TRANSPORT RESEARCH LABORATORY

Alternative textures for concrete roads: results of M18 and A50 trials

Prepared for QS (CE) Pavement Engineering Group, Highways Agency

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Executive Summary

In recent years, concrete road surfaces have gained a reputation for being noisier than bituminous road surfaces. This Report gives the results of performance trials of a type of concrete road surface material which is produced with a randomised surface texture pattern similar to that occurring on conventional bituminous surfaces such as Hot Rolled Asphalt (HRA). The surfacing is known as Exposed Aggregate Concrete (EAC). Previous studies in Belgium and Austria, where there had been experience of the EAC surface over a number of years, had indicated that lower noise levels were achievable when compared with other types of concrete surfacing.

The first of two trials of EAC to be built in the UK took place between August and December 1993 during the reconstruction of the M18 motorway between Junctions 5 and 6 near Thorne in South Yorkshire. In addition to the exposed aggregate surfacing, the M18 trial also included a concrete surfacing constructed using an American practice of using a burlap drag followed by transverse tining to texture the surface. Conventional brushed concrete and HRA surfacings were also laid as part of this trial. The second trial took place on the A50 Hatton-Foston-Hilton Bypass in Derbyshire. This trial consisted of an EAC surface and HRA only. The A50 surfaces were opened to traffic in May, 1995.

The main objective of the research described in this Report was to compare the suitability of the materials and acoustic performance of the different concrete and bituminous surfaces laid on the M18 and A50. This was to help identify a type of surface texture for concrete roads that provides adequate levels of skid resistance, both at high and low speeds, without causing the higher noise levels that had been observed alongside some brushed concrete surfacings. The duration of the study encompassed the first 32 months of exposure to traffic on the M18 and the first 16 months of exposure to traffic on the A50.

It was found that over the duration of the trial, the low-speed skidding resistance of all the trial surfaces was in excess of the levels set down in the Design Manual for Roads and Bridges. After 32 months trafficking on the M18, the trial surfaces were all producing similar levels of Sideways Force Coefficient (SFC) except for the brushed concrete surface where the SFC was lower than that measured on the other trial surfaces. On the A50, the EAC and HRA surfaces were both producing consistently different but acceptable levels of SFC, with the HRA surface giving higher values than the EAC surface.

Measurements of high speed skidding resistance were carried out using the Brake Force trailer. However, the results obtained were not found to be consistent with earlier work. This was attributed to differences in the design and operation of the trailer and to differences in the mechanical properties of the test wheel. For these reasons, the absolute measurements of Brake Force Coefficient (BFC) taken on each surface were not considered to be reliable although differences in BFC between the surfaces was considered to be of value. It was found that the values of ΔBFC were very similar for the EAC and HRA surfaces laid on the M18. On the A50 the values of ΔBFC were substantially higher for EAC surface than for the HRA surface.

The results of vehicle noise measurements showed that the average maximum noise levels generated by vehicles travelling on the EAC surface were, on average, lower than the corresponding levels measured alongside adjacent sections of HRA. The average difference in noise for the two surface types was 2.2 dB(A) for light vehicles and 1.1 dB(A) for heavy vehicles[1]. These differences were found to be statistically significant at the 0.1% level.

For the M18 trial it was found that noise levels taken alongside sections of EAC and HRA at the two road sites had remained fairly constant with noise levels not varying by more than 0.8 dB(A) over the 32 months of the trial. On the A50 variation in the noise levels of the EAC and HRA was found to be slightly greater (1.3 dB(A)) over 16 months of trafficking. However, it is possible that some of this variation could be attributed to the effect of temperature on vehicle noise levels.

For traffic conditions typical of high speed roads, estimates of the differences in traffic noise levels between the different surface types showed that noise levels for the brushed concrete surface were, on average, 1.5 dB(A) higher than for the HRA surface and that the tined and exposed aggregate concrete surfaces were 1.0 and 1.5 dB(A) lower than the HRA surface, respectively[2].

A detailed analysis of surface texture influences on noise generation indicated that the acoustic performance of different surfaces could be accounted for by differences in the amplitudes of surface texture wavelengths. In addition, it was found that noise levels were relatively poorly correlated with measures of the surface texture depth as determined from sand-patch texture depth measurements (SPTD). The results clearly indicate that the monitoring of the amplitudes of texture wavelengths of road surfaces will provide a better indicator of vehicle noise levels than traditional measures based on sand-patch measurements. However, it will be necessary for a technique of monitoring texture profiles routinely to be developed before such a change could be introduced.

This project has shown that the way forward in controlling tyre/surface noise lies in reducing the amplitude of megatexture. Because of the correlation of macrotexture and megatexture[3] for randomly textured surfaces, the need to retain a minimum level of macrotexture to provide skidding resistance may place limitations on what can be achieved. But macrotexture also provides paths under the tyre allowing trapped air pressures and associated air pumping noise to dissipate. This effect is particularly important for transversely textured surfaces for which the overall noise level is reduced by increasing the macrotexture independently of the effect of lowering the megatexture amplitude. Further research into the design of road surfaces is needed to investigate whether the link between macrotexture and megatexture for randomly textured surfaces can be broken.

In summary the main findings of this study were:

- That all the surfaces appeared to perform well in terms of skidding resistance throughout the trial although the lack of consistent results from the high speed BFC trailer means that there remains uncertainty over the absolute values of the high speed skidding performance of the surfaces examined. Further work is in hand to provide this data.
- In terms of noise performance, it is clear that the EAC surfacing studied at the two sites gave noise levels which, over the course of the trial, were significantly lower than the corresponding noise levels from vehicles running over the HRA and brushed concrete surfaces.

1 Introduction

Concrete road surfaces have gained a reputation for being noisier than bituminous road surfaces. In recent years, some concrete pavements have been constructed which have been provided with an excessive amount of texture during the application of the traditional brushed finish which was believed to be the cause of the high levels of tyre/road noise.

In an effort to overcome this problem, research into quieter road surfaces including trials of exposed aggregate concrete (EAC) surfaces was commissioned. This type of surfacing had been used in a number of other European countries.

Two trials of exposed aggregate concrete have been constructed. The first, on the M18, was completed in winter 1993. Also investigated in this trial was an American practice of using a burlap drag followed by transverse tining to texture the surface. These alternative types of texture were compared with control sections of conventional brushed concrete and HRA. The second trial of exposed aggregate concrete and HRA, on the A50, was opened to traffic in spring 1995. The main objective of the trials was to identify a type of concrete road surface that satisfies the surface performance and safety standards required by the Department of the Environment, Transport and the Regions (DETR), without causing unacceptable noise levels.

This Report presents the results of measurements available at the end of 1996 to assess the surface properties related to safety and the results of vehicle noise measurements recorded at the roadside. It also reviews the durability of the trial surfaces to date. To assist in understanding some of the terminology used in the Report a glossary of terms is included in Appendix A.

2 Construction of the trials

2.1 Background

The overall aim of the research is to identify a type of surface texture for concrete roads that provides adequate levels of skid resistance, both at high and low speeds, as well as a low level of surface noise and at the same time being durable.

Valuable insight into the factors controlling the generation of road surface noise has been provided by the work of Sandberg and Descornet (1980) as well as the work within the scope of the Technical Committee on Surface Characteristics of the World Road Association (PIARC, 1987). This work has identified the respective role of three scales of irregularities known as microtexture, macrotexture and megatexture in relation to tyre/road noise. These three categories of texture are defined by the wavelength (λ) of the irregularities as:

microtexture	$\lambda < 0.5$mm,
macrotexture	$0.5\text{mm} < \lambda < 50$mm, and
megatexture	$50\text{mm} < \lambda < 500$mm

See Appendix A for further clarification.

One disadvantage of the transverse brushed texture traditionally used for concrete surfaced roads in the UK is that it is difficult to control the amount of texture as well as the profile of the texture.

Several other European countries are developing strategies to produce low-noise road surfaces, each tailored to local circumstances and constraints. Some have adopted the use of small-sized coarse aggregate in the surface, as recommended by Sandberg (1992). This is designed to produce a surface with high macrotexture and low megatexture which are reported to be associated with lower levels of tyre/road noise.

In the UK, there is a need to make economic use of high polish resistant aggregate and also to utilise the abundance of aggregate which, although unsuitable for exposure in road surfaces, is highly suitable for making good-quality concrete. The technique of creating a two layer construction with an exposed aggregate finish, developed in Austria by Sommer (1992), in which the road slab comprises a thin top layer of concrete made with the more expensive, high polish-resistant aggregate and the bottom of the slab made with cheaper aggregate is seen, therefore, as an attractive proposition.

2.2 Specification of trial sections

On both the M18 and the A50, the EAC was laid as the upper layer of a continuously reinforced concrete pavement (CRCP) constructed in two layers. The lower layer of concrete was required to comply with the Specification for Highway Works (SHW) (DOT et al, 1991a) in all respects except that the nominal size of the coarse aggregate was not to exceed 20mm. The proportions of the concrete used in the lower layer are given in Table 1. The upper layer of concrete, 40mm thick, was a specially designed, air-entrained concrete mix.

Table 1 Mix proportions of concretes (Weights of aggregate in Saturated Surface Dry (SSD) condition)

Constituent	*Bottom layer*		*Top layer*		
	M18	*A50*	*M18 Brushed & tined*	*M18 Exposed aggre -gate*	*A50 Exposed aggre -gate*
Portland Cement (kg/m^3)	320	340	360	400	385
20mm Coarse aggregate (kg/m^3)	1061	917	1110	nil	nil
10mm Coarse aggregate (kg/m^3)	354	393	373	1313	1412
Medium sand (kg/m^3)	550	624	398	nil	nil
Fine sand (kg/m^3)	nil	nil	nil	477	398
Water (l/m^3)	144	165	139	160	145
Admixture (l/m^3)	0.95	nil	1.65	1.78	1.32

2.2.1 Exposed aggregate sections

The specification of the exposed aggregate mix required an aggregate with a Polished Stone Value of 65 on the M18 and 60 on the A50, because of a lower traffic flow. A maximum Flakiness Index of 25 per cent was specified for both sites. The coarse aggregate was required to be a 10 to 6mm crushed rock, graded so that the coarse material retained on the 10mm sieve did not exceed 3 per cent and the amount passing the 6mm sieve did not exceed 10 per cent. It was also specified that at least 60 per cent of this mix (total constituents excluding water) should consist of coarse aggregate.

The sand used in the exposed aggregate mix was to comply with Zone F of Table 5 in Clause 5.2 of BS 882 (British Standards Institution, 1983). Also, at least 99 per cent of the sand was required to pass the 2.36mm sieve. This is more stringent than the normal grading requirement for Table 5 in BS 882 because it was considered necessary to put an upper limit on the maximum sand particle size to ensure that the vehicle tyre ran on the coarse aggregate and not on the sand. A minimum cement content of 375kg/m^3 of Class 42.5N/42.5R Portland cement complying with BS12 (British Standards Institution, 1991) was specified together with a maximum water/cement ratio of 0.40.

The texture depth, to be determined by the sand-patch method in accordance with BS 598: Part 105 (British Standards Institution, 1990), was specified at 1.5mm ± 0.25mm, to give a level of texture typical of that normally required on HRA surfaces. (See also Section 2.2.3 below).

The coarse aggregate was a gritstone, supplied from the Ghyll Scaur quarry in Cumbria for the M18 and from the Ingleton quarry in Yorkshire for the A50. The mix proportions used for the exposed aggregate surfaces are given in Table 1.

The coarse aggregate used in the lower layer concrete on the M18 was a local limestone aggregate from the Stainton Quarry in South Yorkshire. In comparison, the coarse aggregate used for the lower layer on the A50 was a locally produced gravel aggregate.

2.2.2 Brushed and tined sections on the M18

The specification for these two surfaces required that the texture depth, again measured by the sand-patch method, but in this case according to Clause 1031 of the Specification for Highway Works (SHW) (DOT et al, 1991a), should, when the slab is constructed, be 1.0 ± 0.25mm for each 50m section of carriageway tested. This is the requirement currently specified in the SHW for concrete surfaced trunk roads and motorways in the UK. The upper limit was introduced in 1991 to prevent excessive texture which can lead to the generation of high levels of tyre/road noise. It should be noted that the Specification for Highway Works (Series 1000, Volume 1, DOT et al, 1991a) now specifies the use of a longitudinal oscillating float to finally regulate the surface of the pavement.

The tined surface was specified as a two-stage process. The first stage was a preconditioning of the surface, created by dragging a sheet of burlap over the slab in a longitudinal direction. The second stage was to draw a set of randomly spaced spring steel tines, 3mm wide by 0.8mm thick, transversely across the surface. The spacings that were specified were one third of those given for texturing hardened surfaces in Clause 1029 of the SHW. These had been chosen as suitable for achieving the required amount of texture as a result of site trials on the A5 at Shrewsbury.

The concrete was laid in two layers using the same mix for the bottom layer as in the bottom layer of the exposed aggregate sections. The mix proportions used for the upper layer in both the brushed and tined sections are given in Table 1.

2.2.3 Hot rolled asphalt sections

The HRA sections were required to have a texture depth in accordance with Series 900 of the SHW (DOT et al, 1991a). This specifies that “the average texture depth of each 1000m section of carriageway lane shall not be less that 1.5mm” and that “the average of each set of 10 individual measurements shall be not less than 1.2mm”. The texture depth was measured by the sand-patch method in accordance with BS 598: Part 105 (British Standards Institution, 1990).

2.3 Site locations

Figure 1 shows a plan of the M18 and the A50 indicating the location of the survey sites where noise and texture measurements were carried out.

The M18 trial site is situated between Junction 5 (with M180) and 6 near Thorne in South Yorkshire. The trial surfaces were constructed during major carriageway reconstruction on both the northbound and southbound carriageways. The northern end of the trial incorporated lengths of continuously reinforced concrete roadbase (CRCR) where the concrete textures were initially laid to assess the construction and texturing techniques prior to their use on the CRCP. The CRCR was then overlaid with 100mm of bituminous surfacing. The trial sections on the M18 form a 2.3km length of both carriageways of the motorway. The trial lengths on the A50 between Derby and Uttoxeter comprise a 3.65km length on both carriageways during the construction of the new Hatton - Foston - Hilton Bypass.

2.4 Construction techniques

The construction of the trial sections at both the M18 and the A50 sites was carried out by the same contractor using the same mixing and paving plant. In most of the significant operations in the construction process, the same procedures were adopted.

On the M18, the CRCP slabs were paved on top of a bituminous subbase. (The bituminous material was part of the original, fully flexible, pavement structure which was planed off to make way for the CRCP). In comparison, the CRCP on the A50 was paved on top of a lean concrete subbase.

The CRCP slabs were reinforced longitudinally with 16mm diameter steel bars laid at 125mm centres and placed mid-depth in the slabs. The transverse reinforcement consisted of 12mm diameter bars laid at 600mm centres. The transverse and longitudinal

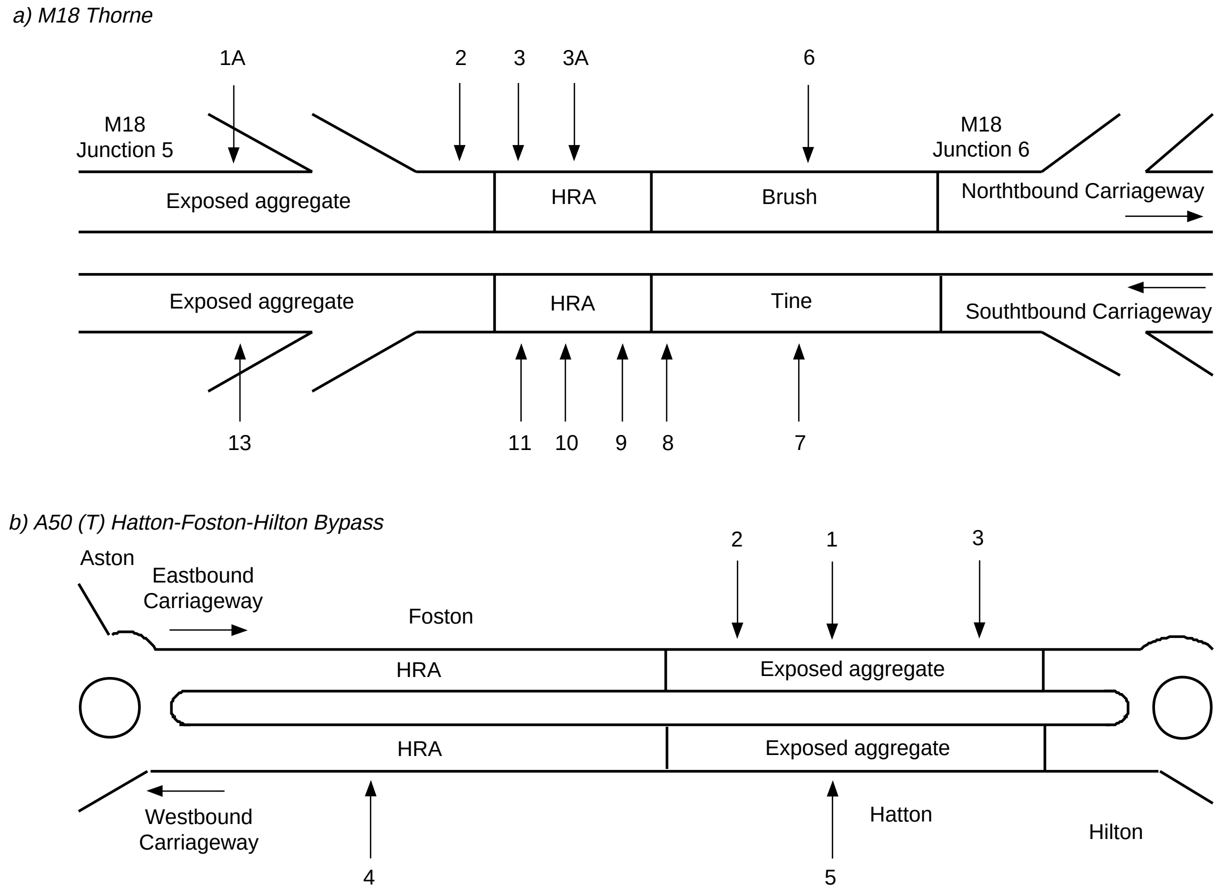

Figure 1 Schematic layout of site locations (site numbers are posted alongside the carriageway)

reinforcement bars were at 90° to one another on the M18, while on the A50 they were at 60° to each other. Anchorages were provided at the ends of each CRCP section in accordance with Volume 3 (Highway Construction Details) of the Manual of Contract Documents for Highway Works (DOT et al, 1991b). The total slab thickness of the CRCP was 250mm on the M18 and 260mm on the A50.

On both sites the concrete was produced by an on-site, Steelfields Major 75 batching plant rated at 75m^3 per hour, and delivered by side-tipping lorries to the paving train. The contractor chose to use a fixed-form paver with rail-mounted equipment. The paving train consisted of a placer for the lower layer of concrete, followed by a compactor/ finisher. As soon as the lower layer had been completed, a second placer deposited the upper layer concrete, followed by a compacting beam/conforming plate and was evenly levelled by an oscillating beam.

Finally, the surface of the second layer was smoothed by a Gomaco longitudinal finisher (known in Europe as a super-smoother) which oscillates in the longitudinal direction while tracking transversely across the surface of the fresh concrete. The purpose of this piece of equipment is to remove surface irregularities in the megatexture range. (NB. It is thought that some texture wavelengths in the megatexture range are responsible for high levels of tyre/surface noise (Sandberg and Descornet, 1980). The influence of surface texture on noise levels is discussed later in the Report). The construction of the CRCP on the M18 was the first contract on which the use of a super-smoother had been specified in the UK for the regulation of the concrete surface.

2.4.1 Exposed aggregate surface

After the final pass of the super-smoother, a sugar-based retarder was sprayed onto the fresh concrete surface. The retarder, which had been coloured green to aid visual checking that a uniform application was achieved, was applied via pressurised sprays mounted transversely on a separate gantry some distance behind the paving train. Hand-held spraying equipment was also available to correct any areas inadequately covered by the main spray bar. Plate 1 illustrates the application of the retarder.

The specification required that the freshly retarded surface be covered with polythene sheeting as soon as possible. This helped to protect the fresh concrete from moisture loss, rainfall, and also reduced the rate at which the retarder evaporated, enabling it to be effective for a longer period. The polythene sheet was pressed down onto the concrete by a sheet of wet hessian (Plate 2) and weighted at the edges to prevent wind getting under the polythene and evaporating the retarder. On the M18, the contractor chose to use clear polythene while on the A50, black polythene was used to cover the fresh surface and hence the contractor could not detect when the retarder had not adequately covered the slab.

It was specified in the contract that removal of the

Plate 1 Application of the retarder to the fresh concrete surface

Plate 2 Application of polythene sheet (after retarder has been applied)

polythene followed by the brushing of the surface should take place after at least 24 hours but not more than 48 hours after concreting. As a result of experience on site, however, the contractor was given permission to brush after only 12 hours in hot weather. During cold weather, it was often necessary to wait for up to 30 hours before the surface was ready to be brushed. If the surface was brushed too soon, coarse aggregate would be dislodged from the surface.

The brushing process was carried out using a rail-mounted rotary brush with wire bristles. The brush moved transversely across the slab rotating on an axis that was aligned at slightly more than 90^{o} to the direction of travel. Plate 3 illustrates the action of the brush. Generally it took about 4 passes of the brush to remove enough mortar to comply with the texture depth requirements.

