Increasing the environmental sustainability of asphalt

J C Nicholls, I Carswell, M Wayman and J M Reid
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Glossary
Abstract

There is increasing interest in improving the sustainability of every aspect of life in order to conserve resources and reduce carbon emissions. Great strides have been made to improve the environmental sustainability of asphalt with the industry implementing measures to improve its durability, reuse reclaimed asphalt and incorporate secondary materials. Durability is a major issue for minimising both the environmental impact of and traffic disruption caused by subsequent maintenance, whilst recycling should be the easiest method of improving environmental sustainability. The incorporation of secondary material has great potential, although its recyclability needs to be considered. The effect on the carbon footprint of these effects and other life-cycle impacts should increase the environmental sustainability of asphalt pavements. This Insight Report describes these measures and considers the resulting life-cycle implications.
Executive summary

There is increasing interest in improving the sustainability of every aspect of life in order to conserve resources and reduce carbon emissions. Those involved with the construction of asphalt pavements have made great strides towards improving the environmental sustainability of asphalt, the principal issues being to implement measures to improve its durability, to reuse or recycle reclaimed asphalt (RA) and to incorporate secondary materials.

The durability of the pavement is important in minimising both the environmental impact and the traffic disruption caused by subsequent maintenance. To start, the foundations to the pavement need to be suitable, or made suitable at minimum environmental cost using such techniques as crack and seat for existing concrete pavements. The drainage needs to be capable of keeping water away from the asphalt as far as practicable and the asphalt needs to be fully compacted. The expected durability of pavements, particularly surface courses as the most exposed part of the pavement, is relatively limited but could easily be enhanced by simple measures. These measures include the wider use of bond coats and ensuring that there is an adequate binder film thickness. The use of binder modifiers is generally designed to enhance certain physical properties, but their effect on the durability of the resulting asphalt and the environmental cost of their production need to be assessed. However, any procedure to enhance durability may have to be moderated because of the conflicting requirements for the performance of other required properties.

Recycling should be the easiest method of improving the sustainability. Although 100% of RA can be recycled, mixtures are not currently produced with 100% RA. However, the proportions being incorporated are increasing steadily, even in the surface course layer. The open-loop use of RA in lower layers has become routine, but higher-level use, known as “closed-loop reuse”, needs to be further encouraged. One particular advantage with recycling is the reduction of transport to get the component materials to where they are needed.

The use of secondary materials for filler tends to be counter-productive because there is usually an excess production of quarry fines when crushing aggregate. However, some use of very fine material, such as cement kiln dust, may have other environmental benefits. The incorporation of secondary material for the coarser fractions has greater potential, with a variety of slags having been used for a long time whilst others, like crushed glass, have started to be incorporated more recently. One aspect of using secondary materials that needs to be considered for true sustainability is their recyclability, including that of binder modifiers. Asphalt is a rare product in that it is 100% recyclable, and any impairment in that situation would be environmentally damaging.

There are several options available to improve the environmental sustainability of asphalt used in highway applications. In particular, reduced transport, better journey planning of wagons, enhanced durability, use of secondary materials and recycling can all be beneficial to varying degrees.

In summary, asphalt is a remarkable material that can be durable, is 100% recyclable and can incorporate secondary materials. However, it can be made more durable, more of it can be recycled and more appropriate secondary materials can be incorporated. The result will improve its sustainability by reducing its carbon footprint and enhancing other life-cycle benefits. However, care and attention is needed in the design, construction and maintenance of the material if these benefits are to be fully realised.
1 Introduction

There is increasing interest in improving the sustainability of every aspect of life in order to conserve resources and reduce carbon emissions. The asphalt industry has made great strides towards improving the sustainability of asphalt pavements. It has implemented measures to increase the environmental sustainability of asphalt, the principal ones being to improve its durability, to incorporate secondary materials and to reuse or recycle reclaimed asphalt (RA).

The 1992 Earth Summit in Rio de Janeiro placed an obligation on the 150 governments attending to promote sustainable development to secure a viable future for our planet. The outcome of the conference was issued as Agenda 21 (Keating, 1993), which set out how countries should work towards sustainability. This approach included reducing the use of finite resources, increasing energy efficiency, minimising waste and protecting the natural world. Agenda 21 is having a considerable effect on the way highway authorities plan and implement new construction and maintenance works. The 2002 Earth Summit in Johannesburg (UN, 2002) assumed a collective responsibility to advance and strengthen the interdependent and mutually reinforcing pillars of sustainable development, economic development, social development and environmental protection at the local, national, regional and global levels.

The UK government has defined five principles that together define sustainable development. These principles are summarised in Figure 1.1. Two of these principles – using sound science responsibly and promoting good governance – are added to the traditional three pillars of sustainability: environment, economy and society. Whilst it is hoped that this Insight Report contributes to sound science and informs good governance, in terms of the shared principles of sustainability it is primarily concerned with the environmental context.

The durability of the pavement is important in minimising both the environmental impact and the traffic disruption caused by subsequent maintenance. To start, the foundations need to be suitable, or made suitable with minimum environmental cost using such techniques as crack and seat (C&S) for concrete pavements. The expected durability of pavements, particularly surface courses as the most exposed part of the pavement, is relatively limited but could easily be enhanced by simple measures. The use of a binder modifier is generally designed to enhance certain physical properties, but their effect on the durability of the resulting asphalt and the environmental cost of their production need to be assessed. Any procedure to enhance durability may have to be moderated because of the conflicting requirements for the performance of other required properties.

Recycling should be the easiest method of improving sustainability. Although 100% of RA can be recycled, mixtures are not currently produced with 100% RA. However, the proportions being incorporated are increasing steadily, even in the surface course layer. The open-loop use of RA in lower layers has become routine, but higher-level closed-loop reuse needs to be further encouraged. One particular advantage with recycling is the reduction of transport to get the component materials to where they are needed.

