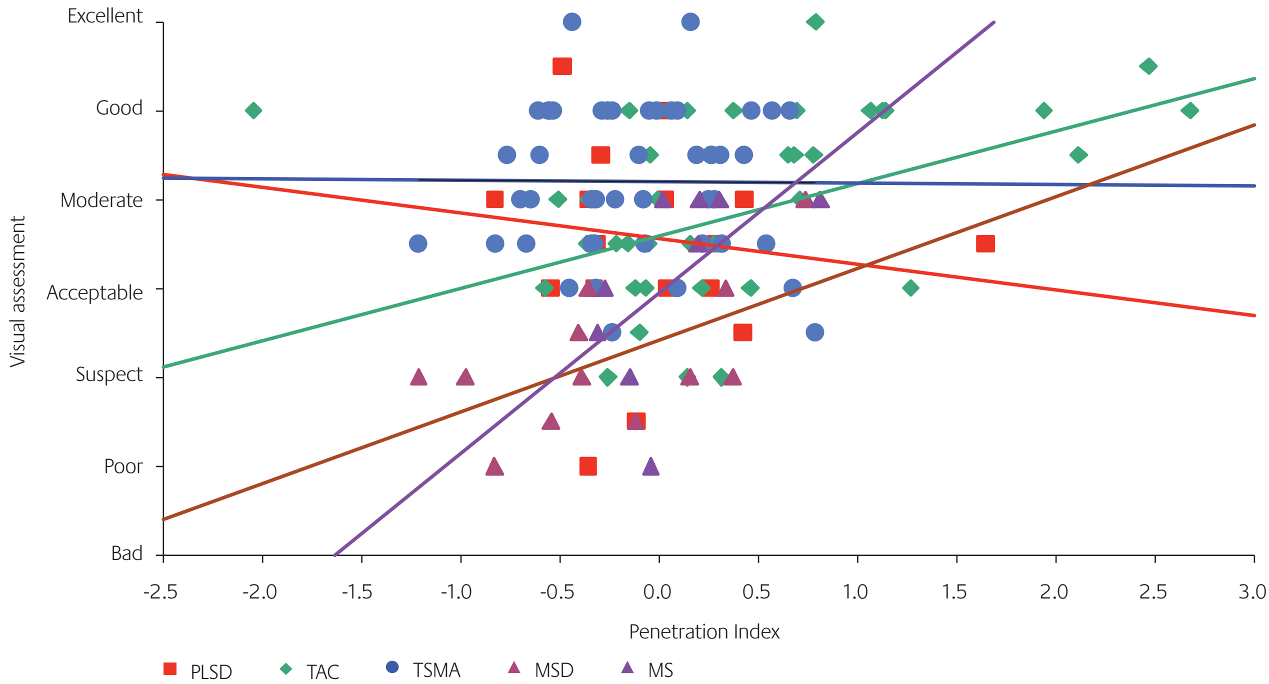

Figure O.8 Penetration Index against visual condition

Appendix P: Photographs of sites at different visual conditions

These photographs show snapshots of various sites that are, overall, at a particular visual condition. However, the markings will have been assessed on the whole site and not just on the area of the photographs alone.

P.1 Sites in *Excellent* condition

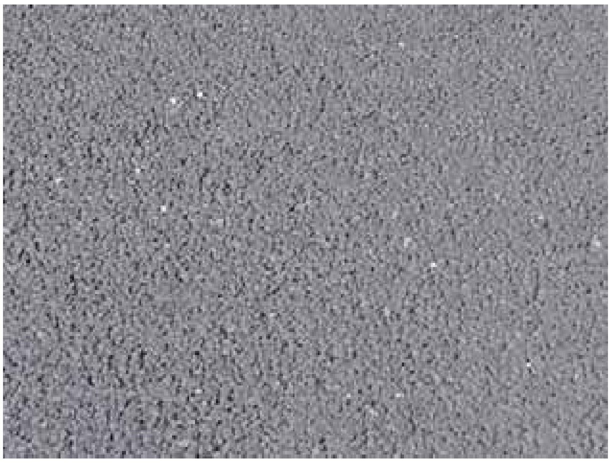

Figure P.1 TAC27 at *E* in 2006

Figure P.2 TAC40 at *E* in 2007

Figure P.3 TAC43 at *E* in 2008

Figure P.4 TSMA29 at *E* in 2007

P.2 Sites in *Good* condition

Figure P.5 PLSD16 at *G* in 2008

Figure P.6 TAC9 at *G* in 2003

Figure P.7 TAC41 at *G* in 2009

Figure P.8 TSMA28 at *G* in 2009

Figure P.9 TSMA33 at *G* in 2009

Figure P.10 MSD5 at *G* in 2008

P.3 Sites in *Moderate* condition

Figure P.11 TAC9 at $M_{-,\,v}$ in 2009

Figure P.12 TAC19 at $M_{-,\,c}$ in 2007

Figure P.13 TSMA31 at $M_{-,\,c}$ in 2009

Figure P.14 TSMA34 at $M_{-,\,c,\,v}$ in 2007

Figure P.15 MSD6 at $M_{-,\,c}$ in 2009

Figure P.16 MS1 at $M_{-,\,d}$ in 2007

P.4 Sites in *Acceptable* condition

Figure P.17 PLSD15 at $A_{-,c,t}$ in 2007

Figure P.18 TAC12 at $A_{-,c}$ in 2007

Figure P.19 TAC23 at A_{-} in 2008

Figure P.20 TSMA11 at $A_{-,c,v}$ in 2009

Figure P.21 TSMA13 at $A_{-,c}$ in 2008

Figure P.22 MSD1 at $A_{+,v}$ in 2002

P.5 Sites in *Suspect* condition

Figure P.23 PLSD14 at $S_{-,c,v}$ in 2009

Figure P.24 TAC2 at $S_{-,c}$ in 2007 (A_{-} excluding effect of joints)

Figure P.25 TAC17 at $S_{-,c,d,v}$ in 2005

Figure P.26 TSMA3 at $S_{-,c,v}$ in 2008

Figure P.27 TSMA18 at $S_{-,c,v}$ in 2007

Figure P.28 MS3 at $S_{-,d}$ in 2006

P.6 Sites in *Poor* condition

Figure P.29 PLSD15 at $P_{-,c,d,t}$ in 2008

Figure P.30 TAC14 at $P_{-,d,v}$ in 2007

Figure P.31 MS3 at $P_{-,d,s,t,v}$ in 2007

Durability of thin asphalt surfacing systems. Part 4: Final report after nine years' monitoring

Thin surfacing systems, as the term is currently understood, were introduced into the UK in 1991. Many sites with thin surfacing systems have reached or are approaching the end of their assumed lives so that a review of the service that can be expected from such surfacings can now be made with some confidence. The information collected from a selection of sites with thin surfacing systems has been evaluated in order to establish this understanding of their serviceable life. In this TRL Report, the results from visual condition, SCRIMtex and recovered binder properties are given for sites monitored over the last three years of this nine-year review (begun in 2001) together with analysis of these data and the results from preceding years on a total of 137 sites. The findings, now extended by a further three years' monitoring since the last published report, indicate that, if a thin surfacing system is in a good condition after its first year in service, it will be serviceable for at least five years and the typical life of a thin surfacing system is about ten years, depending on the type of thin surfacing system and the condition of the substrate. The estimated lives of the most commonly used systems (10 mm and 14 mm thin asphalt concrete and thin stone mastic asphalt systems), however, are all over 12 years.

Related publications

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