Plate 3 Action of the brush used to expose the surface of the concrete

Once the required texture depth had been achieved on the exposed aggregate surface, an aluminised curing compound was sprayed onto the finished pavement surface. The pavement could then be open to site traffic after 2 or 3 days, although experience has shown that early use of the exposed aggregate surface by construction traffic is liable to lead to loss of aggregate from the surface. An example of a finished exposed aggregate surface is shown in Plate 4.

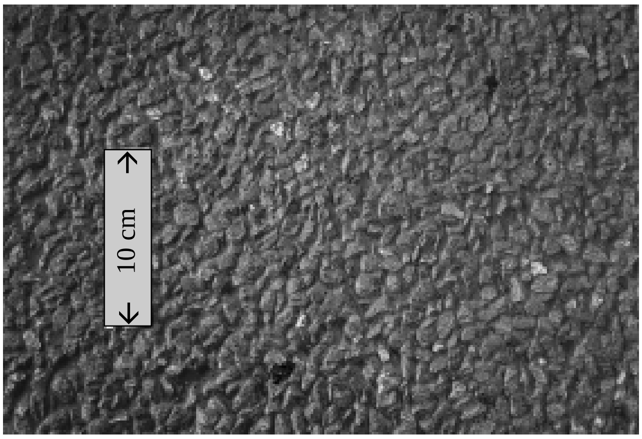

Plate 4 Exposed aggregate surface

2.4.2 Brushed and tined surfaces on the M18

The fresh concrete surface was textured by a single, transverse pass of a brush consisting of wire bristles mounted on a 1m wide head in accordance with clause 1026 of the SHW. The brushing equipment was rail-mounted, and formed part of the paving train. Consistent concrete was required to ensure that this operation was concluded satisfactorily. An example of the finished surface is shown in Plate 5.

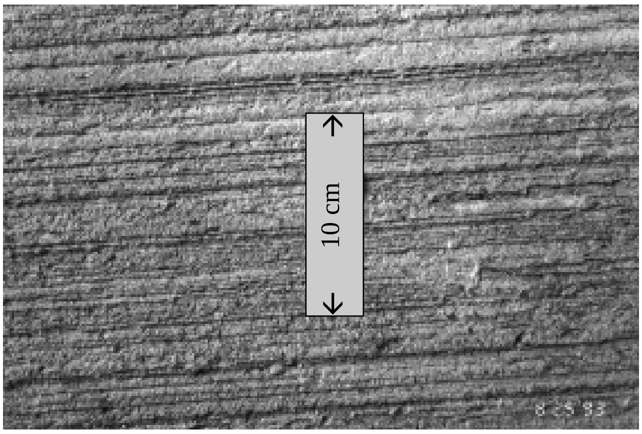

Plate 5 Brushed surface

The tined texture (Plate 6) was produced using the same rail-mounted equipment that applied the brushed texture but with the brush head replaced by a head carrying the steel tines at the spacings described above in section 2.2.2 of this report.

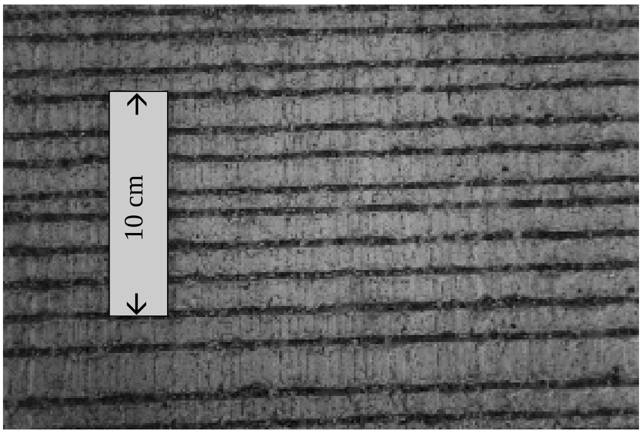

Plate 6 Tined surface

2.5 Lessons learnt during construction

It was found that, to construct each of the three concrete textures successfully, a steady supply of consistent concrete to the paving machine was necessary. The texture depth obtained also generally depended upon the vigilance of the operator controlling the texturing equipment.

The following discussion examines various points that have some influence over the finished exposed aggregate surface. Many of the points arise from observations made during the paving.

2.5.1 Materials

One of the aggregate requirements was for the Flakiness Index to be no more than 25 per cent. This was specified in order to ensure a suitably cubical shape to give sufficient embedment in the surface to overcome the risk of aggregate being dislodged during brushing. The Ghyll Scaur quarry was able to supply aggregate for the M18 with a flakiness of around 25 per cent, but there were still some occasions when flat or flaky particles were lost from the surface. The aggregate supplied from the Ingleton quarry had a lower Flakiness Index, of 12-15 per cent. The more cubical shape of the latter material used on the A50 was judged to give a better overall finish and thought to provide lower noise levels.

On the M18, the aggregate stockpiles on site were not always adequate to ensure a continuous supply of concrete to the paver. Consequently, at times, the progress of the paving train was erratic. However, due to better control of supplies of aggregate on the A50 this problem did not arise.

2.5.2 Construction plant

On the M18, there were some areas, mainly on the northbound carriageway, where the exposed aggregate surface contained some of the limestone aggregate used for the bottom layer concrete. This problem was greatly reduced on the A50 where lorries delivering concrete to the paver were dedicated specifically to one or other of the concrete layers.

On the M18, the super-smoother appeared to successfully achieve the task of smoothing out any striations left by the paver. However, in a few places on the A50 a ridge of mortar, running diagonally across the full-width of the carriageway, was still visible after the brushing had been completed. This effect is shown in Plate 7. It should be noted that these ridges were relatively few on the A50 and were not a feature of the M18 exposed aggregate concrete surface. This slight difference in the quality of the surfaces may have been a result of the super-smoother being used differently between sites.

Plate 7 Diagonal ridges on road surface left by super-smoother

2.5.3 Texturing

During the construction of both trials, the rate of spread of the retarder appeared to be inconsistent. The low viscosity of the retarder was such that ponding occurred in unwanted surface depressions on the slab. Although the effect of this on the retarding process was not clear, it was felt that the addition of a gelling agent to the retarder would help prevent ponding and thereby minimise the risk of inconsistencies occurring.

The trials demonstrated the importance of keeping the polythene sheeting in close contact with the pavement surface and well weighted down at the sides. Creases in the polythene tended to cause the fluid retarder to be drawn into the area of the crease and hence lead to a variable rate of coverage, possibly leading to variable texture depth results.

It was found to be important to remove the polythene over short lengths at a time prior to brushing so that the surface remained damp during the brushing operation. This also helped to keep the generation of dust to a minimum.

The skill and judgement of the brush operator was found to be crucial in deciding when the surface was ready to be brushed. In warm settled weather, it was possible to start brushing within 12 hours after paving. In contrast, when the air temperature was about 8°C, brushing was often not started until 24 to 30 hours after paving. During wet and variable weather conditions, it was very difficult to judge when to remove the polythene cover. Consequently, areas produced during poor weather conditions were found to have more variable texture.

It was also found to be important for the texture depth to be monitored regularly during exposure of the surface in order to achieve the specified texture depth. It was also apparent that a single transverse brush limited the daily output of the concrete paving train. Having a second brush for exposing the surface would have increased the rate of progress. Furthermore, on the A50, the method of operating the brush repeatedly across the same area of surface produced transverse markings or stripes that are visually apparent to drivers using the surface (Plate 8). Longitudinal brushing is now a requirement of the specification.

Plate 8 Transverse stripes across the road as a result of brushing the exposed aggregate surface

In some areas, where surface mortar was not adequately removed by the brushing operation, grit blasting of the surface when it was one or two days old proved to be an effective, if laborious, method of obtaining the specified texture depth.

2.5.4 Repairs and maintenance

On the A50 trial site, limited experience of repairing the exposed aggregate concrete surfacing was obtained. Two areas of surface had to be repaired. The first area was approximately 100mm wide and several hundred metres long and was caused by a retarder jet becoming blocked resulting in the surface being damaged. The second area of surface, approximately 100m long by 1m wide, had to be repaired due to imprints being made in the surface while it was still fresh. The contractor first defined the area of surface to be removed by making a shallow cut with a diamond saw. This ensured that the edges of the repair were clean and unbroken. The surface was then removed to the full (40mm) depth of the exposed aggregate within the defined area. The edges were treated with a bonding agent, and then the repair area was filled with concrete (supplied by the on-site mixing plant) of identical properties to that of the original mix. The fresh concrete was compacted using a vibrating poker. Retarder was applied to the fresh surface, which was then covered with polythene and left for 24 hours. The retarded surface was then exposed by hand-brushing and water-jets.

Several smaller patches of surface were repaired in the same way elsewhere on the A50, but these were found to be more difficult to repair successfully as the larger patch detailed above. Quality of workmanship and level of supervision were thought to be significant factors contributing to the success of this repair technique. It should be noted that these repairs were carried out to the road before it was opened to traffic and are performing satisfactorily.

In the future, when it is necessary to restore skid resistance, retexturing of the aggregate exposed at the surface could be considered. This could be done using a technique such as grit blasting or water jetting where the microtexture of the exposed aggregate is rejuvenated. Another alternative to this could be to apply an exposed aggregate concrete overlay or a thin surfacing to the worn surface.

2.5.5 Durability

The M18 has been weathered over four winters, during which time it has been exposed to frequent de-icing regimes. During the winter of 1995/96, snowploughs were called out to clear the motorway on several occasions. Despite this, there was very little deterioration of the road surface either at the cracks or in general. In addition, there was very little evidence of chipping loss at the cracks or elsewhere.

The A50 has been weathered over three winters (1994/95, 1995/96 and 1996/97), although it has only been open to traffic during the two most recent winters. The road shows some evidence of chipping loss at several cracks. However, it is possible that this is due to spalling of the cracks, which has been observed elsewhere on CRCP pavements. In addition to this, on the westbound carriageway there are two or three small patches (approximately 80mm x 250mm) where there is extensive chipping loss. Another observation that has been made on the A50 is that placing drainage gullies in the exposed aggregate surfaced carriageways has initiated cracks in the pavement that are visible on the road surface. Other than this, the exposed aggregate surface appeared to be in good condition at the end of the trial period covered by this Report.

3 Performance testing of trial surfaces

Although the prime objective of the trial was to identify a concrete road surface with more acceptable noise characteristics than the traditional brushed finish, (and at the same time durable), it is also required that any new surface satisfies all the performance and safety standards required by the Highways Agency (HA).

Apart from surface regularity, the relevant surface requirements are those that affect the resistance to skidding.

Early work at the TRL, summarised by Salt (1977), established that low-speed skid resistance is dependent on the microtexture in the surface but, in order to maintain a given level of skid resistance as speed increases, macrotexture must also be built into the road surface. The effectiveness of new forms of macrotexture therefore should be assessed by measuring the change in skidding resistance with speed.

A number of test lengths were selected on each of the three types of concrete surface and on the HRA surfaces which were suitable for carrying out both noise and skid resistance testing. The results of the various tests to measure the texture and skidding resistance are discussed below.

3.1 Texture

3.1.1 Sand-patch texture depth

The sand-patch test method was used for all compliance testing carried out on the A50 and M18 sites by the Engineer in accordance with the SHW (DOT et al, 1991a). This required testing to be carried out at 5m intervals over a 50m diagonal across one lane width. TRL also carried out localised sand-patch tests over lengths of 10m and 50m in the nearside wheel-track of the nearside lane at the locations chosen for noise measurements. The approximate positions of the noise measurement positions are shown in the plans in Figure 1. The 10m lengths were measured by carrying out sand-patch tests at 2.5m intervals centred on the cross section of the carriageway where noise measurements were taken. The 50m lengths were measured by taking sand-patch measurements either side of the 10m length for a further 20m at 5m intervals. The results of all sets of measurements taken to date are summarised in Table 2.

On the M18, the 50m values for the random textures (HRA and exposed aggregate surfaces) have increased over the 32 month period. This could have been due to the general cleaning effect of the traffic on the surface helping to remove detritus. In comparison, the two transversely textured surfaces (brushed and tined) have shown an overall reduction in texture depth over 32 months in relation to the initial values recorded on the road. This was probably caused by the more friable upstanding ridges wearing under traffic. The 10m values for the randomly textured surfaces (ie. HRA and EAC) have increased over the 32 month period. However, the most recent survey shows that the texture depth has reduced slightly in comparison with previous surveys. The 10m values for the transversely textured surfaces have also reduced over the 32 months since the road was open to traffic. However, it

Table 2 Results of sand-patch tests

		M18								*A50*						
		50m length				*10m length*					*50m length*			*10m length*		
Type of surface	*Site no.*	*Initial*	*After 8 months*	*After 20 months*	*After 32 months*	*Initial*	*After 8 months*	*After 20 months*	*After 32 months*	*Site no.*	*Intial*	*After 2 months*	*After 16 months*	*Initial*	*After 2 months*	*After 16 months*
HRA	3	1.19	1.68	-	-	1.10	1.83	-	-	4	1.40*	1.90	1.86	-	1.72	1.68
	3A	-	2.03	2.01	+	-	2.49	2.49	2.23							
	4	1.63	-	-	-	1.63	-	-	-							
	9	1.82	-	-	-	-	-	-	-							
	10	1.80*	2.33	2.33	2.32	-	2.22	2.22	2.06							
	11	1.87	-	-	-	-	1.78	-	-							
	Average	1.66	2.01	2.17	2.32	1.37	2.08	2.36	2.15		1.40	1.90	1.86		1.72	1.68
Exposed aggregate	1A	1.47	1.34	1.27	+	1.28	1.41	1.50	1.26	1	1.40*	2.10	2.06	-	2.22	2.15
	2	(0.74)	-	-	-	0.91	-	-	-	2	1.31*	1.72	1.56	-	1.65	1.60
	12	1.41	-	-	-	0.90	-	-	-	3	1.50*	1.78	1.84	-	1.72	1.84
	13	1.35	1.26	1.28	1.39	1.19	1.36	1.39	1.32	5	1.43*	1.72	1.67	-	1.81	1.75
	Average	1.24	1.30	1.28	1.39	1.07	1.39	1.45	1.29		1.41	1.83	1.78	-	1.85	1.84
Brushed	5	0.97	-	-	-	0.97	-	-	-							
	6	1.15	0.82	0.86	0.95	1.00	1.02	0.93	0.99							
	Average	1.06	0.82	0.86	0.95	0.99	1.02	0.93	0.99							
Tined	7	0.89	0.59	0.65	0.79	0.67	0.60	0.73	0.79							
	8	1.19	-	-	-	0.87	-	-	-							
	Average	1.04	0.59	0.65	0.79	0.77	0.60	0.73	0.79							

** Denotes average value taken over 50m diagonal, supplied by Engineer*
+ Denotes positions where measurements could not be made due to poor weather
Value in brackets denotes site that was later retextured

should be noted that the most recent survey shows the texture depths to be approaching the initial values originally measured. This could be a result of small areas of the transverse texture breaking off, resulting in an overall increase in the texture depth of the surface.

On the A50, the initial 50m values on the exposed aggregate surface were measured by the Engineer on 50m diagonal lines of the carriageway (as required by the SHW). All complied with the specification. However, half of the 50m and 10m values measured by TRL after 2 months exceeded the specification. These values were for research purposes only, not contractual compliance, and in order to relate to noise and skidding, measurements were concentrated in the nearside wheel-track of the nearside lane. After 16 months from opening, both the 50m and 10m texture depths on the exposed aggregate concrete surface have reduced slightly in comparison with the values recorded at 2 months. This is probably due to the general cleaning effect of the traffic on the surface.

3.1.2 Sensor Measured Texture Depth

The High Speed Texture Meter (HSTM) consists of a vehicle-mounted, contactless laser sensor and processing unit which continuously measures the distance between the sensor and the road surface (Roe, 1993). The average texture depth in the nearside wheel-track for each 10m travelled is computed and the result, known as the Sensor Measured Texture Depth (SMTD), is recorded onto cassette tape.

The HSTM measures the surface texture along a longitudinal path, whereas the sand-patch test is influenced also by texture with a transverse component. Consequently the two parameters are not consistently related.

HSTM measurements were taken on the M18 three times during the summer months in 1994 and the average values of Sensor Measured Texture Depth (SMTD) for 50m lengths covering the full length of each surface type on the northbound and southbound carriageways are given in Figures 2 and 3 respectively. It is not meaningful to compare the absolute values of SMTD's either between surface types or with the specified limit values for each surface because the relations between SMTD's and sand-patch texture depths are known to be different for different surface types. However, the results are useful in showing the variability in texture within the various sections and can be used as a basis for monitoring changes of surface texture with time. It can be seen from the data that the textures obtained on the southbound section of exposed aggregate concrete, which was constructed after the northbound section, had a much more consistent level of texture indicating, as has been found elsewhere, that the quality of the process had improved with experience (Sommer, 1994). The considerable variability in the texture produced on the HRA is clear on both Figures 2 and 3. This variability is typical of HRA surfaces.

SMTD measurements taken on the M18 three times during the summer months of 1995 are shown in Figure 4. This survey shows there to be little change in the SMTD compared with the 1994 survey.

The SMTD measurements taken on the M18 during the summer months of 1996 are shown in Figure 5. This survey

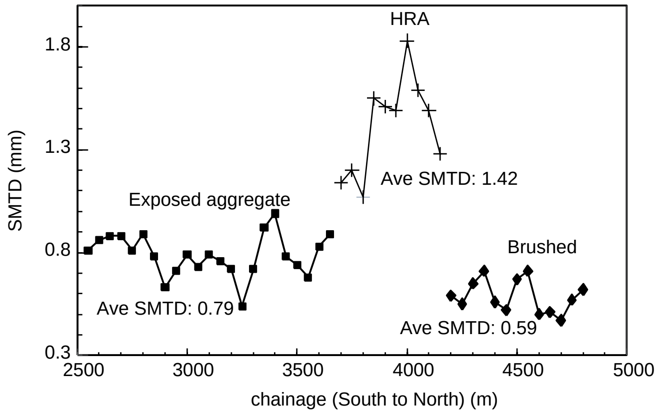

Figure 2 Average Sensor Measured Texture Depth (SMTD) survey of northbound M18, 1994

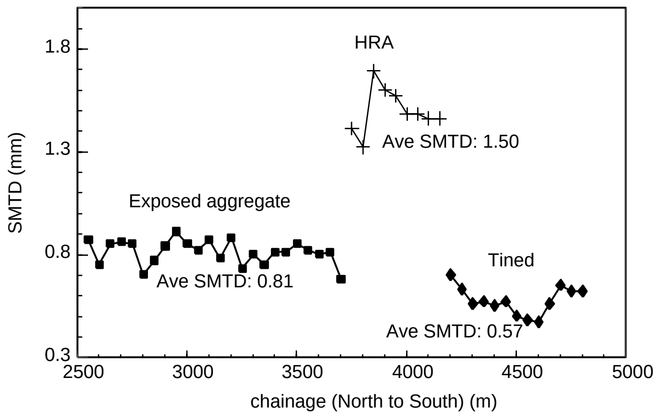

Figure 3 Average Sensor Measured Texture Depth (SMTD) survey of southbound M18, 1994

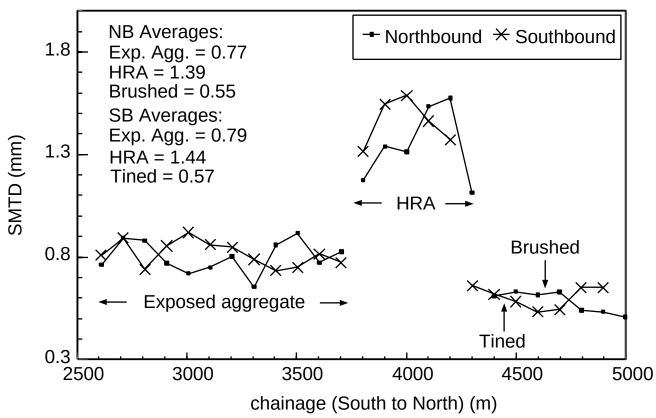

Figure 4 Average Sensor Measured Texture Depth (SMTD) survey of M18, 1995

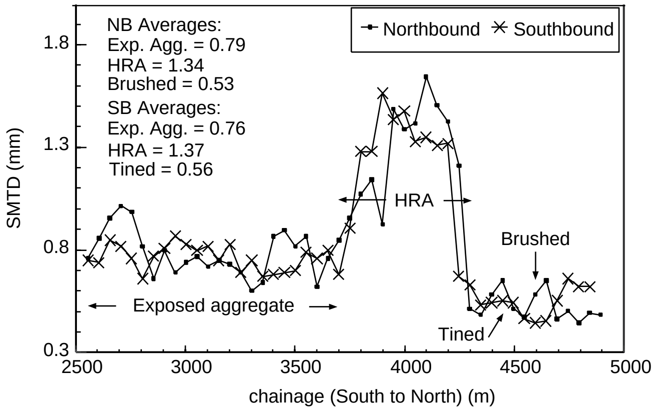

Figure 5 Average Sensor Measured Texture Depth (SMTD) survey of M18, 1996

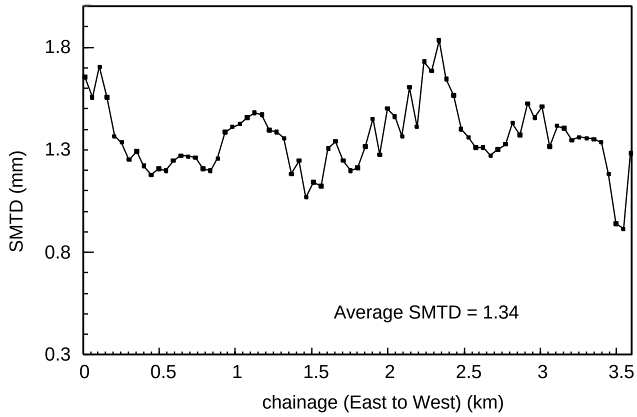

Figure 7 Average Sensor Measured Texture Depth (SMTD) survey of A50 westbound HRA (west end) 1995

shows a general, but relatively small, reduction in SMTD for all the surfaces, except for the northbound exposed aggregate surface, in comparison with the 1995 survey.