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**Figure 1.1 The UK’s shared principles of sustainable development**

(Source: Defra, 2008)

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1 The terms “sustainability” and “sustainable development” are used interchangeably in this Insight Report.

2 Where material removed is used for an alternative application.

3 Where material removed is reused for the same application.
The use of secondary material for filler tends to be counter-productive because there tends to be excess production when crushing aggregate, but the use of some very fine materials, such as cement kiln dust (CKD), may have other environmental benefits. The incorporation of secondary material for the coarser fractions has greater potential, with a variety of slags having been used for a long time whilst others, like crushed glass, have started to be incorporated more recently. One aspect of using secondary materials that needs to be considered for true sustainability is their recyclability, including that of binder modifiers. Asphalt is a rare product in that it is 100% recyclable, and any impairment in that situation would be environmentally damaging.

There are several life-cycle impacts of the options available to increase the environmental sustainability of asphalt construction. In particular, the effect of reduced transport (particularly by reuse of wagons by better journey planning), the effect of enhanced durability, the effect of using secondary materials and of recycling on the carbon footprint of asphalt will be examined. This Insight Report reviews these issues in order:
• to help engineers find information to enhance the sustainability of any structures for which they are responsible;
• to provide evidence that planning for sustainability in all its forms can bring rewards of longer-lasting and more sustainable construction; and
• to encourage more engineers to think about the issues needed to improve sustainability.
2 Durability

2.1 Concept

2.1.1 Philosophy of durability

The importance of durability has increased with the need to improve sustainability. Constructing pavements that do not need to be maintained, or with an increased time between maintenance operations, is often the most sustainable option provided that it does not require significant increases in the use of virgin materials, the consumption of additional energy and/or the carbon footprint.

Road Note 42 (Nicholls et al., 2008) sets out the main criteria that need to be considered if asphalt products are to be designed, constructed and maintained in order to maximise their service life. However, the Road Note does not include much detail about how to undertake a specific project with specific requirements and constraints.

The main issues covered in the Road Note are:

• Job planning
  • Supervision
  • Risk assessment
  • Equipment and manpower availability
  • Timing
  • Continuity of work
  • Established practice and latest technology

• Constraining influences
  • Foundations (impermeability, strength, consistency)
  • Drainage (new pavement construction, highway improvements, coordinated design, maintenance of drainage systems)

• Design
  • Pavement (durability as a performance requirement, layer thickness)
  • Materials (selection of component materials, temperature)

• Joints and sealing
  • Joints (location, method of forming joints, free edges, painting of joints, surface sealing joints)
  • Tack and bond coats (cleanliness of substrate, properties, sealing, adhesion, uniformity)
  • Edge sealing

• Application
  • Compaction (job mixture trials, number of rollers, over-running of edges, around ironwork, weather)
  • Finish
  • Maintenance

Some, but not all, of those topics are covered in more detail later in this chapter.

2.1.2 Definition of durability

An asphalt material or a pavement can be said to be durable if it maintains its structural integrity and functional properties at a satisfactory level within its nominal design life when exposed to the effects of the environment and the expected traffic loading. However, two distinct definitions are given in Road Note 42 (Nicholls et al., 2008) for asphalt durability and pavement durability.

Asphalt durability is defined as “the maintenance of the structural integrity of compacted material over its expected service life when exposed to the effects of the environment (water, oxygen, sunlight) and traffic loading”. Asphalt durability is dependent on:

• the component materials used;
• the weather conditions during laying;
• the mixture, both the generic type and the job mix design;
• the workmanship during mixing, transport, laying and compaction; and
• the site conditions, including geometry, local weather conditions immediately after construction, drainage and (possibly) traffic.

Pavement durability is defined as “the retention of a satisfactory level of performance over the structure’s expected service life without major maintenance for all properties that are required for the particular road situation in addition to asphalt durability”. Pavement durability is dependent on:

• the asphalt durability;
• the traffic and other site conditions;
• the performance requirements set; and
• the asphalt performance characteristics.

The performance requirements could include any or all of the following:

• Stiffness
• Resistance to fatigue
• Texture depth
• Transverse rutting
• Longitudinal ride quality
• Skid resistance
• Noise level
• Colour

However, the major problem in estimating the typical service life of asphalt surfacings, if not all layers, is defining the criterion that describes when a surfacing is deemed to be no longer in an acceptable condition for continued use. Thin surfacing sites being monitored for the Highways Agency (HA) included some that have remained in service long after an Inspection Panel deemed them unserviceable, whilst others were removed when still in a relatively good condition (Nicholls et al., 2007a). The latter included a surfacing that was replaced because it was located within a section for which a major maintenance scheme was being implemented and three surfacings (out of a trial with four different surfacings) that were surface dressed because they were still in a good enough condition to remain serviceable for longer with that dressing (the fourth site not surface dressed was in worse condition). Therefore, when numerical criteria such as texture depth and skid resistance are not infringed, the condition when a surfacing would be deemed to be at the end of its service life is not universal. This situation also applies to structural layers, although there are different numeric criteria.

2.2 Inherent factors affecting durability

2.2.1 Continuity of supply of asphalt

A continuous paving operation brings many performance advantages as well as maximising the use of the equipment for the organisation laying the pavement. It reduces the number of stops during laying, which can disrupt the
surfacing operation, reduce the ride quality and, in extreme cases, require day joints. However, oversupply can also cause problems, with asphalt having to be stored hot in the delivery vehicles for extended periods. The ideal situation is to have only one delivery vehicle waiting whilst another is discharging, but the vagaries of traffic, particularly on busy roads, often make it difficult to achieve this timing consistently. Nevertheless, the supply from the plant to each job should be planned to be consistent with the amount that can be laid by the gangs and equipment on those jobs. Good communications between the plant and site, particularly on larger contracts, can mitigate any problems of temporary oversupply or undersupply.