Corresponding measurements were taken on the A50 during 1995 and 1996. Figure 6 shows the 1995 HSTM measurements for the exposed aggregate surface while Figure 7 shows the 1995 measurements for the HRA section that included the TRL monitoring site. It can be seen from Figure 6 that the SMTD measurements are variable and that, on average, the westbound carriageway has a greater level of texture. As on the M18, the variability in the texture produced on the HRA was considerable and is clearly shown in Figure 7.

SMTD measurements taken on the A50 during the summer months of 1996 are shown in Figures 8 and 9. This survey shows there to be very little overall change in the SMTD in comparison with the 1995 survey.

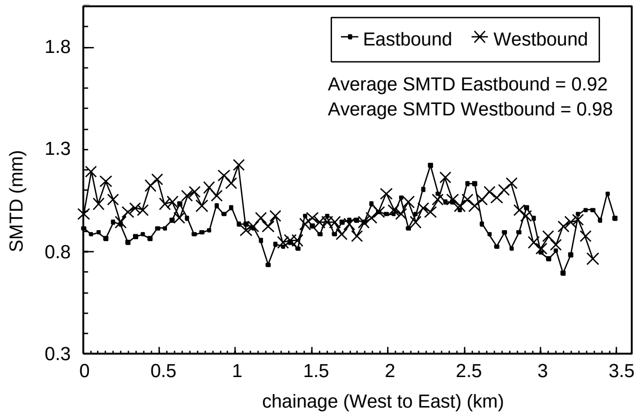

Figure 8 Average Sensor Measured Texture Depth (SMTD) survey of A50 exposed aggregate surface, 1996

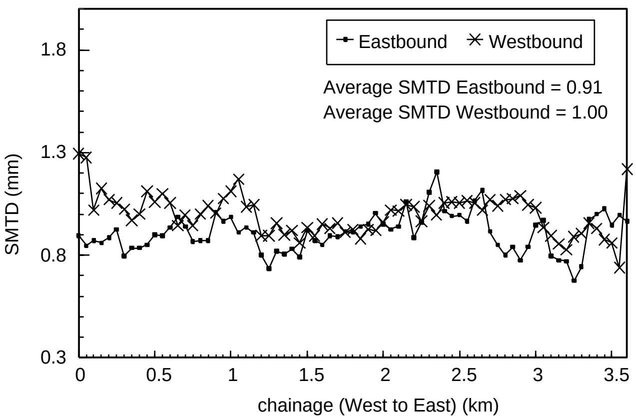

Figure 6 Average Sensor Measured Texture Depth (SMTD) survey of A50 exposed aggregate surface, 1995

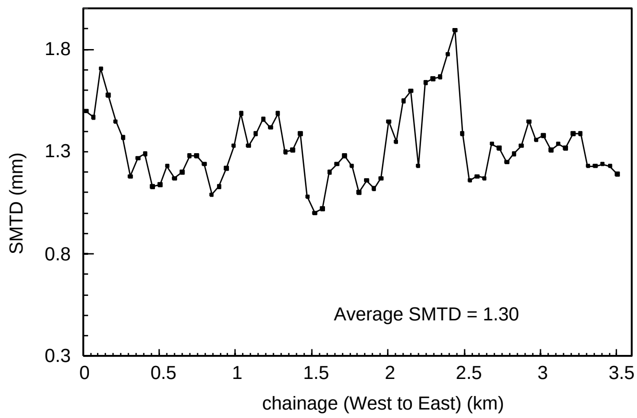

Figure 9 Average Sensor Measured Texture Depth (SMTD) survey of A50 westbound HRA (west end) 1996

3.1.3 Texture profile RMS amplitude

A method of examining road surface texture in detail involves the use of a portable laser known as the close-proximity laser profilometer (CPLP). This instrument is placed on the road and measures the surface profile over a 1 metre long section. The CPLP scans the surface at 0.2 mm longitudinal increments and can determine the surface profile with a vertical resolution of 0.01 mm.

At each site where noise measurements were made, 5 separate 1m long profiles were taken using the CPLP. The measurements were located in the nearside wheel-track of the nearside lane covering a distance along the road of approximately 10 metres, i.e. 5 metres either side of the microphone position. The CPLP measurements were taken at the same locations as the 10m length sand-patch measurements referred to in Section 3.1.1 of this Report.

The texture profiles measured using the CPLP were analysed using Fourier techniques to convert each profile into a series of individual component wavelengths. The RMS amplitude of the texture profile in each of the octave bands with central wavelengths at 2.5, 5, 10, 20, 40, 80 and 160mm were derived for each 1m length profile and the average from the 5 separate measurements was calculated. Details of the analysis method are given in Section B.1 of Appendix B.

The texture profile surveys, including the 10m length sand-patch measurements, were carried out near to the time when each of the vehicle noise surveys were carried out, as described in Section 3.3 of this Report. This allowed the relationship between RMS amplitude in each octave band wavelength and the noise emission from vehicles to be examined. The results from each texture profile survey are shown in Tables B.1 and B.2 in Section B.3.1 of Appendix B for the M18 and A50 respectively. They are presented alongside the results from the corresponding vehicle noise survey and average sand-patch texture depth value derived from the 10m length measurements.

3.2 Skidding resistance

Standards of in-service skidding resistance for road surfaces have been established in relation to a low-speed skidding parameter measured by the Sideways-force Coefficient Routine Investigation Machine (SCRIM), a vehicle that continuously monitors the surface whilst travelling in the normal traffic flow at 50km/h. The Sideways Force Coefficient (SFC) is measured by a test wheel mounted at an angle of 20^o to the direction of travel (Hosking and Woodford, 1976).

As mentioned earlier, Salt (1977) had established that low-speed skid resistance is dependent on the microtexture in the surface but, in order to maintain a given level of skid resistance as speed increases, macrotexture must also be built into the road surface.

The effectiveness of new forms of macrotexture therefore should be assessed by measuring the change in skidding resistance with speed.

Measurements of Sideway Force Coefficient (SFC), using SCRIM, are feasible up to 90km/h and give some indication of the effectiveness of macrotexture. However, speeds on motorways can be considerably higher. In the UK, a single-wheel trailer can provide a Braking Force Coefficient (BFC) at speeds up to 130km/h (Giles and Lander,1956). This testing device has been used to establish a minimum texture level, as measured by the sand-patch, for use in the DOT Specification for Highway Works for new works which is probably more onerous than specifications used for high-speed roads in other countries.

3.2.1 Sideways Force Coefficient

SFC values of the road surface vary with the seasons throughout the year. It is normal, therefore, for measurements to be made three times during the summer months and reported as a Mean Summer SCRIM Coefficient (MSSC). The 1994, 1995 and 1996 values of MSSC measured on the M18 at 50 km/h together with initial measurements made before the road was opened to traffic are given in Table 3. The reported values in all cases are the average values over a 50m length in the nearside lane, centred on the location chosen for noise measurement. SCRIM measurements on the A50 were made in July and November 1995 and during the summer months of 1996. The results are also given in Table 3. The 1995 results are given as individual values because it is likely that the state of polish of the aggregate would have progressively changed during this initial period after opening to traffic. However, the results for 1996 are MSSC values and were measured over a 50m length in the nearside lane, as for the M18. As expected, the initial values were all fairly high. After trafficking, all the surfaces, except for the tined surface, gave reduced SFC values. The SFC values for the tined surface increased slightly between the 1994 and 1995 SCRIM surveys but reduced between 1995 and 1996. The values for the HRA and exposed aggregate surfaces on the M18 have reduced by similar amounts over the course of the 3 years of the surveys. It was not possible to carry out a third SCRIM survey on the A50 in 1995. Consequently, it is not clear whether the differences between the July and November surveys are truly the effect of trafficking or are related to seasonal effects. The 1996 SCRIM survey of the A50 surfaces shows that the exposed aggregate surfaces have a different lower level of SFC compared with the HRA surface. The differences were, however, relatively small and of the order of 15% of the measured SFC values.

It should be noted that on each site, where different aggregates were used, both the exposed aggregate in the concrete and the chippings used to texture the HRA were specified to meet the same respective Polished Stone Value requirement appropriate to the forecast traffic level. It would be expected, therefore, that once the action of the traffic had cleaned off the cement paste and bitumen from the aggregate particles, the friction properties on a given site should be similar. This is consistent with the SFC results obtained on the M18 which gave virtually identical results for the EAC and HRA surfaces. Finally, it should be noted that all values of SFC measured after trafficking were well in excess of those required on motorways as specified in HD 28/94, (DOT et al,1994)[4].

Table 3 Results of SCRIM tests

Type of surface	M18 Site number	Before traffic	MSSC 1994	MSSC 1995	MSSC 1996	A50 Site number	July 1995	Nov 1995	MSSC 1996
HRA	3	0.62	0.53	0.47	0.44	4	0.55	0.51	0.55
	3A	-	0.51	0.48	0.44				
	4	0.63	0.51	0.47	0.44				
	9	0.63	0.52	0.49	0.45				
	10	0.63	0.52	0.50	0.44				
	11	0.64	0.53	0.49	0.45				
	Average	0.63	0.52	0.48	0.44	Average	0.55	0.51	0.55
Exposed aggregate	1A	0.56	0.53	0.48	0.44	1	0.51	0.47	0.48
	2	0.60	0.48*	0.48	0.43	2	0.49	0.46	0.48
	12	0.62	0.51	0.48	0.44	3	0.46	0.43	0.44
	13	0.68	0.50	0.45	0.44	5	0.52	0.45	0.47
	Average	0.62	0.51	0.47	0.44	Average	0.50	0.45	0.47
Brushed	5	0.70	0.51	0.46	0.41				
	6	0.69	0.45	0.47	0.41				
	Average	0.70	0.48	0.47	0.41				
Tined	7	0.64	0.48	0.48	0.44				
	8	0.64	0.44	0.49	0.44				
	Average	0.64	0.46	0.49	0.44				

** This site was retextured in January 1994 by randomly spaced transverse grooves*

3.2.2 Braking Force Coefficient

The BFC tests give a measure of how effective the macrotexture of the surface is in maintaining the skid resistance at high speeds. The percentage change in BFC from 50km/h to 130km/h, often referred to as ΔBFC, is the usual way of expressing the results. Previous research has shown ΔBFC to be related to the sand-patch texture depth, SPTD, (Franklin, Harland and Nelson, 1979). For transversely textured road surfaces (eg. brushed concrete) the empirically derived formula is:

$$\Delta BFC = 90(SPTD) - 70 \qquad ....(1)$$

but for randomly textured surfaces (eg. HRA) a different relationship was found to hold:

$$\Delta BFC = 20(SPTD) - 40 \qquad ....(2)$$

Although the original data set used to derive these functions included examples of both brushed concrete and HRA it did not include surfaces textured using exposed aggregate or tines. Consequently, in the absence of confirming data, it has been necessary to assume that the relationship between skidding performance (as measured using ΔBFC) and surface texture (as measured using SPTD) for exposed aggregate concrete would follow the function derived from randomly textured surfaces. Similarly, the relation for the tined surface was assumed to follow that for the transversely textured surfaces. In order to check these assumptions, BFC values were measured using the single-wheeled trailer at some of the locations where ΔBFC values were derived from the sand-patch measurements.

A comparison of the measured and predicted ΔBFC values shown in Table 4 indicate large differences with significantly higher values predicted from the measured textures than measured directly using the trailer in all cases. A possible explanation is that the single-wheeled trailer was operated differently than in previous surveys. In order to reduce wear on the tyres and, thereby to maintain a dwindling stock of tyres, manufactured to the same specification as the tyres used in previous surveys, the dead load on the wheel was reduced. However, over the years that these tyres have been in storage it is likely that the rubber would have hardened, reducing the hysteresis loss and leading to lower values in ΔBFC compared with ΔBFC values measured in previous surveys. Consequently, it was clear that the results of the BFC measurements obtained using the trailer could not be confidently compared with previous data, but nevertheless it was felt the data should still be used for comparative evaluation of the exposed aggregate surfaces and tined surfaces relative to the lengths of brushed concrete and HRA laid as control sections.

On the M18, despite the fact that the measured sand patch texture of the exposed aggregate concrete was in the lower half of the specified tolerance (ie initial average 50m SPTD was 1.24mm compared with 1.25mm minimum SPTD for contractual purposes), the measured ΔBFC was similar to that of the HRA which had considerably greater texture depth. On the A50, the EAC and HRA sections had similar texture depths yet the ΔBFC of the exposed aggregate was considerably better than that obtained on the HRA surface. This could imply that the exposed aggregate texture is more efficient than HRA in maintaining skid resistance as speed increases. As a consequence, it could be argued that it is acceptable to specify a lower texture depth for EAC than for HRA to maintain a comparable high speed skidding performance as defined by ΔBFC values. Further research is being undertaken to establish whether there is a case for recognising a consistent difference in the skidding performance of different types of surfacing.

Table 4 Results of BFC tests

		M18								A50				
		Before trafficking				After 8 months trafficking				Before trafficking				
Type of surface	Site no.	BFC_{50}	BFC_{130}	$\Delta BFC^{\dagger}$	Predicted ΔBFC*	BFC_{50}	BFC_{130}	$\Delta BFC^{\dagger}$	Predicted ΔBFC*	Site no.	BFC_{50}	BFC_{130}	$\Delta BFC^{\dagger}$	Predicted ΔBFC*
HRA	3	-	-	-		0.42	0.26	-38	-3	4	0.52	0.27	-48	-6
	3A	-	-	-		0.42	0.29	-31	+10					
	4	0.47	0.34	-28	-7	-	-	-						
	9	0.39	0.28	-28	-4	-	-	-						
	10	0.49	0.32	-35	-4	0.40	0.31	-23	+4					
	11	0.52	0.30	-42	-3	-	-	-	-4					
	Average	0.47	0.31	-33	-5	0.41	0.29	-31	+2	Average	0.52	0.27	-48	-6
Exposed aggregate	1A	0.55	0.39	-29	-14	0.44	0.29	-34	-12	1	0.51	0.42	-18	+4
	2	0.40	0.22	-45	-25	-	-	-		2	0.45	0.36	-20	-7
	12	0.48	0.32	-33	-22	-	-	-		3	0.45	0.31	-31	-6
	13	0.62	0.36	-42	-16	0.45	0.34	-24	-13	6#	0.52	0.38	-27	-7
	Average	0.51	0.32	-37	-19	0.45	0.32	-29	-13	Average	0.48	0.37	-24	-4
Brushed	5	0.61	0.38	-38	-17	-	-	-						
	6	0.62	0.47	-24	+20	0.41	0.29	-29	+22					
	Average	0.62	0.42	-31	+2	0.41	0.29	-29	+22					
Tined	7	0.64	0.27	-58	-10	0.45	0.34	-24	-16					
	8	0.58	0.28	-52	+37	0.42	0.29	-31						
	Average	0.61	0.28	-55	+14	0.44	0.32	-28	-16					

†$\Delta BFC = 100(BFC_{130} - BFC_{50})/BFC_{50}$ %

** The predicted skidding resistance (ΔBFC) is derived from the sand-patch texture depth value (SPTD) using the empirical relationship:*

$\Delta BFC = 90(SPTD) - 70$ for transverse textures

and $\Delta BFC = 20(SPTD) - 40$ for random textures (Franklin, Harland and Nelson, 1979)

 # Could not test site 5 so tested site 6 at CH5070 on the Westbound carriageway. SPTD supplied by Engineer = 1.67mm

3.3 Vehicle noise

3.3.1 Details of site surveys

The location for the sites where vehicle noise levels were monitored are shown in Table 5 and Figure 1.

Table 5 Location of survey sites

Road	Site number	Location	Surface finish
M18	**Northbound**		
	1A	MP 283.1	Exposed aggregate
	3	MP 283.7 + 30m	HRA
	3A	MP 283.9 - 20m	HRA
	6	MP 284.4	Brushed
	Southbound		
	7	MP 284.4	Tined
	10	MP 283.9 - 20m	HRA
	11	MP 283.7 + 30m	HRA
	13	MP 283.1	Exposed aggregate
A50	**Eastbound**		
	1	Chainage 6300	Exposed aggregate
	2	Chainage 5400	Exposed aggregate
	3	Chainage 7500	Exposed aggregate
	Westbound		
	4	Chainage 1500	HRA
	5	Chainage 6350	Exposed aggregate

The sites were chosen after considering a number of factors. Briefly, these were that:

i the measurements were to be conducted alongside representative sections of the road surface studied and where the road surface was free from obvious defects such as bumps or cracking which could influence the noise results

ii the section of road studied should be flat (of particular concern is the avoidance of any uphill sections where the noise from the vehicle engines might be excessive, this is especially critical for the measurement of noise from heavy vehicles)

iii the measurement microphone was to be located at the standard distance of 7.5m from the centre of the nearside lane and where the intervening ground was flat and acoustically “hard”, i.e. reflecting (this condition is generally satisfied by measuring across a lay-by or motorway hard shoulder)

iv the area in the vicinity of the selected site would be clear of all objects that could either reflect or obstruct sound, such as walls, bridges, noise barriers, safety fences, foliage etc.

Alongside most of the M18 sites there was a safety fence and in order to carry out the noise measurements at the standard distance of 7.5m, a section of the safety fence was removed. This ensured that the noise from the vehicles was not screened by the fence.

The first vehicle noise survey alongside the M18 was carried out in January 1994, soon after the relevant section of the motorway was opened to traffic. Six sites were identified: two HRA sites (Sites 3A and 10); two EAC sites (Sites 1A and 13); a brushed concrete site (Site 6) and a tined concrete site (Site 7). Prior to the road opening to traffic, a surface texture survey was carried out which had intended to include all the sites that had been identified for vehicle noise surveys. Unfortunately, due to poor weather conditions, initial texture surveys on the HRA surface at sites 3A and 10 could not be carried out before opening.

In the following July/August 1994, another vehicle noise and surface texture survey was carried out at these sites plus an additional two sites which had been surfaced with HRA (ie. sites 3 and 11). One year later, in July/August 1995, a further survey of vehicle noise and texture was carried out at the 6 sites identified in the initial survey. A final survey of noise and texture at these 6 sites was completed in August 1996.

In June/July 1995, a vehicle noise and texture survey was carried out alongside the A50, two months after opening to traffic. Five sites were chosen. Sites 1, 2 and 3, on the eastbound carriageway, were located alongside sections of exposed aggregate concrete and Sites 4 and 5, on the westbound carriageway, were located alongside sections of HRA and exposed aggregate concrete respectively (see also Figure 1). A second survey of noise and texture surveys undertaken at these 5 sites was completed in September 1996.

At all sites, vehicle noise levels were measured using the Statistical Pass-by (SPB) method developed at TRL for road surface noise studies (Franklin, Harland and Nelson, 1979). This method is described in Section B.2 of Appendix B. The technique is now used by researchers in many other countries and has recently been adopted as an international standard method of assessing differences in traffic noise on different road surfaces (ISO,1996).

The results of the vehicle noise measurements together with the relevant surface texture measurements for the M18 and A50 trials are shown in Tables B.1 and B.2, respectively, in Section B.3.1 of Appendix B.

3.3.2 Comparing average vehicle noise levels from the M18 and A50 surveys

An important objective of this study was to compare noise levels from vehicles travelling on the exposed aggregate concrete surfaces with those travelling on the conventional HRA surfaces. However, before carrying out this comparison it is useful to compare the noise levels obtained from the exposed aggregate surfaces laid on the M18 and A50 to establish the degree of consistency between the results obtained at the two locations.

Table 6 shows the results of a statistical analysis comparing the average maximum noise levels for light and heavy vehicles measured alongside the exposed aggregate sites located on the M18 and A50. It can be seen that the noise levels for both vehicle categories on the M18 were slightly higher than those measured alongside the A50. But the statistical analysis revealed that these small differences were not significant. Included in the Table are the average air temperatures recorded during the surveys. The influence of air temperature on vehicle noise levels is discussed in Appendix C. In this case, the small differences in temperatures observed at the two locations was not expected to significantly affect the vehicle noise results obtained.

Table 6 Comparison of average maximum vehicle noise level for exposed aggregate concrete

Road[1]	*Average air temperature (°C)*	*Average maximum noise level dB(A)*[2] *[90km/h at 7.5m]* *Light*	*Heavy*
M18 (n=8)	19	79.7 (0.42)	87.1 (0.44)
A50 (n=8)	22	79.6 (0.97)	86.8 (0.63)
Difference[3] (M18 - A50)	-3.0	+0.1	+0.3

[1] The value of n shows the sample size.
[2] Values in brackets are the standard deviations.
[3] Differences in noise levels were found not to be statistically significant.

Having established that there were no significant differences in the average noise levels from the exposed aggregate surfaces laid on the M18 and A50, the data from these two locations were combined in order to compare the results with those obtained from the HRA surfaces. This comparison is shown in Table 7, together with the number of sites included in the statistical analysis. It can be seen that the average noise levels obtained alongside the exposed aggregate concrete sites were lower than those obtained alongside the HRA surfaces. The differences were 2.2 and 1.1 dB(A) for light and heavy vehicles respectively. A great deal of confidence can be placed in these results as the differences between the average values were shown to be highly significant, i.e. 0.1% probability of a chance occurrence.

Table 7 Comparison of average maximum vehicle noise level for exposed aggregate concrete (EAC) and hot rolled asphalt (HRA)

Surface finish[1]	*Average air temperature (°C)*	*Average maximum noise level dB(A)*[2] *[90km/h at 7.5m]* *Light*	*Heavy*
HRA (n=12)	22	81.8 (0.30)	88.0 (0.54)
EAC (n=16)	21	79.6 (0.74)	86.9 (0.56)
Difference[3] (HRA - EAC)	+1	+2.2	+1.1

[1] The value of n shows the sample size.
[2] Values in brackets are the standard deviations.
[3] Differences in noise levels were found to be statistically significant at the 0.1% level

The average air temperatures recorded during the surveys are also shown in Table 7. The difference in the average air temperature between the two data sets was only 1°C, and therefore the differences in the vehicle noise levels between EAC and HRA surfaces cannot be explained by the differences in air temperature (see Appendix C).

3.3.3 Change in noise over time

(i) Average noise levels

The average noise levels from the four surveys carried out alongside the M18 covering a period of 32 months from opening to traffic are shown in Table B.3, Section B.3.1 of Appendix B. The corresponding results for the two surveys carried out alongside the A50 covering a period of 16 months from opening are given in Table B.4, Section B.3.1 of Appendix B. Figure 10 shows the results plotted in histogram form for the M18 survey sites. Figure 11 compares the results obtained from both the M18 and A50 for the EAC and HRA surfaces only.

The main feature of the data shown in Figure 10 is the higher noise levels recorded alongside the brushed concrete surface compared with the other surfaces examined, particularly the exposed aggregate surface. For example, after 32 months from opening to traffic, the average noise levels for the brushed concrete surface were 3.6 and 3 dB(A) higher than the corresponding levels recorded alongside the EAC surfaces for light and heavy vehicles, respectively.

It should also be noted from the data shown in Figure 10 that the noise levels from the brushed concrete surface and, to a lesser extent from the tined surface, tend to show a small increase over the duration of the study. Possible

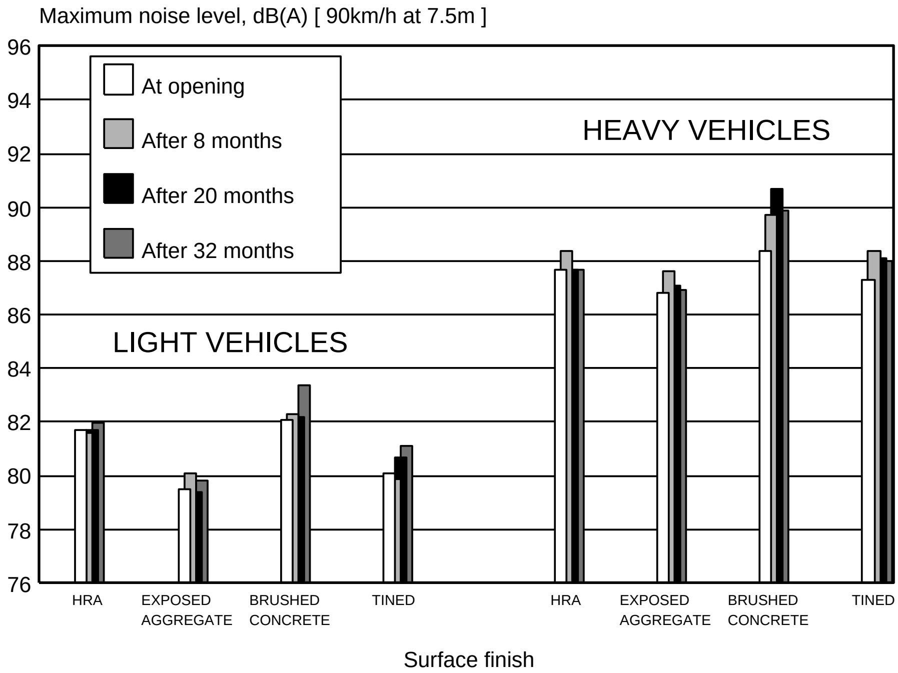

Figure 10 Average maximum vehicle noise levels for different surfaces laid on the M18 over a 32 month period of trafficking

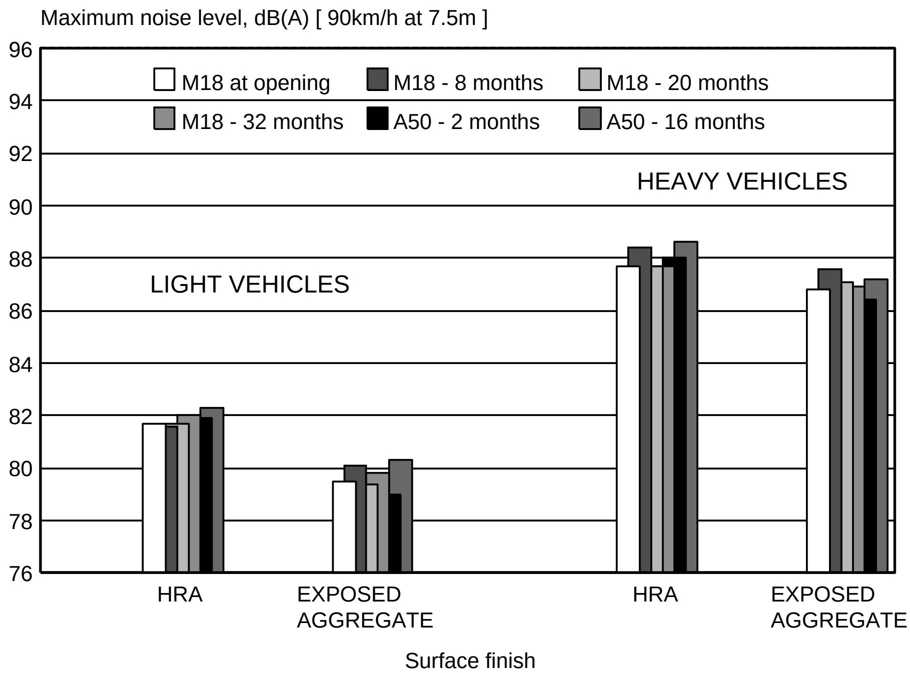

Figure 11 Comparing vehicle noise levels for exposed aggregate and HRA surfaces on the M18 and A50

explanations for these increases are presented later in this Report (see Section 3.3.4 (ii)).

In general, the results for the HRA and EAC surfaces shown in Figures 10 and 11 and in the Tables show little change over time at both road sites i.e. variations of less than 1 dB(A) over the duration of the study. The only exception was the EAC surface laid on the A50 where the average light vehicle noise levels increased by 1.3 dB(A) over the period 2 - 16 months from opening to traffic. One possible explanation for this slight increase in noise could be attributed to the considerable difference in air temperature between the two measurement surveys. The average air temperature recorded during the EAC survey carried out 2 months from opening of the A50 was 26°C, whereas during the 16 month EAC survey the temperature averaged 18°C. This temperature difference of 8°C could account for about 0.8 dB(A) of the observed difference between the average noise levels at the 2 and 16 month periods (see Appendix C). The residual difference in the noise levels, having adjusted for temperature in this way, is then much more consistent with the variations observed with the other data.

However, it should also be noted that although the HRA surveys on the A50 were carried out at similar times as the EAC surveys, the average air temperature recorded during these surveys were the same i.e. 19°C, therefore any differences in noise levels between the HRA surveys were not temperature dependent.

As mentioned previously, the influence of temperature on vehicle noise levels are discussed further in Appendix C. In this study, no corrections for temperature have been made to the measured data in view of the current uncertainty associated with the precise form of the relationship between vehicle noise level and temperature. However, the approximate effects of temperature are quoted, where appropriate, in order to aid the interpretation of the data.

(ii) Frequency spectra

In addition to overall noise levels, 1/3rd octave band noise spectra for both vehicle types were obtained for each of the surveys carried out at the M18 and A50. Spectra for the exposed aggregate surfaces are shown in Figures 12 and 13 for light and heavy vehicles respectively. The spectral levels in each band show very little change over the period of the study.

Further comparisons of the noise spectra are given in Figures 14 and 15 which show the variation in spectra from light and heavy vehicles respectively, over the 32 months of trafficking for the HRA, brushed, tined and exposed aggregate concrete surfaces laid on the M18.

For light vehicles, Figure 14, the general shape of all the spectra were fairly similar at the time of opening, with the exposed aggregate surface providing the lowest levels in each of the frequency bands examined. As the surfaces aged it can be seen that the spectral levels below 1.25kHz for the HRA and brushed concrete surfaces remained generally higher than those for the tined and exposed aggregate surfaces. Spectral levels above 1.25kHz for the brushed and tined surfaces progressively increased above the corresponding levels for the HRA and exposed aggregate surfaces by about 4 dB after 32 months of trafficking.

A similar pattern can be seen from the heavy vehicle spectra shown in Figure 15. After 32 months trafficking spectral levels above 1.25kHz were about 3 dB higher for the transversely textured surfaces compared with the randomly textured surfaces.

The change in spectral shape with age, which is particularly noticeable for the brushed and tined concrete surfaces, are likely to be influenced by changes in surface texture amplitudes. This will be discussed further in Section 3.5 (ii) of this Report.

3.3.4 Effect of surface texture on noise levels

The final objective of the noise analysis was to examine the relationship between overall vehicle noise levels, in dB(A), for each vehicle category with various measures of surface texture for each of the surface types examined.

To gain a better understanding of the relationship between noise and surface texture it has been shown that it is helpful to classify surfaces into two broad groups defined by the method of texturing (Franklin, Harland and Nelson, 1979 and Huschek, 1996). The texture of HRA and exposed aggregate concrete are both created by a random distribution of the stone aggregate and will be referred to as *randomly textured surfaces*, whereas the brushed and tined concrete surfaces are examples where the texture is predominately applied transversely across the carriageway and will therefore be referred to as *transversely textured surfaces*. (NB. Although a burlap mat was dragged longitudinally over the tined surface the dominant texture was still transverse for this surface as can be seen by examining Plate 6).

The following paragraphs compare the results obtained from the M18 and A50 sites with similar data collected from previous surveys at other road sites. The analysis includes comparisons in terms of skidding performance (ΔBFC) derived from the sand-patch texture depth (SPTD), and RMS amplitudes within the surface texture wavelength spectrum.

(i) Skidding performance (ΔBFC)

Previous studies carried out at TRL had included an examination of the relation between vehicle noise and skidding performance (ΔBFC) estimated from measurements of the sand-patch texture depth (SPTD). This work included data collected from over 60 different road surfaces (Nelson and Abbott, 1987). The method of noise measurement employed was the same as that used in this Report, ie. the Statistical Pass-by method (SPB) described in Section B.2 of Appendix B.

A statistical analysis of the previous data set had shown that regression lines could be drawn through the data set of vehicle noise for light and heavy vehicle categories and the estimated skidding performance (ΔBFC) for all surface types studied. The previous data set and the 95% prediction boundaries are shown in Figures 16 and 17 for light and heavy vehicles respectively.

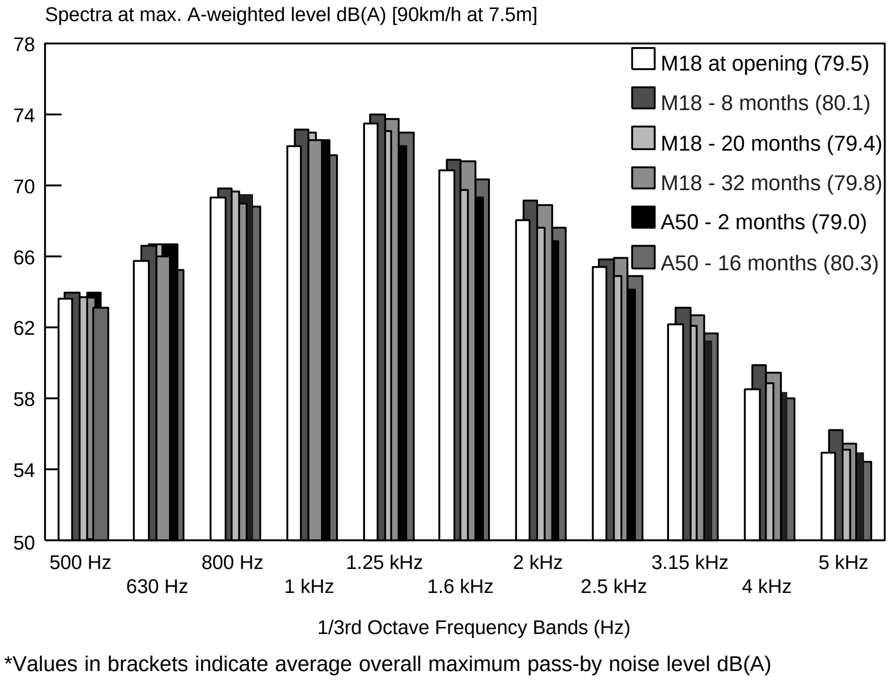

Figure 12 Noise spectra for light vehicles travelling on exposed aggregate road surfaces, M18 and A50 surveys

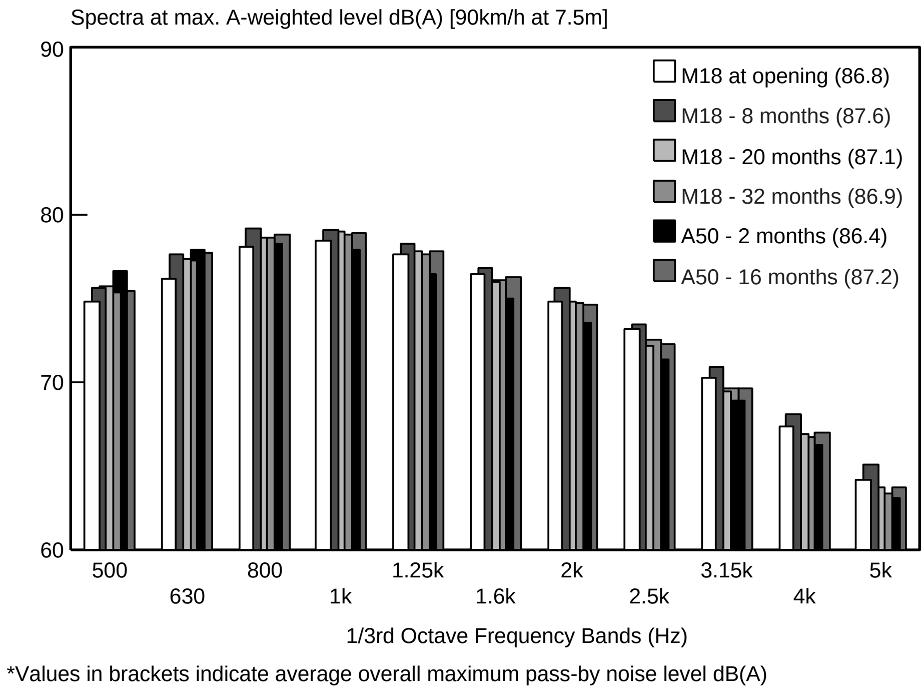

Figure 13 Noise spectra for heavy vehicles travelling on exposed aggregate road surfaces, M18 and A50 surveys

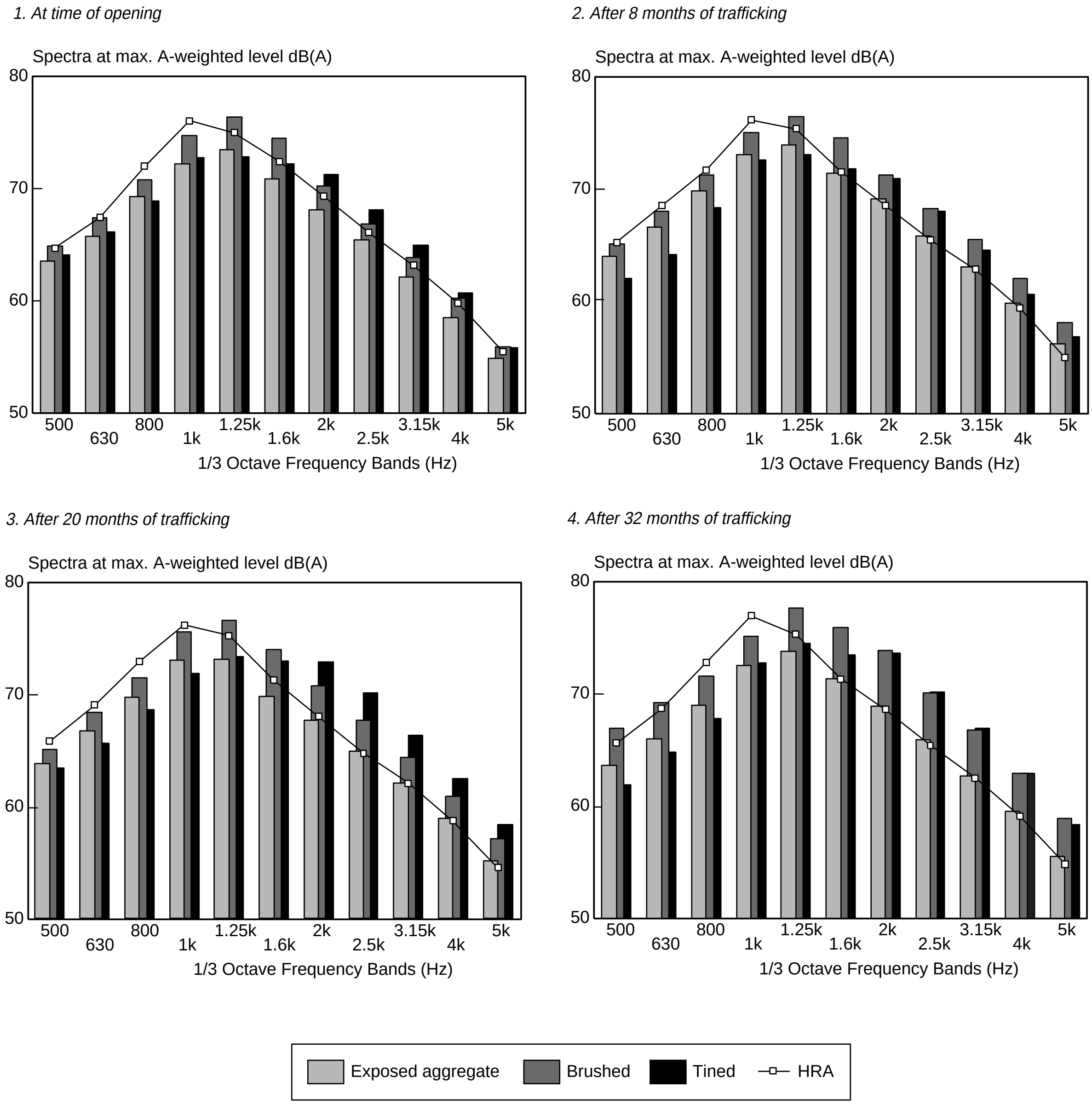

Figure 14 Noise spectra from light vehicles on the M18 over 32 months of trafficking

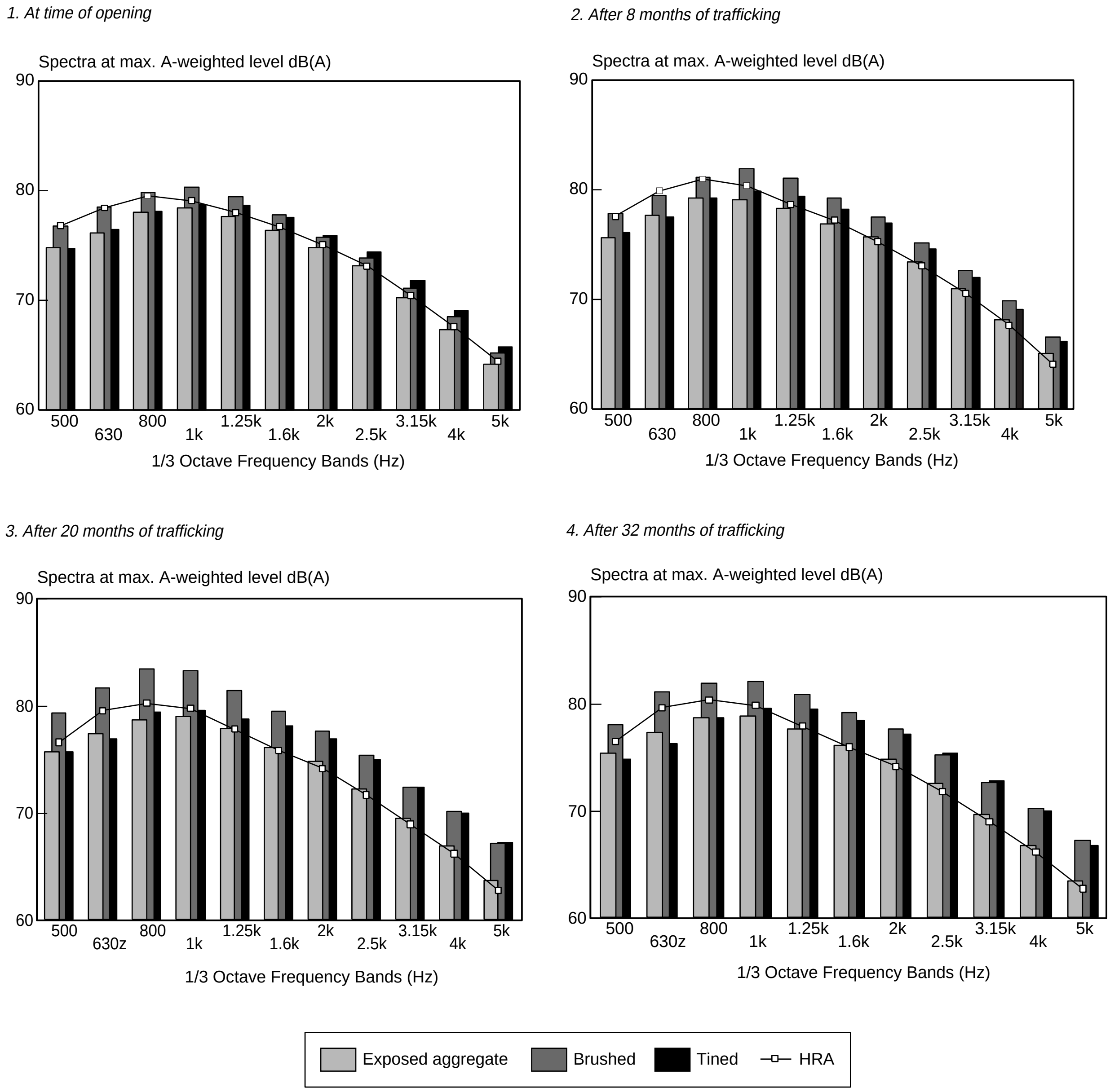

Figure 15 Noise spectra from heavy vehicles on the M18 over 32 months of trafficking