### 2.2.2 Appropriate materials

#### 2.2.2.1 Quality products

The use of quality component materials is necessary to achieve good durability, although durability is not necessarily coexistent with the best quality for other performance requirements – for example, the most robust aggregates will not necessarily have high polished stone values (PSVs). Furthermore, the practical considerations of value for money and sustainability must be balanced against using the best possible quality on every occasion. Therefore, the choice of materials, whether between mixtures or components of those mixtures, must be a compromise between consistently achieving the initial performance requirements, maintaining those properties in service and reaching an acceptable level of durability.

With the introduction of harmonised European standards, many of the products (asphalt, aggregate, bitumen) can be, or will soon be able to be, purchased with a CE Mark. In some European countries, all products that can be CE Marked will have to be CE Marked before they can be put on the market as a requirement of the Construction Products Directive (European Commission, 1988). However, this requirement is not the case in the UK because of a UK opt-out, but public procurers (which include the majority of ultimate clients for highway and airfield pavements) are required by the Public Procurement Directive (European Commission, 2004) to take the best available advice, which could be regarded as using CE Marked products whenever possible. However, generally the ultimate client buys the final pavement and not the components of that pavement.

CE Marks are not explicitly intended for quality control, but they do contain the supplier’s assessment of how the product meets the mandated properties, for which they are legally liable. Among those properties is the durability of the other properties, so that it does have implications for durability, even if maintenance of performance properties is not included in the definition of asphalt durability given in Section 2.1.2. Nevertheless, CE Marking only provides assurance about the quality of a product insofar as those of the required properties that are included on the CE Mark with an adequate class being quoted.

#### 2.2.2.2 Performance

Different properties of component materials are important for different mixtures and usages and these are generally listed in the relevant clauses of the appropriate specification, for example the Specification for Highway Works (SHW) (HA et al., 2009). However, the properties considered are those required to achieve initial performance and not necessarily long-term durability. With current moves to increase the range of secondary component materials into mixtures, it is important not to assume that they will behave in the same manner as natural aggregates and binders and further checks may be needed. Examples of where additional checks are required for specific aggregates are given in the SHW, where air-cooled blast furnace slag (BFS) has to be free from iron dicalcium silicate disintegration and iron disintegration whilst steel slag has a volume expansion limit. None of these requirements apply to other aggregates although both slags have a proven track record as an aggregate. This subject is dealt with more thoroughly in Chapter 4.

#### 2.2.2.3 Compatibility

There are usually very few problems with components being incompatible with each other; generally, an aggregate is either compatible with all sources of bitumen or with none. Binder modifiers can be more variable in their compatibility with different sources of binder, but compatibility is generally taken into account by the binder supplier in their premixed binders. There are tests for compatibility of the component materials in a mixture and others for the associated property of water sensitivity of the mixture. The compatibility tests include BS EN 12697-11 (CEN, 2003a) and the saturation ageing tensile stiffness (SATS) conditioning test (HA et al., 2009). The water sensitivity tests include BS EN 12697-12 (CEN, 2003b) and Appendix A.2 of the Highway Authorities’ Product Approval Scheme (HAPAS) thin surfacing guidelines (BBA, 2008). However, there is no general consensus about the reliance of these tests.

#### 2.2.2.4 Recycleability

Asphalt manufactured with traditional component materials is one of the few products that can be completely recycled back into asphalt, even if no asphalt is manufactured entirely from RA. Therefore, it is important to ensure that any secondary materials that are incorporated into asphalt do not jeopardise this property. Some past component materials, in particular tar, have prevented recycling into hot mixtures because of the health and safety issues that were subsequently identified (although tar-bound materials have been successfully recycled using cold processes). Therefore, new component materials should be checked for any potential inherent hazards (Nicholls et al., 2005) before use. Mixtures should be designed so as not to damage the potential for reclaiming and recycling that material when it reaches the end of its useful service life.

#### 2.2.3 Binders

Increasing the binder content of asphalt is generally accepted to be a way of achieving improved durability. Hardening of the binder exposed to the atmosphere is the principal result of binder ageing, so that the use of a higher binder content, and hence thicker binder-film on the aggregate particles and lower voids in the mixed asphalt, is logical. However, the use of
high binder contents also reduces stiffness and increases the potential for deformation. Therefore, this approach, at least in its full form, tends to be limited to mixtures for roads carrying low volumes of traffic. The main exceptions are porous asphalt (PA) and Category 2 enrobé à module élevé (EME2). In PA, the extra binder merely reduces the air voids content marginally with the main problem being to avoid binder drainage (Daines, 1992). In EME2 (Sanders and Nunn, 2005), the binder is sufficiently strong and deformation resistant to counteract the loss of strength and deformation resistance from having a high binder content.

2.2.4 Permeability and air voids content
Voids, and particularly interconnected voids, are generally detrimental to durability because they allow oxygen and water to get into close proximity with a larger surface area of the binder. The result will be more rapid ageing of that binder and, in more extreme cases, the potential for the water to debond the binder, leading to stripping. Surfacings and some mixture types are designed to have voids (surface texture in the case of surfacings) where the mixture design has to provide a thick binder-film so that the binder not on the surface is adequately protected.

2.2.5 Asphalt temperature
To create a durable asphalt pavement, the asphalt should be mixed, delivered, laid and compacted within the material temperature limits for a given mixture design. The temperature of the asphalt is critical to its workability and the ability to achieve adequate compaction. The mixing temperature, as the starting point of the process, is critical: it will damage the binder if it is too high whilst it will prevent complete coating of the aggregate particles and proper compaction of the mixture if it is too low.