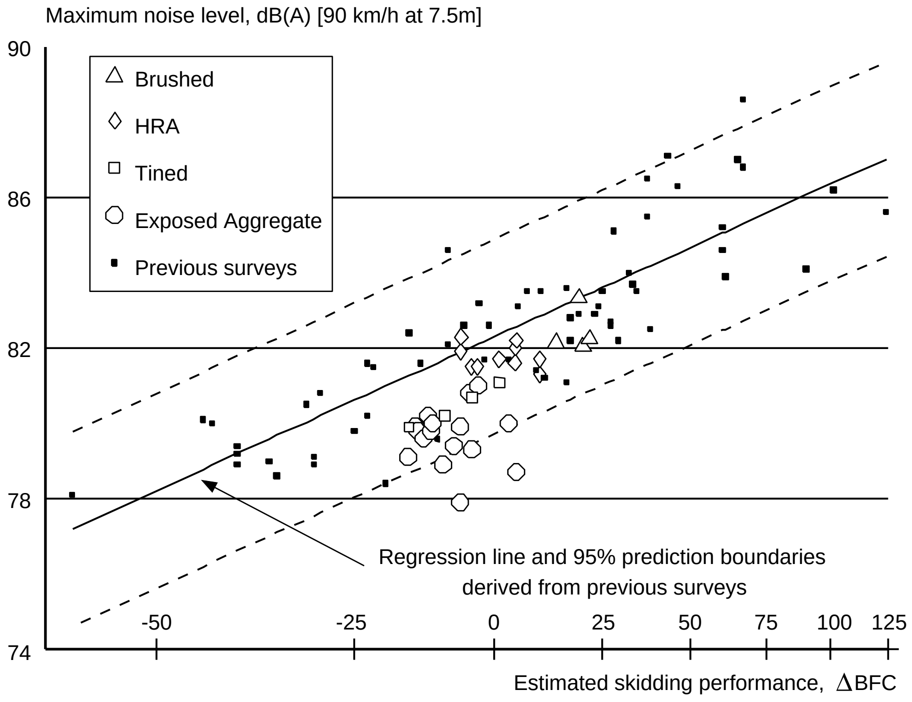

Figure 16 Light vehicle noise levels and estimated skidding performance

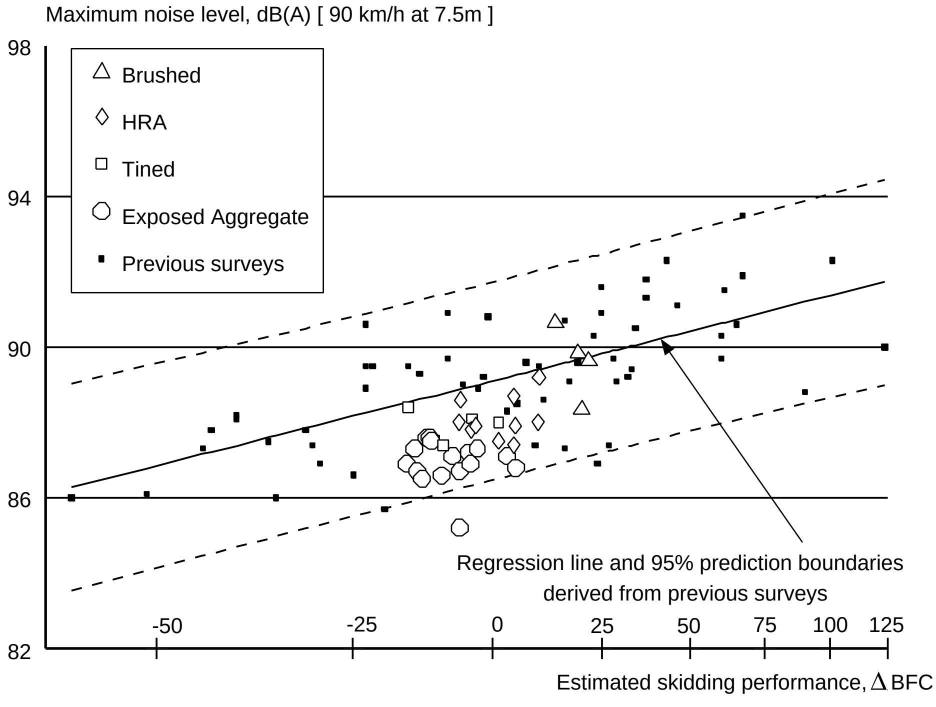

Figure 17 Heavy vehicle noise levels and estimated skidding performance

The data obtained from the various surfaces measured on the M18 and A50 are also shown on these Figures. It should be noted that in deriving the estimated skidding performance (ΔBFC) for the M18 and A50 data it was assumed that the relationship between ΔBFC and sand-patch texture depth (SPTD) for the exposed aggregate surfaces follows the relationship for randomly textured surfaces (ie. Equation 2 of this Report) and that the relationship for the transversely textured surfaces (ie. Equation 1) is valid for the tined and brushed concrete surfaces.

Figures 16 and 17 show that, in general, the data points obtained from this study fall below the regression lines obtained from the previous surveys. However, the majority of the data still lie within the 95% prediction boundaries defined by the previous data set and this suggests that the surfaces examined in this current study do not exhibit a statistically different relationship with ΔBFC than that found in the earlier work. However, it is interesting to note that two of the data points for light vehicles and one point for heavy vehicles lie significantly below the lower 95% prediction boundary. These data points were all obtained during the first survey alongside sections of EAC on the A50 when the average air temperature at each of these sites was about 30°C which may have resulted in below average noise levels as discussed earlier in Section 3.3.3(i) of this Report and shown in Figure C.1 in Appendix C.

Until further work is carried out to establish whether or not the assumption about the relationship between SPTD and ΔBFC for exposed aggregate surfaces, discussed above, is correct, the significantly lower noise levels found for the EAC surfaces compared with the corresponding levels for the HRA surface, as shown in Table 7, can only partly be explained by the lower estimated skidding performance of the EAC surfaces compared with the HRA surfaces as shown in Figures 16 and 17.

(ii) Texture profile RMS amplitude

At each of the noise measurement sites, surface profiles were measured over a 10m section located in the nearside wheel-track opposite the microphone position using the close-proximity laser profilometer (CPLP), as described in Section 3.1.3 of this Report. Details of the analysis procedure are given in Section B.1 of Appendix B.

The texture profile RMS amplitudes in each of the selected octave bands derived from the analysis of the CPLP data are given in Figures 18 and 19 for the M18 and A50 surfaces respectively.

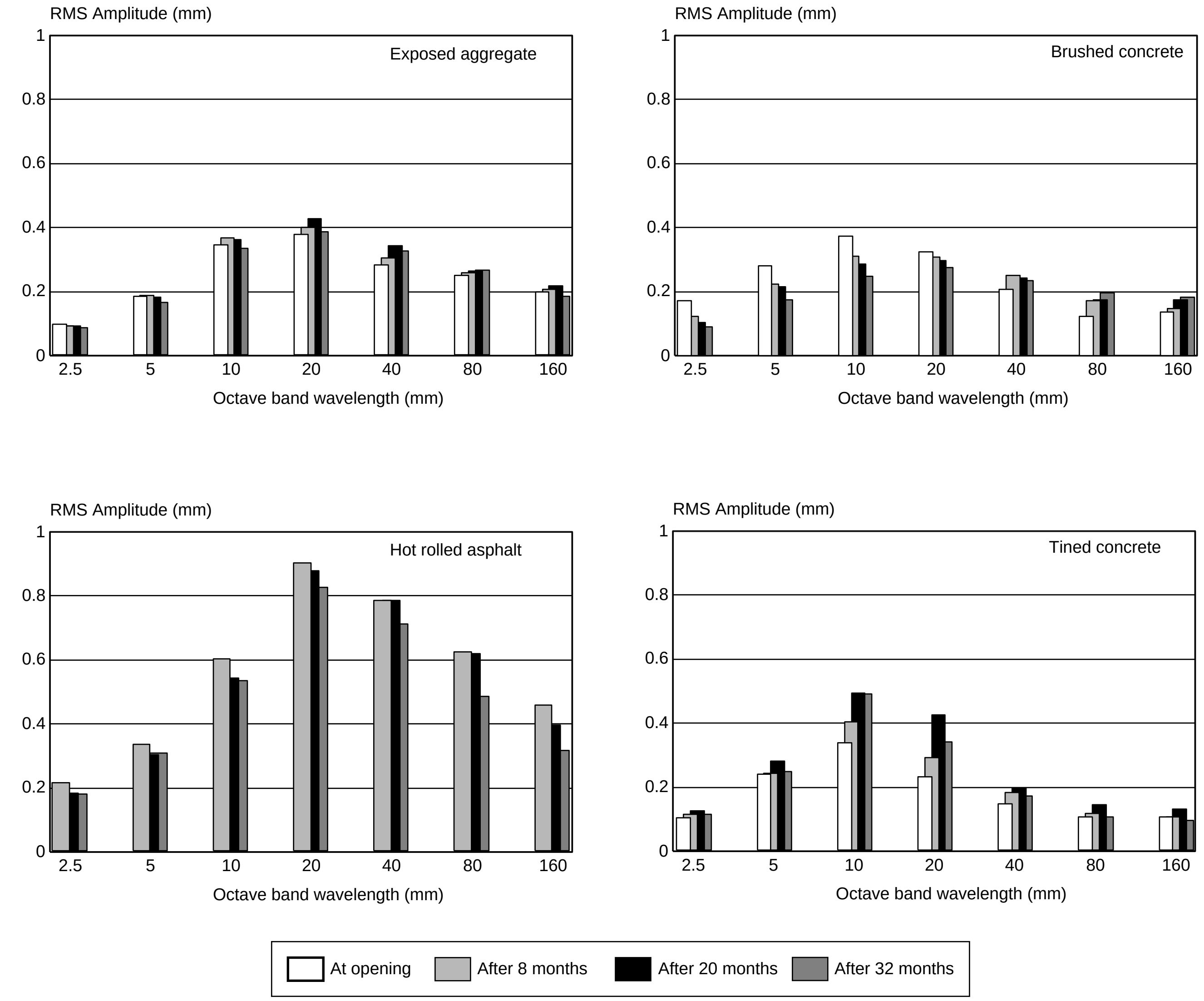

Figure 18 Comparison of texture levels from different surfaces on the M18

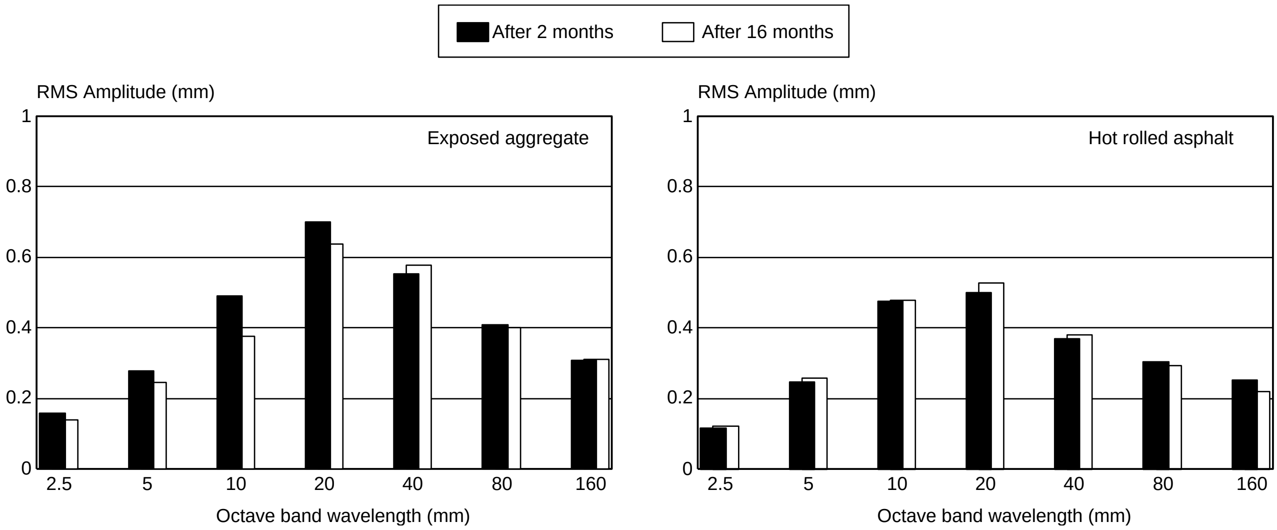

Figure 19 Comparison of texture levels from different surfaces on the A50

It can be seen that the RMS amplitudes for the EAC and HRA surfaces tended to remain fairly stable over the period of the study with the highest values tending to be recorded in the macrotexture range. However, interesting trends can be seen in the data presented for the brushed concrete surface laid on the M18 (Figure 18). For this surface it is noticeable that the megatexture levels, centred on the 80 mm and 160mm octave bands, tended to increase with time whereas levels in the macrotexture range, particularly at 10mm and shorter wavelengths, tended to decrease with time. Recent work by Sandberg (1996) and Huschek (1996) indicates that increasing texture amplitudes in the megatexture range tends to be associated with increases in noise levels whereas increasing texture amplitudes in the short wavelength macrotexture range i.e. below the 10mm octave band wavelength, tends to produce lower noise levels. Consequently, the increase in noise over the study period for the brushed concrete surface, which was noted earlier in Section 3.3.3(i), accords with the observed trends in the texture profile spectrum.

It can also be seen in Figure 18 that increases in megatexture levels were noted for the tined concrete over the period of the study. This is also consistent with the observed trends in noise levels measured over the study period for this surface.

(iii) Correlation of noise with texture profile RMS amplitude

As indicated in the previous section, a possible qualitative explanation for the observed differences in noise from different surfaces is emerging in terms of the RMS amplitudes of certain wavelengths within the texture profile. In order to examine this possibility further it is useful to incorporate additional data from sites where both vehicle noise and texture profiles have been measured using the same standard procedures as described in this Report. Section B.3.2 of Appendix B contains a list of recent sites where noise levels have been obtained using the SPB method and texture profiles measured using the CPLP instrumentation. Tables B.5 and B.6 give the results obtained for transverse and random texture patterns respectively.

A regression analysis was carried out on this data, together with the data collected from the M18 and A50 surveys, to determine the correlation of vehicle noise levels with various measures of texture. The results of this analysis are shown in Figure 20. Correlations are shown separately for light and heavy vehicles travelling on transversely and randomly textured surfaces.

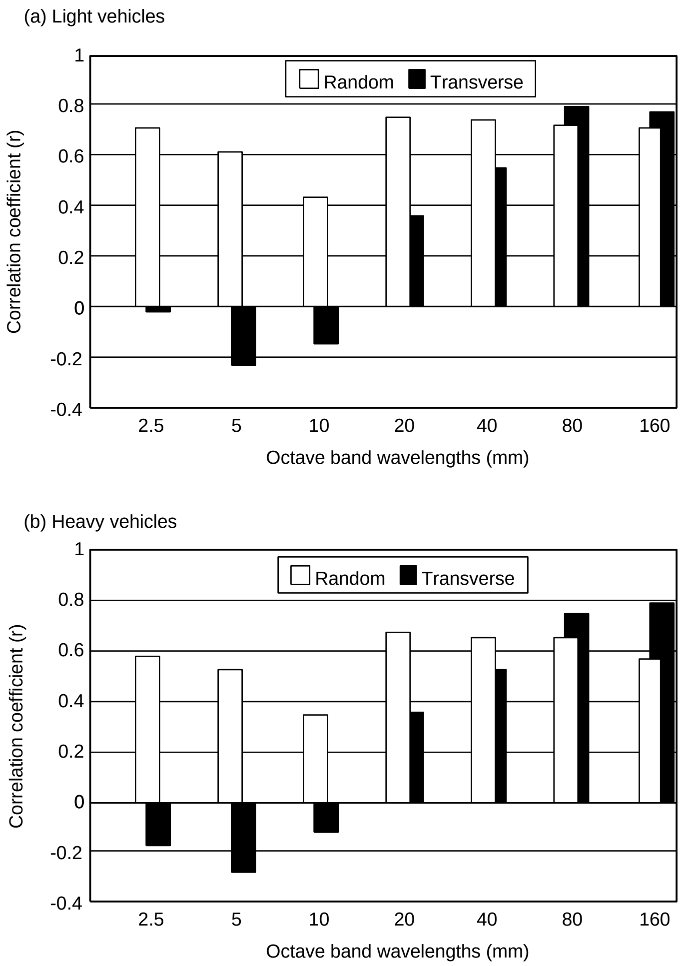

Figure 20 Variation in the correlation between vehicle noise and texture amplitude for different surface types

In the Figure, correlation coefficients are given for vehicle noise against RMS amplitudes in each of the octave bands with central wavelengths at 2.5, 5, 10, 20, 40, 80, and 160mm. The actual values of the correlation coefficients together with the level of significance attached to each value are listed in Table B.7, Section B.3.3 of Appendix B.

The results show some interesting differences between randomly and transversely textured surfaces. For the randomly textured surfaces it can be seen that fairly strong positive correlations were obtained for nearly all the octave band wavelengths. Correlation with the 10mm octave band wavelength was noticeably weaker than for the other measures. For transversely textured surfaces, however, strong positive correlations were obtained only for texture wavelengths in the megatexture range, i.e. octave bands with central wavelengths at 80 and 160mm. In addition, relatively weak negative correlations were found for the shorter macrotexture wavelengths, i.e. octave bands with central wavelengths at 2.5, 5 and 10mm. The largest negative correlation was found to occur for the wavelength centred on the 5mm octave band.

A further examination of the differences between randomly and transversely textured surfaces has been made using the composite texture measures, A_{mega} and $A_{macro<10mm}$ which are defined in Appendix A.

Figure 21 shows light and heavy vehicle noise plotted against values of A_{mega} for the different surfaces listed in Appendix B. Regression lines for transversely and randomly textured surfaces are also shown on the Figure. A statistical analysis showed that the randomly textured and transversely textured surfaces form distinctly separate populations.

Although the correlation coefficients were all relatively high there was still some scatter about each regression line which is clearly not explained by the A_{mega} variable. A possible explanation for some of the residual scatter could be associated with some measure of macrotexture of the surface. This possibility is examined in Figure 22 which shows plots of the noise level data for light and heavy vehicles where the residual variation of noise levels from the regression lines, given in Figure 21, have been plotted against the macrotexture variable, $A_{macro<10mm}$. It can be seen that there is a relatively weak negative correlation between residual vehicle noise and the macrotexture variable for the transversely textured surfaces but no evidence of any correlation between residual vehicle noise and macrotexture for the randomly textured surfaces.

It follows that the noise generated from vehicles running on transversely textured surfaces can be related to both the amplitudes of megatexture and the shorter macrotexture wavelengths. For randomly textured surfaces it seems likely at present that the principal components of the surface texture wavelength spectrum affecting noise generation are located in the megatexture region and there is no additional effect associated with short wavelength macrotexture amplitudes.

In addition to the correlation statistics associated with vehicle noise and RMS amplitude given in Table B.7 in Appendix B, the corresponding values for sand-patch texture depth (SPTD) and RMS texture amplitude for the composite texture measure, A_{mega}, are also given.

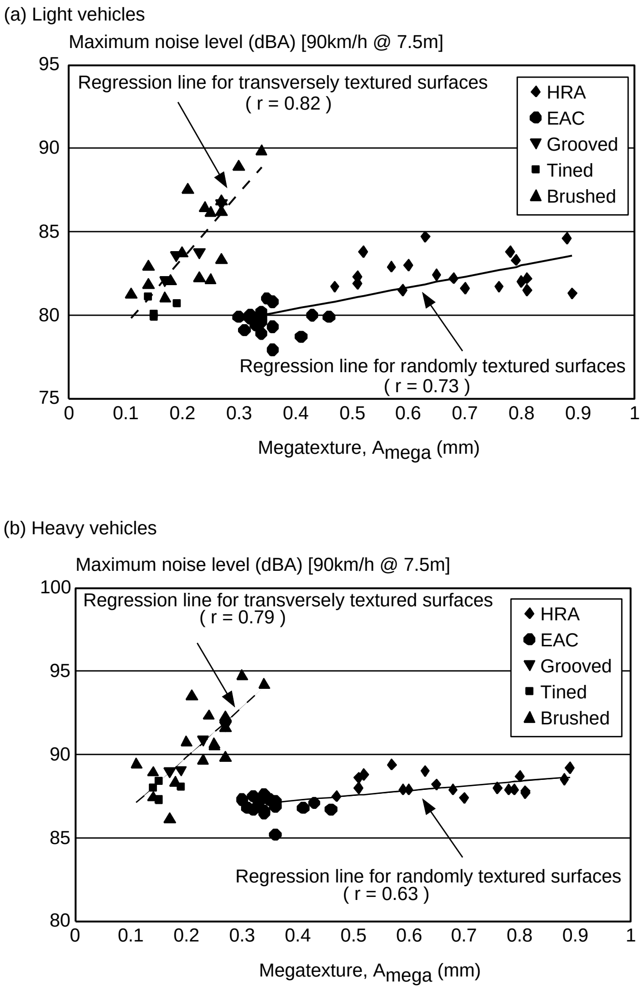

Figure 21 Variation in vehicle noise level and megatexture for different surface types

The magnitude of the correlation coefficients and level of significance found between vehicle noise and SPTD were significantly lower than those obtained for the composite texture measure, A_{mega}. For example, for the randomly textured surfaces it can be seen that the correlation coefficient obtained between light vehicle noise and SPTD values was 0.443 whereas a correlation coefficient of 0.726 was obtained between light vehicle noise and A_{mega}.