The higher the temperature of asphalt during mixing, the more damage that can be done to it and the greater the carbon footprint. However, there are limits for each mixture, below which it cannot be mixed homogeneously and compacted effectively. The damage from overheating generally consists of the binder hardening prematurely, but some aggregates can degrade or shatter at high temperatures. Most aggregates used in construction in the UK are not susceptible to damage, even at inflated mixing temperatures. The damage that results from mixing at too low a temperature is that the binder does not effectively and uniformly coat the aggregate particles, leading to an inhomogeneous mixture that is not protected by a continuous binder-film. The damage that results from a mixture that is compacted at too low a temperature is that the compaction cannot be completed, resulting in high air voids contents and a susceptibility to fretting, water ingress and binder stripping.

Limits on the temperatures, which depend on the mixture type and binder grade, are generally given in standards such as BS 594987 (BSI, 2007a). However, these values can be lowered by inclusion of suitable waxes or polymers, but there are limits to the extent that they can be lowered effectively. It is vital that mixtures are mixed, transported, laid and compacted within the relevant temperature envelope to avoid durability problems associated with premature binder hardening, inhomogeneity, uncoated aggregate particles and/or lack of compaction.

The mixture should be transported to the work site as soon as possible and loaded into the paver hopper, or temporarily stored in a surge silo. It is important that the transport is done without delay and without any change in the characteristics of the mixture (open-graded mixtures that contain excess bitumen will tend to drain whilst stored temporarily in a surge silo and during transportation to the work site by a delivery vehicle). The mixture must arrive at site so that it can be placed when the temperature of the mixture is within its specified compaction range. Adequately insulated round-bottom delivery vehicles with covered beds can reduce mixture temperature loss (Nilsson et al., 2000).

The transport distance and time are important factors in maintaining high mixture temperatures (particularly during cold weather conditions). If long transportation distances are necessary, a material transfer vehicle (MTV) can remix the material at the work site and normalise the temperature of the mixture, minimising the occurrence of “cold” spots on delivery to the paver to only a few degrees. The use of MTVs can also improve capacity because the paving operation can be performed continuously without any unnecessary breaks or interruptions whilst waiting for mixture deliveries. Tarpaulin-covered trucks can also minimise excessive cooling of the mixture. Well-planned production and good coordination of transportation is essential to ensure an even flow of suitably hot material to the site (Nilsson et al., 2000).

The mixture temperature as it comes out from under the paver screed is important in determining the time available for effective compaction: asphalt temperature has a direct effect on the viscosity of the bitumen and thus compaction. As the asphalt temperature decreases, the bitumen becomes more viscous and resistant to deformation, which results in a smaller reduction in air voids for a given compactive effort (WSDOT, 2000). If the initial mixture temperature is too high, the mixture may be tender and difficult to compact until the temperature decreases and the viscosity of the bitumen increases (TRB, 2000). Therefore, mat temperature is crucial to both the actual amount of air voids reduction for a given compactive effort, and the overall time available for compaction.

The time available for compaction is defined as the time for a mixture to cool from its temperature when it passes out from under the paver screed to a minimum compaction temperature. As the initial mixture paver-out temperature is increased, the time available for compaction also increases. Below the minimum compaction temperature for a design mixture, little density gain is achieved with the application of additional compactive effort. Any additional rolling with steel wheel rollers, except to remove roller marks, may result in fracture of the aggregate in the mixture and a decrease in density.

Asphalt is usually produced at temperatures between 130 °C and 165 °C. Depending on environmental conditions, the insulation provided in the wagon and the length of the haul, the mixture can decrease in temperature by between 3 °C and 14 °C between the plant and the paver (TRB, 2000).

The major factors affecting time available for compaction are (Roberts et al., 1996):
- initial mat temperature;
- mat or lift thickness, with thicker lifts, having a smaller surface-to-volume ratio, losing heat more slowly and hence increasing the time available for compaction;
substrate temperature, with hotter surfaces removing heat from the mat at a slower rate and hence increasing the time available for compaction;

- ambient temperature, with hotter air temperatures removing heat from the mat at a slower rate and hence increasing the time available for compaction; and

- wind speed, with higher wind speeds increasing the mat heat loss by convection and hence decreasing the time available for compaction.

2.2.6 Layer thickness

An overall priority for the final pavement is to achieve the required level so that the gradients, crossfalls and drainage paths are as designed. The correct drainage path for surface water is particularly important for durability. However, the actual thickness of the layer is also important for durability, particularly the minimum thickness to ensure no dragging during laying and the maximum thickness to avoid an inability to fully compact the layer or produce an unstable layer that is susceptible to secondary compaction.\(^5\) The thickness of layers, particularly the upper layers, can be compromised if the starting level of that layer is not as in the design. Therefore, it is important to control both the thickness and the level of the top surface within reasonable limits for all layers of the pavement.

Each interface in the pavement is an additional point of weakness where moisture can enter, applying to horizontal joints (i.e. between layers) as well as vertical joints (i.e. between rips). Therefore, it is beneficial to reduce the number of layers subject to the constraints of the maximum thickness that a material can be laid at; the need for different layers to have different properties (particularly the surface course and the base); and the need to conserve stocks of the coarse aggregate used in surface courses that have high PSVs.