This difference in magnitude indicates that, in general, it would be expected that a much better prediction of surface noise performance can be obtained using measured values of A_{mega} than could be obtained with measured values of SPTD. For this particular example, it can be stated that, in terms of variance explained, values of SPTD can account for approximately 20% of the variance in light vehicle noise levels observed at different randomly textured surfaces, whereas the corresponding degree of variance explained using A_{mega} would be approximately 53%. Clearly, this represents a considerable difference in prediction accuracy capability between the two surface texture descriptors but also illustrate that considerable scatter still exists. As mentioned previously, this residual scatter may partly be explained by the influence of temperature on vehicle noise levels, as discussed in Appendix C.

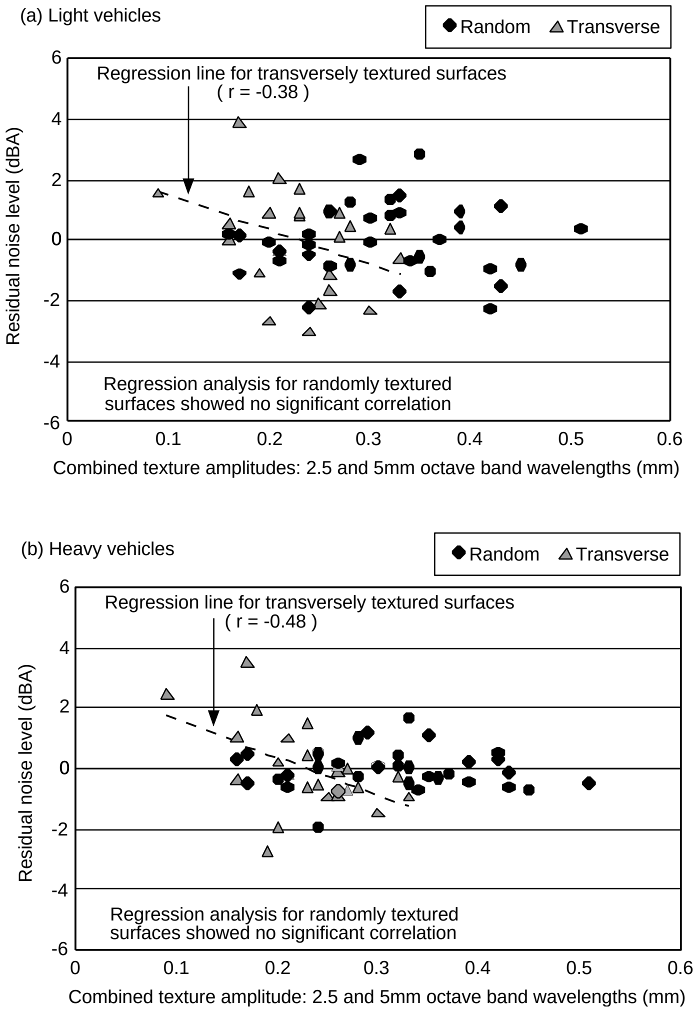

Figure 22 Variation in residual noise and the combined texture amplitudes in the 2.5 and 5mm octave band wavelengths

(iv) Interpretation of the trends in the M18 and A50 results in terms of texture levels

The analysis described above gives general insight into the relationship between vehicle noise and surface texture characteristics. By applying these general findings to the data presented earlier for the M18 and A50 surfaces an interpretation of some of the trends and differences can be given. For example, it has been shown that over the period of the study, the levels of vehicle noise generated on the exposed aggregate and HRA surfaces has remained fairly stable with HRA tending to be 1 to 2 dB(A) higher. This is consistent with the measurements of texture which also showed very little change in megatexture levels over the study period and with generally higher megatexture levels for the HRA surface.

For the transversely textured surfaces the most obvious effect was the increase in noise observed alongside the brushed concrete surface over the 32 months of the study - light vehicle noise levels increasing by 1.3 dB(A) and heavy vehicle noise increasing by 1.5 dB(A). These trends in the acoustic performance can also be associated with changes observed in the surface texture amplitudes. The data shown earlier in Figure 18 shows substantial increases over the study period in RMS amplitudes in the megatexture range coupled with a reduction in RMS amplitudes in the macrotexture range at texture wavelengths of 10mm or less. Both these aspects have been shown to be associated with increases in noise from vehicles running on transversely textured surfaces.

3.4 Traffic noise

The results so far have dealt with the influence of different types of surfaces on vehicle noise emissions for both light and heavy vehicles. However, in order to compare noise levels from general traffic travelling on different types of road surfaces it is necessary to combine the noise from all the vehicles in the traffic stream taking into account both the speed and the proportion of vehicles of each type. This section of the Report describes the method adopted to convert the measured vehicle noise levels to typical traffic noise levels and discusses the results obtained for the surfaces examined on the M18 and A50.

3.4.1 Estimating differences in traffic noise levels for different surface types

In this Report traffic noise levels have been estimated using the L_{Aeq} scale because, unlike L_{A10}, a simple method exists for converting vehicle noise levels into traffic noise L_{Aeq} levels (Noise Advisory Council, 1978)[5]. Details of the method are given in Appendix D.

Values of L_{Aeq} have been determined for each surface type and for each of the survey periods studied for traffic conditions typical for high speed roads. It was assumed that the proportion of heavy vehicles was 14% and that their mean speed was 90km/h. The mean speed of light vehicles was assumed to be 110km/h. Table 8 shows the average differences in L_{Aeq} to be expected for the assumed mix of traffic travelling on the various concrete surfaces and the HRA surfaces for the same degree of trafficking. These results are also presented in histogram form in Figure 23.

Table 8 Estimated difference in traffic noise levels, L_{Aeq}. (Differences are noise from the concrete surfaces minus noise from the corresponding HRA exposed to the same degree of trafficking)

Surface finish	*Estimated difference in traffic noise levels, L_{Aeq} dB(A) compared with HRA (age of surfaces after opening - months)*					
	0	*2*	*8*	*16*	*20*	*32*
M18						
Exposed aggregate	-1.5		-1.4		-1.4	-1.8
Brushed concrete	0.6		1.0		1.7	1.7
Tined concrete	-1.1		-0.9		-1.0	-0.7
A50						
Exposed aggregate		-2.0		-1.9		

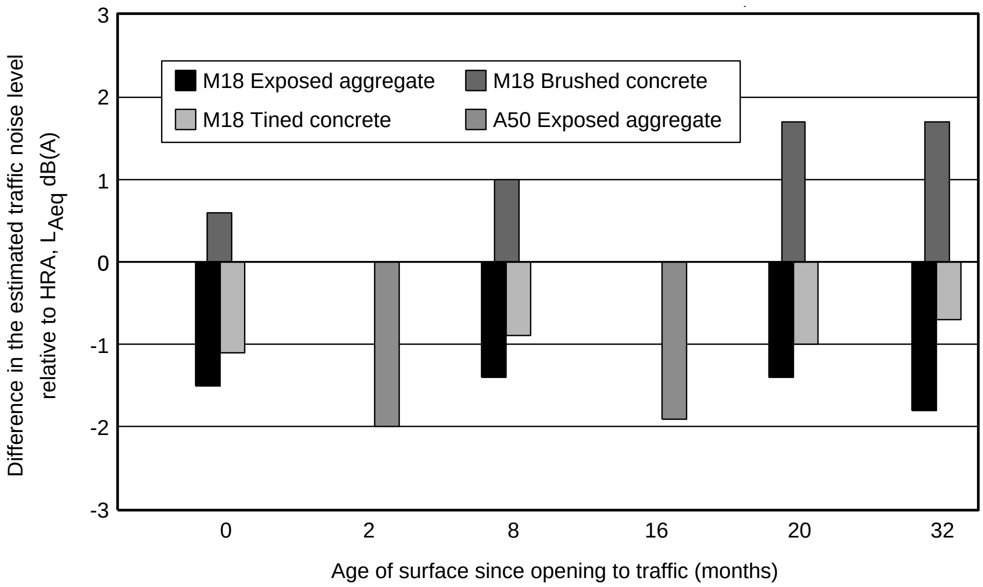

Figure 23 Difference in the estimated traffic noise level, L_{Aeq} *dB(A)*
(Differences are noise from concrete surfaces minus noise from HRA)

The results exhibit similar trends as that found previously when comparing vehicle noise levels; with differences in estimated traffic noise levels falling midway between the differences noted for light and heavy vehicles. For example, from the M18 trials, over the 32 month period of trafficking, noise levels from vehicles travelling on EAC were on average 2.2 and 1.1 dB(A) lower than on HRA for light and heavy vehicles respectively. Over the same period of trafficking, estimated traffic noise levels were on average 1.5 dB(A) lower on EAC compared with HRA.

On the A50, the acoustic performance of the exposed aggregate surface was about 0.5 dB(A) better than the corresponding performance of the exposed aggregate on the M18 when compared with HRA. This may be partly due to temperature effects which were discussed earlier in Section 3.3.3(i) of this Report.

3.5 Summary and discussion of performance results

The main objective of the research described in the Report was to compare the skidding and acoustic performance of different concrete surfaces laid as a trial on the M18 and A50 with control sections of conventional HRA. It was hoped that the trial of exposed aggregate and tined concrete surfaces would confirm that they provided and retained adequate levels of skid resistance, both at high and low speeds, while generating significantly lower noise levels than those associated with conventional transversely brushed concrete surfaces.

(i) Skidding performance

The SCRIM surveys carried out on the M18 prior to trafficking showed that the HRA and exposed aggregate surfaces had, on average, very similar levels of SFC. Initial values were 0.63 on the HRA and 0.62 on the exposed aggregate surface. Subsequent surveys on the M18 in 1994 and 1995 showed that the SFC of the two surfaces was reducing at a similar rate. In 1994, the HRA had an SFC value of 0.52 compared with 0.51 on the exposed aggregate, while in 1995 the HRA had an SFC of 0.48 compared with 0.47 on the exposed aggregate surface. However, the 1996 survey on the M18 show that the SFC of the two surfaces had reduced in comparison with the 1995 survey to a SFC of 0.44 for both surfaces.

To date, the A50 has had one complete season of SCRIM surveys carried out on it. Prior to this, two surveys showed that the HRA surface gave SFC values which were slightly higher (ie. 0.05 on average) than those measured on the exposed aggregate surface. The July and November surveys in 1995 gave average SFC values of 0.55 and 0.51 respectively on the HRA surface, while the exposed aggregate surface gave corresponding values of 0.50 and 0.45. In 1996 a full season of SCRIM surveys were carried out on the A50 which showed that the SFC of the HRA surface was 0.55 compared with 0.47 on the exposed aggregate surface. These results confirmed the two initial surveys carried out in 1995 which showed that the SFC of the HRA surface was, on average, 0.05 greater than measured on the exposed aggregate surface.

Although the high-speed measurements of skid resistance using the BFC trailer could not be compared with previous data it was felt that they could still be used for comparative evaluation of the trial surfaces on the M18 and the A50. Prior to trafficking on the M18, the ΔBFC values for the tined, exposed aggregate, HRA and brushed concrete surfaces were -55%,-37%, -33% and -31% respectively. The tined surface gave relatively poor high-speed skid resistance while the other three surfaces gave similar, increased, levels of high-speed skid resistance. In contrast, after 8 months of trafficking, all the trial surfaces gave increased levels of high-speed skid resistance with the HRA measuring -31%, the exposed aggregate and brushed concrete surfaces measuring -29% and the tined surface measuring -28%.

In comparison, the ΔBFC measurements carried out on the A50 showed that the exposed aggregate surface gave much higher levels of high-speed skid resistance compared with the HRA surface. The exposed aggregate surface had a ΔBFC of -24% compared with -48% on the HRA surface.

Clearly, although the study has shown that all the surfaces appeared to perform well in terms of low speed skidding resistance throughout the trial, the lack of consistent results from the high speed BFC trailer means that there remains uncertainty over the relative skidding performance of the surfaces examined at high speeds. Further work is therefore needed to provide this data before firm conclusions can be drawn concerning the skidding performance of the different surfaces at high speeds.

(ii) Acoustic performance

Statistical analysis has shown that noise levels from vehicles travelling on the exposed aggregate concrete (EAC) on the M18 were not significantly different from the corresponding noise levels from vehicles travelling on the EAC surface on the A50. It was therefore reasonable to combine the data from the two road sites and to average the noise levels for light and heavy vehicles from the combined data set. This was also found to be true for both classes of vehicles travelling on the HRA surfaces.

The vehicle noise measurements showed that the average maximum noise levels generated by vehicles travelling on the exposed aggregate surfaces, at a normalised speed of 90km/h and at a reference distance of 7.5m from the centre of the nearside lane, were 79.6 dB(A) for light vehicles and 86.9 dB(A) for heavy vehicles. The corresponding noise levels for light and heavy vehicles travelling on the HRA surfaces were 81.8 and 88.0 dB(A). The consistent differences in the noise levels between the HRA and EAC (i.e. mean values of 2.2 dB(A) for light vehicles and 1.1 dB(A) for heavy vehicles) were shown to be statistically significant to a high degree of probability.

The results obtained on the M18 enabled comparisons of noise levels for different types of surfaces to be examined, including the effects of trafficking over the first 32 months of exposure. Generally, for the EAC and HRA (i.e. random textured) surfaces it was found that vehicle noise levels had remained fairly constant over the first 32 months of trafficking, with noise levels not varying by more than 0.8 dB(A) over that period.

The transversely textured brushed concrete surface examined provided the highest noise levels of the surface types. At the time of opening these were 82.1 dB(A) and 88.4 dB(A) for light and heavy vehicles respectively. The corresponding noise levels from the EAC surfaces were 79.5 and 86.8 dB(A) respectively. In addition, it was found that the noise from the brushed concrete surface increased over the period of the study by 1.3 and 1.5 dB(A) for light and heavy vehicles respectively. At the end of the 32 month trial the noise from the EAC surface was lower than that from the brushed concrete surface by 3.6 dB(A) and 3.0 dB(A) for light and heavy vehicles respectively. Further monitoring of noise and texture levels at this site is recommended to establish whether or not the differences between noise levels continue to increase with exposure to traffic.

When the vehicle noise data was converted into differences in traffic noise L_{Aeq} levels, it was found that the brushed concrete surface gave higher traffic noise levels than the HRA by approximately 1.5 dB(A) on average over the 32 month period of trafficking. Over the same period the HRA was noisier than the EAC by a similar amount. The tined concrete surface gave traffic noise levels which were approximately 1 dB(A) lower than the the HRA which, on average, meant it gave slightly higher (approximately 0.5 dB(A)) traffic noise L_{Aeq} levels than the EAC.

The analysis of the texture profiles has helped to account for the observed differences and trends in the acoustic performance of the different surfaces laid on the M18 and A50. This analysis showed that noise emission levels from vehicles travelling on a range of surfaces could be related to the RMS amplitude of texture wavelengths in the megatexture region and to certain wavelengths in the macrotexture region. However, the relationship for surfaces with predominantly transverse textures (eg. brushed and tined concrete) was different from those with random textures (eg. HRA and EAC).

For both transversely and randomly textured surfaces increases in vehicle noise were seen to be related to increases in the RMS amplitude of texture wavelengths in the megatexture region (i.e. octave bands with central wavelengths at 80 and 160mm). However, for transversely textured surfaces, both the level and rate of increase of noise with changes in relative amplitude was shown to be significantly greater than for randomly textured surfaces (See Figure 21). This may be explained by considering the influence of surface texture on the mechanisms of tyre noise generation.

Texture wavelengths in the megatexture region are approximately of the same order as the length of the contact-patch of the tyre. The influence of amplitudes in the megatexture region on tyre noise generation is thought, therefore, to be due to tyre vibration (Sandberg and Descornet, 1980). For transversely textured surfaces, the dynamic forces acting on the tyre will tend to act simultaneously across the whole width of the contact-patch and, therefore, are likely to generate higher levels of vibration in the tyre than the non-sychronised forces associated with randomly textured surfaces. Consequently the level and rate of increase in noise generated by tyre vibration is likely to be higher for transversely textured surfaces than for randomly textured surfaces and so more strongly affected by texture amplitudes in the megatexture range.

For transversely textured surfaces increases in vehicle noise were also seen to be related, to some extent, by decreases in the RMS amplitude of texture wavelengths in the short wavelength range of the macrotexture region (i.e. octave bands with central wavelengths at 2.5 and 5mm). This, again, may be explained by considering the influence of surface texture on the mechanisms of tyre noise generation.

The influence of amplitudes in the short wavelength range of the macrotexture region on tyre noise generation is thought to be due to a process often referred to as air pumping which is particularly important at frequencies above about 1kHz (Sandberg and Descornet, 1980). The mechanism governing this behaviour is thought to be related to air pressure fluctuations generated mainly at the rear of the contact patch. Generally, as a tyre rotates the air locked in the tread grooves can become compressed as the tyre deforms during the contact with the road surface. As the tread elements emerge from the rear of the contact patch the compressed air is released creating local air pressure modulations which then propagate as sound waves. It is thought that a surface with a high amplitude of short wavelength textures will tend to provide additional air paths between the tyre and the road surface which allow freer movement of air in the contact patch, thereby helping to prevent air being trapped and then compressed in the tread grooves.

Analysis of the noise spectra for the transversely textured surfaces, particularly the brushed concrete surface, provide further evidence that texture amplitudes in the short wavelength range of macrotexture region govern spectral levels above about 1kHz (i.e. spectral levels increase as texture amplitudes reduce). As the surface aged, texture amplitudes in the short wavelength macrotexture region reduced with corresponding increases in spectral levels above 1.25kHz.

This result is also supported by the views expressed by other researchers of the favourable influence on noise levels provided by texture amplitudes in the short wavelength range of the macrotexture region (Descornet, 1990 and Huschek, 1990).

For randomly textured surfaces, however, increases in vehicle noise were seen to be related by increases in the short wavelength macrotexture amplitudes. This was further explored by examining the relationship between the residual noise (i.e. the resultant noise level after removing the influence of texture amplitudes in the megatexture region) and texture amplitudes in the short wavelength range of the macrotexture region. This analysis did not provide any evidence of an independent correlation between residual noise and short wavelength textures for randomly textured surfaces, whereas, for transversely textured surfaces a weak negative correlation was found. This result is perhaps not surprising when the degree of correlation between texture amplitudes in both the megatexture and short wavelength macrotexture region is considered. Figure 24 shows this comparison for both types of surface studied using the data set listed in Appendix B.

It can be seen from the Figure that for transversely textured surfaces, no significant correlation between the A_{mega} and $A_{macro<10mm}$ was found. However, a positive correlation was found for the randomly textured surfaces examined for this type of texturing. The amplitudes of A_{mega} and $A_{macro<10mm}$ wavelengths tend to increase or decrease together. This behaviour has also been noted by Descornet (1990).

This observation provides an explanation as to why there was no significant correlation of individual noise with the short wavelength macrotexture amplitudes for randomly textured surfaces once the effect of megatexture had been taken into account.

As part of the analysis of surface texture, it was found that noise levels were relatively poorly correlated with conventional measures of surface texture as determined

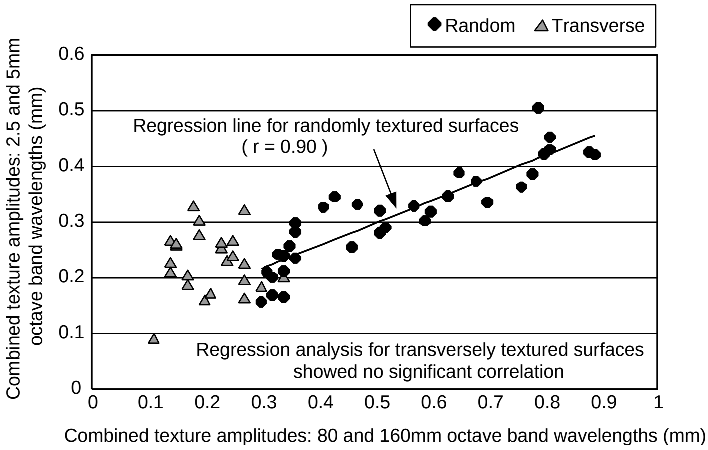

Figure 24 Variation in texture amplitudes in the short wavelength macro and megatexture range for different surface types

from sand-patch tests (SPTD) and that monitoring of RMS amplitudes of texture profiles will provide a better indicator of vehicle noise levels. However, it will be necessary for a technique of monitoring texture profiles routinely to be developed before such a change could be introduced.