2.2.7 Compaction

2.2.7.1 General

Compaction is the process by which the asphalt is compressed and reduced in volume, thereby reducing air voids and increasing the unit weight or density of the mixture. As a result of the compaction process, the bitumen-coated aggregates in the mixture are forced closer together, increasing aggregate interlock and inter-particle friction. Adequate compaction of the asphalt (TRB, 2000):

- increases fatigue life;
- decreases permanent deformation (rutting);
- reduces oxidation and ageing;
- decreases moisture damage;
- increases strength and stability; and
- decreases low-temperature cracking.

Asphalt with all the desirable mixture design characteristics will perform poorly under traffic if it has not been compacted to the proper density level.

Asphalt compaction is influenced by a myriad of factors, some relating to the environment, some determined by mixture and structural design and some under contractor control during construction. The primary factors that affect the ability to compact an asphalt (TRB, 2000; WSDOT, 2000) are:

- **Environmental factors**: Wind speed, solar flux, ground and air temperatures,
- **Aggregate factors**: Grading, size, shape, fractured faces and aggregate volume,
- **Binder factors**: Bitumen content, film thickness, chemical and physical properties,
- **Construction factors**: Lift thickness, type of roller, number of rollers, number of passes, speed and timing,
- **Other factors**: Foundations, mixture temperature, haul distance and haul time.

Environmental factors are determined by when and where paving occurs, and are beyond the control of the contractor. In response to pressure for the timely completion of paving projects, it is impractical for contractors to wait for optimal weather conditions for paving. Mixture and structural design factors are determined before construction and, although they should account for construction practices and the anticipated environment, they often must compromise ease of construction and compaction to achieve design objectives (WSDOT, 2000).

The construction factors highlighted above are the most controllable and adaptable of all the factors affecting compaction. Although some factors, such as haul distance/time, asphalt production temperature, lift thickness and type/number of rollers, may be somewhat predetermined, other factors associated with roller timing, speed, pattern and number of passes can be manipulated as necessary to produce an adequately compacted mat (WSDOT, 2000).

2.2.7.2 Influence of aggregates

The compactibility or stiffness of an asphalt is influenced by the nature of the aggregate particles and the grading of the aggregate mixture. The particle size distribution affects the way that the aggregate interlocks and thus the ease with which the aggregate can be rearranged under roller loads.

In general, aggregate effects on compaction can be broken down by aggregate size (TRB, 2000; WSDOT, 2000):

- **Coarse aggregate**: Surface texture, particle shape and the number of fractured faces can affect compaction. Angular and rough surface textures, cubical or block-shaped aggregate (as opposed to round aggregate) and highly angular particles (high proportion of fractured faces) will all increase the resistance to reorientation by rollers, and hence increase the resistance to orientation and the required compactive effort to achieve a specific density.

- **Fine aggregate**: High amounts of fine aggregate will cause a mixture to displace laterally ("shove") rather than compact under roller loads, particularly when the aggregate is rounded (i.e. usually natural sand). Excess fine aggregate results in a mixture with insufficient voids in the mineral aggregate, leaving only a small voids volume available for the asphalt to fill. Therefore, one consequence of the filler content being too high is that, with the binder, it completely fills the available voids and the excess serves to resist compaction by forcing the aggregate apart, lubricating the aggregate and making it easy for the mixture to be displaced laterally.

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\(^5\) Secondary compaction is compaction from traffic after the pavement has been opened to traffic, which is generally limited in extent.

\(^6\) The voids in the mineral aggregate are the air voids content of the aggregate skeleton before binder is added.
Filler: Generally, a mixture with a high filler content will be more difficult to compact than a mixture with a low filler content.

A continuously graded (dense-graded) aggregate, from coarse to fine, is generally the easiest to compact. Open-graded or gap-graded mixtures typically require a significant increase in compactive effort to obtain the desired level of density. In general, aggregates with properties that improve resistance to fatigue and permanent deformation require increased compaction effort to obtain a desired density (TRB, 2000).

2.2.7.3 Influence of binder

The grade and amount of bitumen used affect the ability to compact the asphalt. The bitumen grade affects compaction through its viscosity; a bitumen that is higher in viscosity will generally result in a mixture that is more resistant to compaction. Additionally, the more a bitumen hardens (or ages) during production, the more resistant it will be to compaction. Bitumen lubricates the aggregate particles during compaction. Mixtures with low bitumen content are generally difficult to compact because of inadequate lubrication, whereas mixtures with high bitumen content will compact easily but may ‘shove’ under roller loads (TRB, 2000).

The workability of the mixture is also affected by the temperature susceptibility of the bitumen. For a bitumen that is highly sensitive to temperature, less time will be available for compaction because the mixture will increase in stiffness more quickly with a decrease in temperature than a mixture containing a less temperature-sensitive bitumen (TRB, 2000).

The fluids content of the mixture also affects the compactive effort needed to achieve a required density. The fluids content is the sum of the bitumen content and the moisture content of the mixture. If the amount of moisture in the mixture from the plant is high (greater than 0.2% by weight of the mixture), the extra fluids content will act like bitumen and may make the mixture unstable and difficult to compact. Thus, the moisture content of plant-produced mixture should be measured regularly (TRB, 2000).

2.2.7.4 Compaction equipment

Adequate compaction is essential to the durability of an asphalt mixture. Compaction is required by the SHW (HA et al., 2009) to be carried out using 8 t to 10 t deadweight smooth-wheeled rollers having a width of 450 mm or greater, or by multi-wheeled pneumatic-tyred rollers of equivalent mass, or by vibratory rollers or a combination of these rollers (vibratory rollers cannot be used in vibrating mode on bridge decks). The surface course has to be finished with a smooth-wheeled roller, which may be a deadweight roller or a vibratory roller in non-vibrating mode.

The type of equipment used to compact the asphalt has a significant effect on the density that can be obtained with a given number of passes. For projects within the UK, three primary types of self-propelled compaction equipment are currently being used: static steel wheel rollers, pneumatic tyre rollers and vibratory steel wheel rollers. A combination roller, equipped with both a vibratory drum and a set of four pneumatic tyres, is also sometimes used. The compaction equipment should be selected on the basis of its ability to produce a uniformly compacted surface with the required density (TRB, 2000). Asphalt with all the desirable design characteristics will perform poorly under traffic if it has not been compacted to the proper density level.

All compaction equipment utilised must be operated by skilled and experienced drivers. All rollers must be in good condition and fitted with smooth, rapid-acting reverse controls, thereby minimising time spent stationary and any unnecessary displacement of the hot mixture. The rollers should be fitted with roll scrapers, absorbent mats and tanks connected to spray pipes on both front and rear rolls to ensure a uniform and minimal application of water or parting fluid. For hot rolled asphalt (HRA) and dense bitumen macadam (DBM) on airfield pavements, the weight to which each roller should be ballasted should be agreed with the client’s project manager during the laying of the trial area(s) (DE, 2008a).

Although vibratory rollers are generally used for initial rolling and pneumatic tyre rollers for follow-up rolling, a higher density with fewer roller passes may be obtained for some stiff mixtures when a large pneumatic tyre roller is used initially with the vibratory roller following on.

There are several variables associated with rollers that can be adjusted from job to job, including:

- roller speed;
- the location at which each roller works (rolling zone);
- the number of roller passes over a given area of the mat;
- the pattern that each roller uses; and
- the sequence and number of rollers.

Although these variables are not infinitely adjustable, a rolling plan can be developed by adjusting a combination of them that will optimise mat compaction.

Depending on the width of each roller and the width of the lane, complete compaction across the paving width can be effectively accomplished if two rollers can be operated side by side. The purpose of using two rollers for basic compaction (rather than finishing) is to maximise the application of compactive effort to the mat before it cools.

Uniform compaction depends on getting the same number of roller passes over each area of the mat. This requirement means that a pattern must be developed that covers the entire mat with an equal number of roller passes from each type of roller. If two different rollers, such as a vibratory steel wheel roller and a pneumatic tyre roller, are performing the basic compaction (as opposed to finishing) rolling, each roller should cover the entire mat an equal number of times, otherwise compaction may be non-uniform (WSDOT, 2000).

Overlap between two successive passes should be at least 150 mm (Roberts et al., 1996). This ensures that small steering inaccuracies do not leave gaps between successive passes that will not be adequately compacted. However, the overlap, which will not necessarily be at the same location for each set of passes, should not cause overcompaction.

During rolling, the roller wheels should be kept moist with only enough water to avoid picking up material, causing inhomogeneity at the surface. A water bowser should be provided alongside each spreading unit to ensure that rolling continues with the minimum interruption (DE, 2008a).
2.2.7.5 Roller speed

The ability to achieve successful compaction of an asphalt layer is related to the time available for the weight of a roller to exert a compactive effort. The slower the movement of a roller across a point on the asphalt surface, the more time is available for the weight of the roller to place a compactive effort on that point. Alternatively, as roller speed increases, the amount of density gain achieved with each roller pass decreases. The roller speed selected is dependent on a combination of factors (including paver speed, layer thickness, position of the equipment in the roller train and the number of rollers) and requires very careful consideration to achieve both effective and efficient compaction. The DE (2008a) recommends that rollers move at a slow but uniform speed, which should not exceed 5 km/h, and any pronounced change in direction of the roller shall be made on stable material.

The limiting factor on paving output is the rolling capacity rather than the paver speed or the availability of the asphalt. In addition to the maximum speeds achievable with standard compaction equipment, there are several critical variables that limit the speed of rolling:

- There is a maximum rolling speed, above which the compactive effort applied by the roller is insufficient to achieve the required material density.
- Any variation to the roller speed along the length or across the width of a pavement is likely to cause variations in density and performance.
- The properties of the mixture being placed by the paver can necessitate a reduction in roller speed (i.e. the tenderness of the mixture\(^7\)).

Unless the tenderness of the mixture necessitates a reduction in roller speed, the roller speed is fixed for a design mixture and should not be influenced by increased material production or paver speed; any alteration to the roller speed during the process of paving is likely to significantly reduce the effectiveness of the compaction process. Skilled equipment operatives are required to observe and react to any undesirable displacement of the asphalt.

Facing an increase in paver speed, the roller operator must either keep up by increasing the rolling speed or allow the roller to fall away from the paver. Both increasing the roller speed and attempting to compact the cooler asphalt further away from the paver reduces the effectiveness of the roller and its ability to achieve a suitable asphalt density. If the paver continually pulls ahead of the rollers, several courses of action can be taken to maintain an efficient and effective compaction. Firstly, paver speed can be reduced to match both asphalt production and roller speed, potentially utilising a MTV (see Section 2.2.5). If plant production capacity necessitates continued higher paver speeds, additional and/or wider rollers can be utilised to achieve adequate density.

In the event that the paver moves more slowly than the desirable roller speed, allowing the roller to stay stationary on the hot asphalt and/or allowing the asphalt to cool before it is compacted must be avoided. The roller should keep rolling at a uniform speed until the established pattern and number of passes over each point has been completed and the roller either moved on to the next section laid or taken off the mat. Stoppages in the rolling can lead to variations in layer density due to variations in compaction temperature.

The ability to achieve effective and uniform compaction of asphalt is increased by operating the paver at a consistent speed (TRB, 2000). Careful planning is required to ensure that the rollers can travel at a uniform speed, without excessive stopping or manoeuvring, along both the length and width of a pavement. A “slow and steady” approach will increase both the quality and the long-term durability of the pavement.