This project has shown that the way forward in controlling tyre/surface noise lies in reducing the amplitude of megatexture. Because of the correlation of macrotexture and megatexture for randomly textured surfaces, the need to retain a minimum level of macrotexture to provide skidding resistance may place limitations on what can be achieved. But macrotexture also provides paths under the tyre allowing trapped air pressures and associated air pumping noise to dissipate. This effect is particularly important for transversely textured surfaces for which the overall noise level is reduced by increasing the macrotexture independently of the effect of lowering the megatexture amplitude. Further research into the design of road surfaces is needed to investigate whether the link between macrotexture and megatexture for randomly textured surfaces can be broken.

When the noise spectra from vehicles travelling over the two types of surfaces on the M18 and A50 were compared it was found that, at frequencies above about 1.25kHz, noise levels from transversely textured surfaces were generally higher than for randomly textured surfaces. For example, at frequencies above 1.25kHz it was shown that for heavy vehicles, average spectral band levels for transversely textured surfaces were about 3dB higher than for randomly textured surfaces. Similarly for light vehicles, spectral band levels above 1.25kHz were about 4dB higher for the tined surface compared with the exposed aggregate surface.

These differences in the vehicle noise spectra may influence the perception of noise from the two types of surfacing. For example, it is possible that the noise generated by vehicles travelling on the tined surface may be perceived differently to the noise generated when the same vehicles travel over the exposed aggregate surfaces by a degree which is greater than that implied by the relatively small difference in the overall dB(A) noise level. Further research under controlled listening conditions would be needed in order to gain insight into the differences in perception of noise from different road surfaces. It is recommended that such studies should use recordings of light vehicle noise to accentuate the differences in spectral levels between the different surface types.

4 Conclusions

Two trials, constructed on the M18 motorway and the A50 in Derbyshire to examine alternative methods of texturing concrete pavements, have been assessed after 32 months trafficking and 16 months trafficking respectively. The results of various measurements of texture and skidding resistance have been compared with the results of vehicle noise surveys. The main conclusions from this study have been:

Construction

1 The construction of exposed aggregate texture on concrete roads was successfully demonstrated using UK materials and specifications. It is likely that a reduction of the specified Flakiness Index to less than 15 could provide some improvements to the final quality and possibly to the durability of these surfaces. Strict control of the rate of application of retarder and the time before the surface mortar is removed should also be beneficial. Recent remedial work on the A50 has demonstrated that an exposed aggregate surface can be satisfactorily repaired, if necessary.

Skidding performance

2 The low-speed skidding resistance of all the trial surfaces after trafficking was well in excess of the levels set down in the Design Manual for Roads and Bridges. After 32 months on the M18, the trial surfaces are all producing similar levels of SFC with the exception of the brushed concrete surface which gave slightly lower values than the other surfaces. On the A50, after 16 months of trafficking, the exposed aggregate and hot rolled asphalt surfaces were producing consistently different but acceptable levels of SFC; however, only one full season of SCRIM surveys had been carried out since opening to traffic in 1995.

3 Measurements of high speed skidding resistance carried out using the BFC trailer were not found to be consistent with earlier work. This was attributed to differences in the design and operation of the trailer and to differences in the mechanical properties of the test wheel. For these reasons absolute measurements of BFC taken on each surface were not considered to be reliable although differences in BFC between the surfaces was considered to be of some value. Given these concerns over the high speed BFC data, it was found that the values of ΔBFC were very similar on the M18 surfaces. On the A50 the values of ΔBFC were higher for the EAC surface than for the HRA surface.

4 The lack of consistent results from the high speed BFC trailer means that there remains uncertainty over the absolute skidding performance of the surfaces examined at high speeds and consequently firm conclusions cannot be drawn at present concerning the skidding performance of the different surfaces at high speeds. However, further work is currently being undertaken to provide this data using “state of the art” equipment.

Durability

5 Both the M18 and A50 exposed aggregate trial lengths have experienced at least three winters now and are proving to be durable. The M18 shows there to be very little deterioration of the road surface either at the cracks or in general. However, the A50 shows some chipping loss at several cracks; this may be due to spalling of the cracks, which is often observed on CRCP pavements. There are also two or three small areas of chipping loss. In addition, drainage gullies placed in the exposed aggregate carriageway have initiated cracks which can be seen in the road surface. Otherwise, the exposed aggregate concrete surfaces appear to be in good condition.

Acoustic performance

6 The results of vehicle noise measurements showed that the average maximum noise levels generated by vehicles travelling on the exposed aggregate concrete (EAC) surfaces on the M18 and A50 were, on average, lower than the corresponding levels measured alongside adjacent sections of hot rolled asphalt (HRA). The differences were 2.2 dB(A) for light vehicles and 1.1 dB(A) for heavy vehicles and were shown to be statistically significant to a high degree.

7 Monitoring the noise levels for the different road surfaces on the M18 over the first 32 months of trafficking showed that noise levels alongside sections of EAC and HRA at the two road sites had remained fairly constant with noise levels not varying by more than 0.8dB(A) over the period of the trial.

8 Of the four surface types studied, the brushed concrete surface was associated with the highest vehicle and traffic noise levels. In addition, it was found that the noise from the brushed concrete surface increased slightly over the period of the study by 1.3 and 1.5 dB(A) for light and heavy vehicles respectively. At the end of the 32 month trial the noise from the EAC surface was lower than that from the brushed concrete surface by 3.6 and 3.0 dB(A) for light and heavy vehicles respectively.

Further monitoring of noise and texture levels at the brushed concrete site is recommended to establish whether or not noise levels continue to increase with exposure to traffic.

9 When the vehicle noise data was converted into traffic noise, L_{Aeq}, levels it was found that the brushed concrete surface gave higher traffic noise levels than

the HRA surface by approximately 1.5 dB(A) on average and the HRA was noisier than the EAC by a similar amount. The tined concrete surface gave traffic noise levels which were approximately 1 dB(A) lower than the HRA which, on average, meant it gave slightly higher traffic noise L_{Aeq} levels than the EAC.

10 The surface texture analysis showed that vehicle noise levels were highly correlated with texture amplitudes in the megatexture range with different relationships for surfaces with predominantly transverse textures (eg. brushed and tined concrete), compared with random textures (eg. HRA and EAC). It was also found that noise levels were relatively poorly correlated with measures of the surface texture depth as determined from sand-patch texture measurements (SPTD). The results therefore clearly indicate that the monitoring of texture amplitudes of road surfaces will provide a better indicator of vehicle noise levels than traditional measures of surface texture based on sand-patch measurements. However, it will be necessary for a technique of monitoring texture profiles routinely to be developed before such a change could be introduced.

11 For the transversely textured surfaces it was found that increases in vehicle noise were seen to be related to increases in the amplitudes of texture in the megatexture wavelength region (i.e. 80mm - 160mm) and, to a lesser extent by decreases in the amplitude of texture wavelengths in the short wavelength end of the macrotexture range (i.e wavelengths < 10mm). For the randomly textured surfaces the main effects on noise seemed to be associated with megatexture amplitudes.

12 This project has shown that the way forward in controlling tyre/surface noise lies in reducing the amplitude of megatexture. Because of the correlation of macrotexture and megatexture for randomly textured surfaces, the need to retain a minimum level of macrotexture to provide skidding resistance may place limitations on what can be achieved. But macrotexture also provides paths under the tyre allowing trapped air pressures and associated air pumping noise to dissipate. This effect is particularly important for transversely textured surfaces for which the overall noise level is reduced by increasing the macrotexture independently of the effect of lowering the megatexture amplitude. Further research into the design of road surfaces is needed to investigate whether the link between macrotexture and megatexture for randomly textured surfaces can be broken.

13 When the noise spectra from vehicles travelling over the two types of surface laid on the M18 and A50 were compared it was found that, at frequencies above about 1.25kHz, noise levels from transversely textured surfaces were generally higher than for randomly textured surfaces. This observation may have an influence on the perception of noise from vehicles travelling over different surfaces. In particular for light vehicles, the overall noise levels of both the exposed aggregate and tined surfaces differed by less than 1dB(A) but the spectral levels above 1.25kHz for the tined concrete surface was about 4dB higher than for the exposed aggregate at the end of the trial. Further work under controlled listening conditions would be needed to determine differences in perception of noise from these different surfaces.

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Appendix A: Glossary of terms

$A_{RMS,\lambda}$ or A_λ :	RMS amplitude of the texture wavelength in the octave band with a central wavelength, λ e.g. A_{80} is the RMS amplitude of the texture wavelength in the octave band with a central wavelength of 80mm.
$A_{macro<10mm}$:	The combined RMS amplitude of the texture wavelength in the octave bands with central wavelengths at 2.5 and 5mm and defined as: $$A_{macro<10mm} = \sqrt{\left(A_{2.5}^2 + A_5^2\right)}\ mm$$
A_{mega} :	The combined RMS amplitude of the texture wavelength in the octave bands with central wavelengths at 80 and 160mm and defined as: $$A_{mega} = \sqrt{\left(A_{80}^2 + A_{160}^2\right)}\ mm$$
BFC or BFC_v :	Brake Force Coefficient at a reference speed v km/h.
ΔBFC:	The percentage change in the Brake Force Coefficient between 50 and 130km/h and defined as: $$\Delta BFC = 100\left(BFC_{130} - BFC_{50}\right) / BFC_{50}\,\%$$
Estimated ΔBFC :	Estimated ΔBFC is the percentage change in the Brake Force Coefficient derived from the sand-patch texture depth (SPTD) and defined as: $$\textit{Estimated } \Delta BFC = 90(SPTD) - 70 \textit{ for traverse textures}$$ $$\textit{Estimated } \Delta BFC = 20(SPTD) - 40 \textit{ for random textures}$$
dB(A) :	The unit of sound level or in the context of this Report, noise level, is the decibel (dB) and is defined as: $$\textit{Noise level} = 20 \log_{10} \frac{\textit{(Observed sound pressure)}}{\textit{(Reference sound pressure)}}\ dB$$ the reference pressure is fixed at 20µPa, the level of the quietest sound that an average listener can perceive. The symbol (A) refers to the frequency-weighting circuitry which is incorporated in the instrumentation for measuring noise so that the frequency response of the equipment is similar to that of the human ear for sounds at different frequencies.
L_{A10} :	L_{A10} is a noise scale used for describing the statistical variability of a fluctuating noise level and is defined as the noise level which is exceeded for 10% of the time within a given period.
L_{Aeq} :	L_{Aeq} is a noise scale for describing the energy content of the noise and is defined as the continuous equivalent noise level which if maintained constant would contain the same acoustic energy as the actual fluctuating noise in a given period.
Macrotexture :	Macrotexture is the deviation of a road surface from a true planar surface with the characteristic dimensions along the surface of 0.5 - 50mm
Megatexture :	Megatexture is the deviation of a road surface from a true planar surface with the characteristic dimensions along the surface of 50 - 500mm
Microtexture :	Microtexture is the deviation of a road surface from a true planar surface with the characteristic dimensions along the surface of less than 0.5mm

MSSC :	Mean Summer SCRIM Coefficient is the average of at least three SCRIM coefficient measurements carried out along the same length of road at well spaced intervals during the summer testing period (May to September inclusive) in any one year and takes account of any seasonal variation which may influence the SFC SCRIM readings.
Randomly textured road surfaces :	Surfaces which exhibit similar texture characteristics in all directions within the plane of the surface.
SCRIM :	Sideways force Coefficient Routine Investigation Machine
SFC :	A general term for the ratio of the sideway-force to the normal force obtained with sideway-force road friction testing equipment such as SCRIM.
Significant :	In this Report, the word 'significant' is sometimes used with reference to differences in noise levels and indicates the result from a statistical analysis of physical data. It does not necessarily indicate a perceptual difference between noise levels.
SMTD :	Sensor Measured Texture Depth. Derived from the root-mean-square (rms) deviation of laser based surface displacement measurements.
SPTD :	Sand-Patch Texture Depth derived from the volumetric method as defined in BS598 (British Standards Institution, 1990).
Transversely textured road surfaces:	Surfaces which exhibit some texture characteristic within the plane of the surface in the direction of the traffic.

Appendix B: Vehicle noise and texture profiles

B.1 Analysis of texture profiles

The texture profiles measured using the close proximity laser profilometer (CPLP) were analysed using Fourier techniques to convert the profile into a series of individual component wavelengths (λ) with amplitudes (a_λ). For each octave band wavelength in the range 2.5 to 160mm the texture level T_λ in the octave band centred on a wavelength of λ (mm), is derived from

$$T_\lambda = 10 \log (p_\lambda . W_\lambda) \text{ dB} \qquad ....B.1$$

where p_λ is the average power spectral density within the octave bandwidth, W_λ, and determined from

$$p_\lambda = (1/N).\Sigma_{\text{over octave bandwidth}} [a_N^2 / (10^{-12} . W)]$$

where N is the number of data points derived from the Fourier Analysis within the octave band centred on wavelength l, with a resolution of W, a_N is the amplitude (m) of the texture wavelength for each of the N data points and 10^{-12} m^2 is a reference level (Sandberg, 1987).

If we define the RMS amplitude, $A_{RMS,\lambda}$ (m) in the octave band centred on a wavelength of λ (mm) as

$$A_{RMS,\lambda} = [(1/N).\Sigma_{\text{over octave bandwidth}} a_N^2]$$

then we can rewrite Equation B.1 in terms of the RMS amplitude, $A_{RMS,l}$ (m) as

$$T_\lambda = 10 \log (A_{RMS,\lambda}^2 / 10^{-12}) \text{ dB} \qquad ....B.2$$

To express texture levels T_λ dB in terms of the RMS amplitude, $A_{RMS,\lambda}$ (m) we can rearrange Equation B.2 to give:

$$A_{(RMS.\lambda)} = 10^{(T_\lambda - 120)/20} \; m$$

or converting to mm gives:

$$A_{(RMS.\lambda)} = 10^{(T_\lambda - 60)/20} \; mm \qquad ......B.3$$

Figure B1 shows graphically the relationship between texture level, T_λ , and the RMS amplitude, $A_{RMS,\lambda}$ (mm) as described in equation B.3.

In this Report texture levels are expressed in terms of RMS amplitudes which highway engineers may find easier to understand.

Recent work by Sandberg (1996) and Huschek (1996) indicates that increasing texture amplitudes in the megatexture range tends to be associated with increases in noise levels whereas increasing texture amplitudes below the 10mm octave band wavelength tends to produce lower noise levels. To explore this further two composite texture amplitudes were derived A_{mega} and $A_{macro<10mm}$. These are defined in the Glossary of Terms in Appendix A.

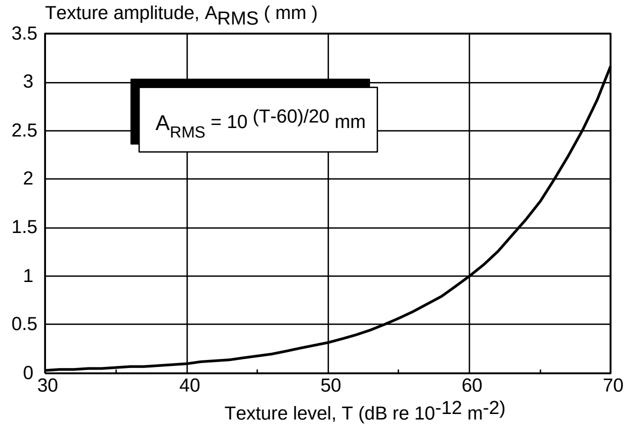

Figure B1 Relationship between texture level (T) and texture amplitude (A_{RMS})

B.2 The statistical pass-by method

The Statistical Pass-by (SPB) method requires the simultaneous measurement of maximum noise level and speed of individual vehicles in the traffic stream travelling in the nearside lane of the carriageway. Vehicles are categorised into “light” vehicles, which include all cars and vans with an unladen weight less than 1.5 tonnes, and “heavy” vehicles, which include all goods vehicles with unladen weight greater than 3.5 tonnes. Measurements of at least 50 vehicles in each group are required to characterise the surface. A regression of noise against the logarithm of vehicle speed is performed for each vehicle group[6].

The regression lines obtained for each vehicle category are used to determine the noise levels at a reference speed of 90km/h. These normalised noise levels are used to compare the acoustic performance of different road surfaces. This method has been found to give results which are repeatable to within 1.0 dB(A).

At each survey site the measurement microphone was positioned 7.5 metres from the centre of the nearside lane and 1.2 metres above the level of the road surface. The measurement microphone was connected to a real-time frequency analyser located and operated in a vehicle parked some distance away. The analyser was configured to record the noise level at the point when the A-weighted sound level reached a maximum during each selected individual vehicle pass-by.

During the surveys, the operator selected vehicles judged to be sufficiently separated from the rest of the traffic stream so that their noise and speed characteristics were not influenced by other vehicles. The operator monitored the approach of the vehicle visually and via the analyser display, once the vehicle had passed the microphone the operator confirmed that the maximum noise spectrum had been captured before storing the data.

Vehicle speeds were measured using a portable radar antenna connected to a controller with digital display indicating the measured speed in kilometres per hour. The radar antenna was positioned to be as unobtrusive as possible and the detector sensitivity adjusted so as to isolate individual vehicles travelling in the nearside lane of the carriageway. The measurements of speed and the classification of vehicle types were recorded on a laptop computer by the operator.

All measurements were taken when the road was dry and during light wind conditions, ie wind speeds less than 5m/s. To further minimise the effects of any turbulence due to wind, the microphone was fitted with a foam windshield. The air temperature before and after each survey was recorded.

In addition to determining normalised vehicle noise levels, regression analyses were carried out for each 1/3rd octave band in the range 20Hz - 10kHz. From the regression lines obtained, the reference levels for a speed of 90km/h were determined for each frequency band. This frequency analysis was carried out for both light and heavy vehicle categories. The average spectra for a passing speed of 90km/h were then compiled from the individual 1/3rd octave band reference levels.

B.3 Results

B.3.1 M18 and A50 surveys

Table B.1 M18 - Results from noise and texture surveys

Surface finish and site number	*Age [months after opening]*	*Maximum vehicle noise level [90km/h at 7.5m]*		*Surface Texture*							
		Light dB(A)	*Heavy dB(A)*	*SPTD[1] (mm)*	*$A_{2.5}$[2] (mm)*	*A_5 (mm)*	*A_{10} (mm)*	*A_{20} (mm)*	*A_{40} (mm)*	*A_{80} (mm)*	*A_{160} (mm)*
Exposed aggregate concrete (EAC)											
1A	0	79.8	86.7	1.28	0.11	0.17	0.31	0.32	0.29	0.24	0.22
	8	80.0	87.5	1.41	0.08	0.15	0.30	0.34	0.27	0.22	0.23
	20	78.9	86.6	1.5	0.08	0.14	0.29	0.39	0.37	0.25	0.24
	32	79.9	87.3	1.26	0.07	0.14	0.29	0.37	0.30	0.24	0.19
13	0	79.1	86.8	1.19	0.08	0.19	0.38	0.43	0.27	0.26	0.17
	8	80.2	87.6	1.36	0.10	0.22	0.43	0.46	0.34	0.29	0.18
	20	79.8	87.6	1.39	0.10	0.22	0.43	0.45	0.31	0.28	0.19
	32	79.6	86.5	1.32	0.09	0.19	0.38	0.40	0.34	0.29	0.18
Hot rolled asphalt (HRA)											
3	8	81.5	87.9	1.83	0.16	0.25	0.43	0.72	0.59	0.45	0.37
3A	0	81.6	87.6	-[3]	-	-	-	-	-	-	-
	8	81.3	89.2	2.49	0.22	0.36	0.60	1.01	0.97	0.78	0.44
	20	81.7	88.0	2.49	0.19	0.31	0.55	0.99	0.74	0.65	0.41
	32	82.2	87.9	2.23	0.19	0.32	0.55	0.94	0.74	0.60	0.33
10	0	81.7	87.7	-[3]	-	-	-	-	-	-	-
	8	82.0	88.7	2.22	0.22	0.36	0.62	0.91	0.81	0.64	0.48
	20	81.6	87.4	2.22	0.17	0.29	0.53	0.75	0.83	0.58	0.38
	32	81.7	87.5	2.06	0.17	0.29	0.51	0.71	0.68	0.37	0.29
11	8	81.5	87.8	1.78	0.24	0.35	0.74	0.96	0.76	0.62	0.52
Brushed concrete											
6	0	82.1	88.4	1.00	0.17	0.28	0.37	0.33	0.21	0.12	0.14
	8	82.3	89.7	1.02	0.12	0.22	0.31	0.31	0.25	0.17	0.15
	20	82.2	90.7	0.93	0.10	0.22	0.29	0.30	0.24	0.17	0.18
	32	83.4	89.9	0.99	0.09	0.17	0.25	0.28	0.23	0.20	0.18
Tined concrete											
7	0	80.1	87.3	0.67	0.10	0.24	0.34	0.23	0.14	0.10	0.10
	8	79.9	88.4	0.6	0.11	0.24	0.40	0.29	0.18	0.11	0.10
	20	80.7	88.1	0.73	0.12	0.28	0.49	0.42	0.19	0.14	0.13
	32	81.1	88.0	0.79	0.11	0.24	0.49	0.34	0.17	0.10	0.09

[1] *SPTD are the sand patch texture depth values derived from the 10m length measurements*
[2] *$A_{2.5}$ to A_{160} are the corresponding RMS texture amplitudes derived for each octave band wavelength centred at 2.5, 5, 10, 20, 40, 80 and 160mm*
[3] *Texture parameters were not measured due to poor weather conditions*

Table B.2 A50 - Results from noise and texture surveys

Site	*Age [months after opening]*	*Maximum vehicle noise level [90km/h at 7.5m]* Light dB(A)	Heavy dB(A)	*Surface Texture* SPTD[1] (mm)	$A_{2.5}$[2] (mm)	A_5 (mm)	A_{10} (mm)	A_{20} (mm)	A_{40} (mm)	A_{80} (mm)	A_{160} (mm)
Exposed aggregate concrete (EAC)											
1	2	78.7	86.8	2.22	0.14	0.29	0.57	0.54	0.42	0.30	0.28
	16	80.0	87.1	2.15	0.15	0.31	0.58	0.62	0.46	0.37	0.23
2	2	77.9	85.2	1.65	0.09	0.22	0.39	0.43	0.31	0.27	0.24
	16	79.4	87.1	1.60	0.10	0.22	0.40	0.45	0.34	0.25	0.21
3	2	79.9	86.7	1.72	0.11	0.23	0.47	0.54	0.39	0.35	0.30
	16	81.0	87.3	1.84	0.11	0.23	0.46	0.52	0.38	0.27	0.23
5	2	79.3	86.9	1.81	0.12	0.26	0.48	0.49	0.35	0.30	0.20
	16	80.8	87.2	1.75	0.12	0.27	0.49	0.53	0.36	0.28	0.22
Hot rolled asphalt (HRA)											
4	2	81.9	88.0	1.72	0.16	0.28	0.49	0.70	0.55	0.41	0.31
	16	82.3	88.6	1.68	0.14	0.24	0.38	0.64	0.58	0.40	0.31

[1] SPTD are the sand patch texture depth values derived from the 10m length measurements
[2] $A_{2.5}$ to A_{160} are the corresponding RMS texture amplitudes derived for each octave band wavelength centred at 2.5, 5, 10, 20, 40, 80 and 160mm.