2.2.7.6 Number of roller passes

Multiple roller passes are needed to completely compact each point in the pavement surface to the required density over the longitudinal length and transverse width of the lane being paved. The number of required passes depends on many variables, including the position of the roller in the roller train, and the type of compaction equipment. Three-wheel steel rollers, tandem steel wheel rollers, pneumatic tyre rollers and single- or double-drum vibratory rollers all have different capabilities. The basic capabilities of each type of roller also vary in relation to mat thickness, mixture temperature, mixture design properties (bitumen content, bitumen stiffness, aggregate characteristics) and environmental conditions. Due to the number of variables involved, it is impossible to generalise about the best combination of rolling and roller pattern to use in all cases.

2.2.7.7 Compaction of stiff and tender mixtures

Asphalt that is properly designed will be reasonably stiff and stable and will require a considerable amount of compactive effort to attain the required degree of density. Stiff asphalt will support the weight of the compaction equipment directly behind the paver. A tender mixture has an internally unstable aggregate/binder matrix that will not adequately support the weight of the compaction equipment when hot; excessive movement of the material will occur under the applied compactive effort. The movement of the mixture can take various forms including transverse movement at unsupported edges, humping at the outside edge of rollers, a bow wave in front of the paver and cracking.

When excessive tenderness is encountered, roller operators should trail some distance behind the paver waiting for the mixture to cool sufficiently for it to be able support the roller. However, if the mixture is used on a heavily trafficked route, it may be necessary to redesign it because tenderness is usually a sign of a deformable mixture (TRB, 2000).

2.2.7.8 Over-running of edges

To construct a durable pavement, it is very important that the roller passes are distributed uniformly over the width and length of the mat. Frequently, the centre of the paver lane receives adequate roller coverage, whereas the edges of the mat receive considerably less compactive effort. Due to the location of the wheel-track zones, the typically under-compacted pavement edges are the most heavily loaded areas of the pavement.

Roller patterns should be designed to ensure uniform compaction of the entire lane width. If the number of roller passes made on each edge of the lane being compacted

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\(^7\) A tender mixture is one that is relatively unstable so that it tends to displace laterally (“shove”) rather than compact whilst being rolled.
is adequate to meet specifications, the density level in the centre of the lane will always be more than enough to also meet the specification because the bulk of the roller width will always be towards the centre of the lane (TRB, 2000).

The mixture placed by the paver will typically have a slope on its outside edge of approximately 60° (Figure 2.1), depending on the type of end or edger plate on the paver (Benson and Scherocman, 2006). The density of this outside edge will affect the density and performance that is obtained at the longitudinal joint and the extreme edges of the pavement. As the edge is not confined, it tends to move transversely underneath the rollers, making it difficult to obtain adequate compaction on the free edge. The amount of movement that occurs is dependent upon the properties of the mixture; a tender mixture will "shove" more easily than a stiff mixture.

Material at the free edge can also break over when compacted, resulting in loose material immediately adjacent to the edge of the lane. When the adjacent lane is placed, it is very difficult to adequately compact this loose material (Brown, 2006). Furthermore, the movement of the mixture creates a dip at the unsupported edge of the lane, making it much more difficult to match the longitudinal joints when the second lane is placed.

The type of roller used and its position with regard to the unsupported edge of the pavement significantly affect the density obtained (Benson and Scherocman, 2006). A pneumatic tyre roller normally cannot be used within 150 mm of the unsupported edge without pushing the mixture sideways due to the high pressure in the rubber tyres, or alternatively, rounding off the edges (Brown, 2006). A steel wheel roller, operating near the unsupported edge of the pavement lane, can result in the transverse movement of the mixture and the formation of a crack at the edge of the drum. Operating the wheel of the roller directly over the unsupported edge of the lane is also likely to result in the transverse movement of the mixture under the force of the roller. However, cracking is unlikely to occur. In both cases, it is not possible to achieve adequate density at the free edge due to the transverse movement of the mixture.

The best location for the edge of the steel drum is extended over the edge of the lane by approximately 150 mm (Figure 2.2) (Brown, 2006). In this case, there will be no transverse movement of the mixture because there is no shear loading at the edge of the steel drum, and cracks will also be avoided. Density is achieved because the edge of the steel drum is compacting air instead of shoving the mixture sideways (Benson and Scherocman, 2006). The transverse movement of the mixture can also be minimised by proper selection and application of a tack coat. With a good bond between the underlying layer and the layer being compacted, there will be less movement underneath the rollers, thus making it easier to compact the edge (Brown, 2006).

Successful compaction of the free edge can be aided by attaching a restraining edge to the roller. The technique utilises an edge-compacting device, which provides lateral resistance at the edge of the lane being rolled. The restraining device consists of a hydraulically powered wheel that rolls alongside the compactor drum, pinching the unconfined edge and providing lateral resistance. The restrained edge method produces a fairly consistent edge with a good density. However, it is difficult for the plant operator to see the edge-compacting device, making it difficult to produce a neat and straight edge. Any deviation from the edge line leaves debris in the opposite lane that must be removed before the second mat is placed.

2.2.8 Bond

The bond between layers is essential to ensure composite action and to stop water travelling between asphalt layers. The structural performance for which pavements are designed assumes that the whole bound depth works together, and for it to act as a series of thinner, (semi)independent structures will lead to overstressing and possible damage. Water between unbonded layers is not uncommon and can lead to
severe damage from pumping under traffic loading as well as the potential for water stripping the binder from aggregate particles once it breaks the binder-film. Furthermore, inadequate bonding between layers can result in delamination (debonding) followed by longitudinal wheel-path cracking, alligator cracking, potholes and other distresses such as rutting that greatly reduce pavement life.