Table B.3 M18 - Change in average vehicle noise levels over a period of 32 months trafficking

Vehicle type and surface finish	*Average maximum noise level dB(A) [90km/h at 7.5m][1] and age of surface (months)* At opening	*8*	*20*	*32*
Light vehicles				
Hot rolled asphalt (HRA)	81.7	81.6 (-0.1)	81.7 (0.0)	82.0 (+0.3)
Tined concrete	80.1	79.9 (-0.2)	80.7 (+0.6)	81.1 (+1.0)
Brushed concrete	82.1	82.3 (+0.2)	82.2 (+0.1)	83.4 (+1.3)
Exposed aggregate concrete (EAC)	79.5	80.1 (+0.6)	79.4 (-0.1)	79.8 (+0.3)
Difference (brushed - EAC)	+2.6	+2.2	+2.8	+3.6
Heavy vehicles				
Hot rolled asphalt (HRA)	87.7	88.4 (+0.7)	87.7 (0.0)	87.7 (0.0)
Tined concrete	87.3	88.4 (+1.1)	88.1 (+0.8)	88.0 (+0.7)
Brushed concrete	88.4	89.7 (+1.3)	90.7 (+2.3)	89.9 (+1.5)
Exposed aggregate concrete (EAC)	86.8	87.6 (+0.8)	87.1 (+0.3)	86.9 (+0.1)
Difference (brushed - EAC)	+1.6	+2.1	+3.6	+3.0

[1] Values in brackets indicate the change in vehicle noise level from the time of opening to traffic

Table B.4 A50 - Change in average maximum vehicle noise levels over a period of 16 months trafficking

Vehicle type and surface finish	*Average maximum noise level dB(A) [90km/h at 7.5m][1] and age of surface (months)*	
	2	*16*
Light vehicles		
Hot rolled asphalt (HRA)	81.9	82.3 (+0.4)
Exposed aggregate concrete (EAC)	79.0	80.3 (+1.3)
Heavy vehicles		
Hot rolled asphalt (HRA)	88.0	88.6 (+0.6)
Exposed aggregate concrete (EAC)	86.4	87.2 (+0.8)

[1] Values in brackets indicate the change in vehicle noise level from 2 months after opening to traffic

B.3.2 Recent surveys

Table B.5 Additional vehicle noise and surface texture for transversely textured surfaces

Site and surface finish	*Maximum vehicle noise level [90km/h at 7.5m]*		*Surface Texture*							
	Light dB(A)	*Heavy dB(A)*	*SPTD[1] (mm)*	*$A_{2.5}$[2] (mm)*	*A_5 (mm)*	*A_{10} (mm)*	*A_{20} (mm)*	*A_{40} (mm)*	*A_{80} (mm)*	*A_{160} (mm)*
Brushed concrete										
T1	83.8	90.8	0.81	0.08	0.14	0.16	0.18	0.14	0.13	0.14
T2	86.9	92.3	1.06	0.12	0.19	0.26	0.30	0.22	0.22	0.15
T3	86.2	90.6	1.06	0.13	0.23	0.29	0.34	0.27	0.19	0.16
T4	86.3	91.7	0.87	0.10	0.13	0.16	0.22	0.19	0.20	0.18
T5	86.5	92.4	1.15	0.12	0.20	0.26	0.25	0.19	0.17	0.17
T6	81.1	86.2	0.87	0.11	0.16	0.16	0.14	0.11	0.12	0.12
T7	81.9	87.5	0.82	0.12	0.20	0.18	0.13	0.12	0.10	0.11
T8	81.3	89.5	0.48	0.05	0.08	0.10	0.10	0.08	0.08	0.08
T9	83.0	89.0	0.75	0.11	0.18	0.20	0.17	0.12	0.10	0.09
T10	87.6	93.6	0.75	0.09	0.15	0.23	0.30	0.25	0.14	0.15
T11	89.0	94.8	0.91	0.09	0.16	0.28	0.35	0.31	0.20	0.23
T12	89.9	94.3	1.02	0.10	0.18	0.28	0.41	0.37	0.27	0.21
Grooved concrete										
T13	86.6	91.7	1.16	0.16	0.28	0.53	0.56	0.51	0.23	0.15
T14	83.7	90.8	0.85	0.13	0.23	0.37	0.34	0.35	0.16	0.16
T15	82.0	88.9	0.79	0.11	0.18	0.33	0.30	0.30	0.13	0.11
T16	83.5	89.0	0.89	0.12	0.25	0.40	0.38	0.31	0.14	0.13

[1] SPTD are the sand patch texture depth values.
[2] $A_{2.5}$ to A_{160} are the corresponding RMS texture amplitudes derived for each octave band wavelength centred at 2.5, 5, 10, 20, 40, 80 and 160mm.

Table B.6 Additional vehicle noise and surface texture for randomly textured surfaces

Site and surface finish	*Maximum vehicle noise level [90km/h at 7.5m]*		*Surface texture*							
	Light dB(A)	*Heavy dB(A)*	*SPTD[1] (mm)*	*$A_{2.5}$[2] (mm)*	*A_5 (mm)*	*A_{10} (mm)*	*A_{20} (mm)*	*A_{40} (mm)*	*A_{80} (mm)*	*A_{160} (mm)*
Hot rolled asphalt (HRA)										
R1	82.9	89.4	1.94	0.19	0.27	0.41	0.70	0.57	0.46	0.33
R2	82.4	88.2	2.09	0.24	0.31	0.51	0.87	0.71	0.53	0.37
R3	83.8	88.8	1.74	0.13	0.26	0.42	0.69	0.54	0.44	0.27
R4	83.0	87.9	1.54	0.17	0.27	0.47	0.72	0.65	0.49	0.35
R5	82.2	87.7	1.94	0.26	0.37	0.60	0.82	0.72	0.63	0.50
R6	84.6	88.5	2.40	0.27	0.33	0.53	0.97	0.87	0.67	0.57
R7	83.3	87.9	2.00	0.32	0.39	0.67	0.91	0.81	0.63	0.48
R8	83.8	87.9	1.93	0.21	0.32	0.59	0.89	0.85	0.62	0.47
R9	84.7	89.0	1.80	0.17	0.30	0.50	0.80	0.62	0.50	0.38

[1] SPTD are the sand patch texture depth values.
[2] $A_{2.5}$ to A_{160} are the corresponding RMS texture amplitudes derived for each octave band wavelength centred at 2.5, 5, 10, 20, 40, 80 and 160mm.

B.3.3 Correlation of vehicle noise and texture

Table B.7 Comparison of correlation coefficients (r) from linear regression of vehicle noise level and surface texture parameters

Vehicle type and texture pattern[1]	*Values of r for each surface texture parameter[2]*								
	SPTD[3] (mm)	*$A_{2.5}$[4] (mm)*	*A_5 (mm)*	*A_{10} (mm)*	*A_{20} (mm)*	*A_{40} (mm)*	*A_{80} (mm)*	*A_{160} (mm)*	*A_{mega}[5] (mm)*
Light vehicles Random (n=35)	*0.443* (**)	*0.714* (***)	*0.614* (***)	*0.436* (**)	*0.750* (***)	*0.743* (***)	*0.72* (***)	*0.705* (***)	*0.726* (***)
Transverse (n=24)	0.580 (**)	-0.023	-0.229	-0.146	0.364	0.549 (**)	0.790 (***)	0.773 (***)	0.817 (***)
Heavy vehicles Random (n=35)	0.440 (**)	0.574 (***)	0.519 (**)	0.340	0.673 (***)	0.650 (***)	0.650 (***)	0.561 (***)	0.631 (***)
Transverse (n=24)	0.427 (*)	-0.175	-0.281	-0.128	0.353	0.527 (**)	0.739 (***)	0.780 (***)	0.788 (***)

[1] The value n in brackets indicate the number of samples.
[2] The symbols in brackets show the level of significance in the correlation coefficient:
** - significant at the 5% level ** - significant at the 1% level *** - significant at the 0.1% level*
[3] SPTD are the sand patch texture depth values.
[4] $A_{2.5}$ to A_{160} are the corresponding RMS texture amplitudes derived for each octave band wavelength centred at 2.5, 5, 10, 20, 40, 80 and 160mm.
[5] See Appendix A for definition of A_{mega}

Appendix C: Influence of air temperature on vehicle noise levels

It is widely recognised that vehicle noise levels can be influenced by both air and road surface temperature. ISO Working Group 33, although agreeing the standardisation of the Statistical Pass-by method, is now considering how a form of temperature correction could be employed with the standard. At time of writing the precise form of this correction has still to be agreed by the Working Group.

Although there is considerable uncertainty associated with the effects of temperature on surface noise levels, a 'rule of thumb' which appears to be emerging as a general consensus is that light vehicle noise levels tend to decrease as the temperature increases at a rate of about 0.1 dB(A) per °C increase.

In the study described in this Report measurements of air temperature were taken before and after each measurement session and the average value determined. Figure C.1 shows the average temperature and vehicle noise data for both light and heavy vehicles travelling on the exposed aggregate concrete surfaces on the M18 and A50. In both cases the results of a regression analysis on the data are included on the Figure.

It can be seen that for both light and heavy vehicles the regression lines indicate a decrease in vehicle noise with an increase in temperature, but the light vehicle regression line exhibits a steeper slope than that for heavy vehicles.

Although the result does appear to indicate the existence of a relationship between SPB vehicle noise levels and temperature, the correlation is fairly weak. It should be noted that the data set shown in Figure C.1 also includes variations in site noise levels which may be attributed to other factors such as age of the surface. Further work is planned to isolate temperature effects from other factors which may affect vehicle noise levels derived from the SPB method.

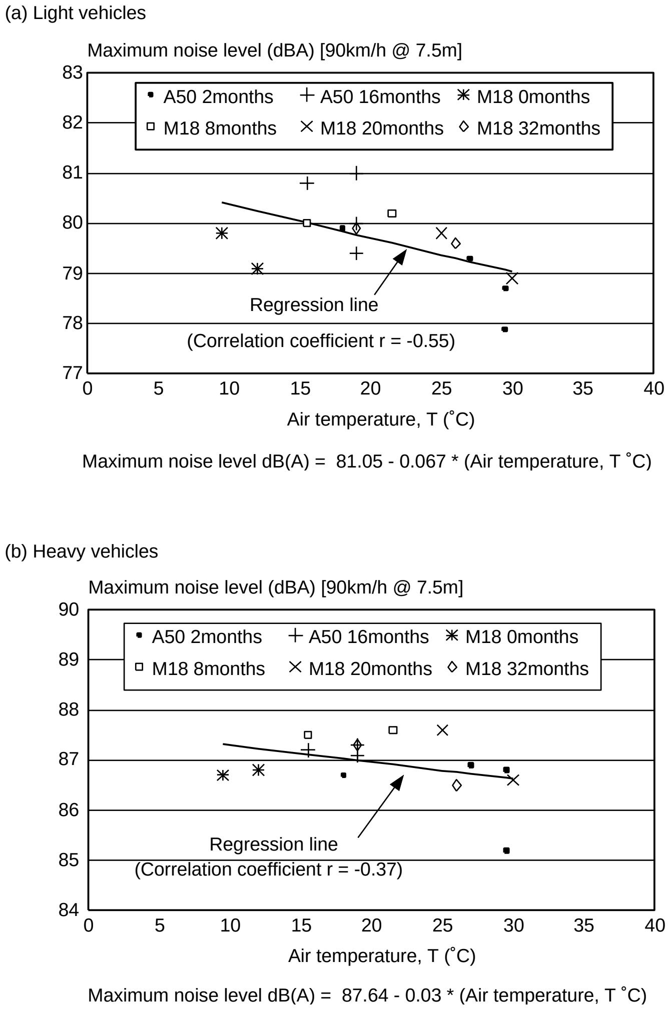

Figure C.1 Variation in vehicle noise level and air temperature (M18 and A50 - Exposed aggregate surfaces)

Appendix D: Estimating traffic noise levels

D.1 Background

A method for estimating traffic noise using the L_{Aeq} scale was developed by a Working Party for the Technical Sub-Committee of the Noise Advisory Council (Noise Advisory Council, 1978). Section D.2, briefly outlines the method and describes the input parameters; Section D.3, then applies the method to estimate traffic noise levels from vehicles travelling on different types of road surfaces for typical traffic conditions on high speed roads.

D.2 Equation for estimating traffic noise levels

The equation for estimating traffic noise L_{Aeq} level is given by the following formula:

$$L_{Aeq} = 10\log_{10}\left[N\sum_{n=1}^{n=m} p_n.10^{Lax_n/10}\right] + C \qquad \text{...... (D.1)}$$

where N = total traffic flow in a given time period
m = the number of different vehicle categories
p_n = the percentage of vehicles in the traffic stream classified as vehicle category n.

and $L_{AXn} = L_{Amax} - 10\log_{10}v$

L_{AXn} is a measure of the average total energy associated with a typical vehicle pass-by for a vehicle classified as vehicle category n where L_{Amax} is the average maximum pass-by noise level from vehicles travelling at a mean speed of v km/h.

The final term C is constant for a given location and site layout.

D.3 Estimating differences in traffic noise levels for high speed roads

To estimate differences in traffic noise levels from vehicles travelling on different high speed road surfaces using Equation (D.1) requires the following input parameters:

a the number of vehicles in each vehicle category expressed as a percentage of the total flow (%) and

b the mean vehicle speed, v km/h, for each vehicle category together with the average maximum pass-by noise L_{Amax} level at the mean vehicle speed.

The total traffic flow, N, and the site layout details were assumed to be the same for comparison purposes and, therefore, were subtracted out from the equation when estimating differences in traffic noise levels.

The traffic flow was assumed to consist of two vehicle categories “light” and “heavy” vehicles as defined in Note 1. The percentage of vehicles in each vehicle category expressed as a percentage of the total vehicle flow was obtained from recent DoT statistics (Department of Transport, 1993) for high speed roads as was the mean vehicle speed for each vehicle category (Department of Transport, 1995). This enabled the comparison in traffic noise levels to reflect typical traffic conditions on high speed roads.

For each survey where noise and texture measurements were carried out on the M18 and A50, the maximum pass-by noise level for each vehicle category at the mean vehicle speed, v km/h, was calculated from the vehicle noise and speed functions derived from the SPB measurements described in Section B.2 of Appendix B. For each survey the average maximum pass-by noise L_{Amax} level was then calculated for each surface finish. Table D.1 shows the relevant input parameters for each survey and each surface finish that were used in Equation D.1 to derive values of L_{Aeq} which are also shown together with the estimated difference in traffic noise levels between the surfaces relative to HRA.

Table D.1 Estimated differences in traffic noise levels for vehicles travelling on different surfaces

Road, age and surface finish	*Average maximum pass-by noise level L_{Amax} dB(A)*[1]		*Traffic noise L_{Aeq} level*[2] *dB(A)*	*Estimated difference in traffic noise level relative to HRA*
	Light	*Heavy*		
M18 - At time of opening				
HRA	84.0	87.7	64.6	-
Exposed aggregate	82.2	86.8	63.1	-1.5
Brushed concrete	84.6	88.4	65.2	+0.6
Tined concrete	82.6	87.3	63.5	-1.1
M18 - At 8 months				
HRA	84.1	88.4	64.9	-
Exposed aggregate	82.3	87.6	63.5	-1.4
Brushed concrete	85.0	89.7	65.9	+1.0
Tined concrete	82.6	88.4	64.0	-0.9
M18 - At 20 months				
HRA	84.0	87.7	64.6	-
Exposed aggregate	82.1	87.1	63.2	-1.4
Brushed concrete	84.9	90.7	66.3	+1.7
Tined concrete	82.2	88.1	63.6	-1.0
M18 - At 32 months				
HRA	84.4	87.7	64.9	-
Exposed aggregate	82.2	86.9	63.1	-1.8
Brushed concrete	85.8	89.9	66.5	+1.7
Tined concrete	83.2	88.0	64.2	-0.7
A50 - At 2 months				
HRA	84.1	88.0	64.8	-
Exposed aggregate	81.9	86.4	62.8	-2.0
A50 - At 16 months				
HRA	85.2	88.6	65.7	-
Exposed aggregate	83.0	87.2	63.8	-1.9

[1] The average maximum noise level, L_{Amax} dB(A) for each vehicle category was calculated assuming the mean vehicle speed for light and heavy vehicles was 110 and 90km/h respectively. (Department of Transport, 1995).

[2] Traffic noise levels, L_{Aeq} dB(A), were calculated assuming the traffic consisted of 14% heavy vehicles. (Department of Transport, 1993).

Notes

[1] Light vehicles are all passenger cars and light vans with an unladen weight of less than 1.5 tonnes. Heavy vehicles are commercial vehicles with an unladen weight of more than 3.5 tonnes.

[2] Changes in traffic noise levels may be difficult to assimilate, particularly when assessing noise disturbance. However, to give some indication, a reduction in noise level of 3 dB(A) would be expected if the traffic flow were halved.

[3] Macrotexture: Macrotexture is the deviation of a road surface from a true planar surface with the characteristic dimensions along the surface of 0.5 - 50mm.
Megatexture: Megatexture is the deviation of a road surface from a true planar surface with the characteristic dimensions along the surface of 50 - 500mm.

[4] The Investigatory level MSSC (at 50km/h) for a site of category B (dual carriageway (all purpose) non event section) is 0.35. (HD 28/94, Volume 7, Section 3, Part 1. DOT et al, 1994)

[5] L_{Aeq} is widely used in Europe and the USA for assessing the impact of traffic noise on the environment, whereas, L_{A10} has been used historically in the UK. Due to the statistical characteristics of the L_{A10} scale it is much more difficult to combine the noise from different sources using L_{A10}. Both scales are defined in Appendix A.

[6] Previous research by Harland (1974) has shown that the maximum noise level in dB(A) of a passing vehicle measured at 7.5m from the centre line of the vehicle path is related to vehicle speed, in km/h, by the general formula

$$L_{Amax} = a + b.\log_{10}v$$

where v is the vehicle speed and a and b are constants.

Abstract

In an effort to tackle road traffic noise, research into quieter road surfaces has included trials of a new type of concrete surfacing called exposed aggregate concrete, which had been used in a number of other European countries. Two trials of exposed aggregate concrete have been constructed in the UK; the first on the M18 in South Yorkshire which was completed in winter 1993 and the second on the A50 in Derbyshire which opened in Spring 1995. The M18 trial consisted of exposed aggregate concrete, hot rolled asphalt, brushed and tined textured concrete surfaces for comparison. The A50 trial comprised of exposed aggregate concrete and hot rolled asphalt surfaces only. This report presents the results of measurements available at the end of 1996 to assess the surface properties related to safety (SCRIM, Braking Force Coefficient and texture depth) and the results of vehicle noise measurements recorded at the two trial sites.

Related publications

RR297 *Measurement of the macrotexture of roads, Part 3. Development of the high-speed texture meter* by P G Roe. 1992 (price code E, £20)

RR 120 *Measurement of the macro-texture of roads, Part 2. A study of the TRRL mini texture meter* by J R Hosking, P G Roe and L W Tubey. 1987 (price code B, £15)

RR245 *A model to calculate traffic noise levels from complex highway cross-sections* by D C Tobutt and P M Nelson. 1990 (price code C, £15)

SR696 *Noise from vehicles running on open textured road surfaces* by P M Nelson and N F Ross. 1981 (price code AA, £10)

LR896 *Road surfaces and traffic noise* by R E Franklin, D G Harland and P M Nelson. 1979. (price code AA, £10)

SR340 *Research on skid-resistance at the Transport and Road Research Laboratory. (1927-1977)* by G F Salt. 1997 (price code AA. £10)

LR737 *Measurement of skidding resistance Part 1. Guide to the use of SCRIM* by J R Hosking and G C Woodford. 1976. (price code AA, £10)

LR652 *Rolling noise and vehicle noise* by D G Harland. 1974. (price code AA, £10)

CT67.1 *Road surface noise update (1994-1997)* (price £15)

CR320 *Porous concrete surfacing for roads* by J A Dalziel. 1992 (price code H, £30)

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