Bond coats, or at least tack coats, need to have adequate stability and viscosity in order both to properly penetrate the surface onto which they are applied, and to be able to deposit a good film at the surface. They are required to be applied (HA et al., 2009):
- between all pavement layers;
- on areas that can be covered by the same day’s paving; and
- on all vertical surfaces of existing pavements, kerbs, gutters and joints where new pavement material is likely to be placed.

The pavement surface receiving a tack or bond coat needs to be clean and dry in order to promote maximum bonding. Existing and milled pavements can be quite dirty and dusty and, therefore, their surfaces should be cleaned by sweeping or washing before any tack or bond coat is placed, otherwise the tack/bond coat material may bond to the dirt and dust rather than the adjacent pavement layers. This lack of bond between the layers can result in a reduction in the overall strength of the pavement as well as the tack/bond coat material being free to migrate to the surface and manifest itself as bleeding.

Tack and bond coats should be applied uniformly across the entire pavement surface and result in good surface coverage (Figure 2.3). To achieve this result, application rates will vary based on the condition of the pavement receiving the tack/bond coat. Too little tack/bond coat can result in inadequate bonding between layers. Too much tack/bond coat can create a lubricated slippage plane between layers, or can cause the tack/bond coat material to be drawn into the pavement layers above, negatively affecting mixture properties and even creating a potential for bleeding in thin pavement layers.

2.2.9 Joints
2.2.9.1 General
Regardless of the surface course used, it is necessary to construct a number of joints, both longitudinally and transversely to the direction of the pavement, on all but small jobs. Joints represent the weakest part of the pavement and, therefore, pavement performance can be significantly improved by limiting the number of longitudinal and transverse joints. Meticulous planning for paving works should be undertaken to determine the optimal combination of construction methods, equipment and resources that will increase the options for limiting the number of longitudinal joints and to improve the construction quality.

Longitudinal joints in all pavement layers are required to be situated outside of the wheel-track zones for each lane, where the wheel-track zones are taken to be between 0.5 m and 1.1 m and between 2.55 m and 3.15 m from the centre of the nearside lane markings for each traffic lane as specified in the 900 Series of the SHW (HA et al., 2009). Figure 2.4 identifies these wheel-track zones.

All joints, both longitudinal and transverse, need to also be offset at least 300 mm from parallel joints in the layer beneath to avoid creating a line of weakness in the structure. Furthermore, no longitudinal joints should be formed between a hard strip and the edge of the carriageway, nor within a hard strip, according to the SHW (HA et al., 2009). Longitudinal joints in the surface course of a pavement must coincide with either the lane edge or the lane marking, whichever is appropriate according to the SHW (HA et al., 2009). This specification essentially limits the number of longitudinal joints to the number of lane edges and/or markings. However, careful planning of all pavement layers is required to ensure that both the offset of 300 mm between parallel joints is maintained and that joints in the surface layer lie outside of wheel-track zones.

With the requirement for greater deformation resistance (due to increasing traffic volumes) and retention of high texture depth, asphalts have tended to become stiffer and less workable, with lower binder contents and, hence, they are less forgiving of poor workmanship. This lack of forgiveness often manifests itself initially as fretting at joints so that joint

![Figure 2.3 Uniform tack/bond coat at uniform application rate](image1)

![Figure 2.4 Wheel-track zones](image2)
sealing within the first few years of the life of a surfacing is not unusual. The main causes of joint fretting are poor compaction, low binder content and over-raking at the joint. Therefore, it is vital that asphalt is adequately compacted in the joint area.

During the paving process, the asphalt layer is typically placed and compacted one lane at a time so that traffic does not have to be diverted. A longitudinal joint in an asphalt pavement occurs when a lane of fresh hot asphalt is placed alongside an existing lane of asphalt at ambient temperature (or at any temperature below the minimum material compaction temperatures). The first lane paved is referred to as the cold lane because the hot asphalt in this lane cools off by the time the second lane, or hot lane, is paved.

Transverse joints are required at the end of a day’s work and following any interruption in laying pavement layers that prevents continuity of rolling at, or above, the minimum compaction temperature of the mixture. Although transverse joints are significantly shorter in length than longitudinal joints, efforts to reduce the number of transverse joints can also increase pavement performance. The presence of transverse joints often interrupts the ride quality of the pavement, and the resulting additional dynamic loading can damage the pavement in the long term.

Meticulous planning of the paving works, as well as good quality control adopted during the paving stage, can reduce the number of stoppages during the paving process. This reduction has the advantage of limiting the number of transverse joints that, similar to longitudinal joints, are prone to the ingress of water and the subsequent deterioration of the pavement surface.

2.2.9.2 Influence of job size
Joints are regarded as a potential weakness because many faults are first observed at joints. One way of avoiding the need for joints is to allow the work to be undertaken over longer lengths and more lanes at a time. With multiple lanes, laying in echelon is a possibility with a reduction in the number of longitudinal joints. With longer lengths, there is less need to have transverse joints butting up against a cold existing mat other than at day joints, and even the number of those can be minimised if the site is sufficiently large to warrant multiple laying gangs. However, the client needs to provide larger areas of road to work on before the contractor can consider working in this way.

There are political pressures on clients to minimise the immediate disruption to the travelling public by minimising the amount of road that can be worked at any one time. There is no counterbalancing pressure for a “short sharp shock” treatment of closing larger sections so that the works, and associated disruption, can be completed quicker. Advanced publicity to the public about the timing should allow some motorists to avoid the location for a more limited time. Furthermore, the potential to get the durability right first time with the freedom from having to keep the traffic moving should extend the time until the next intervention is needed on that section of road.

These considerations also apply to restricted times when work can be carried out. Repeated overnight possessions with the road being reopened each morning mean that each discrete section is surrounded by vertical joints on all sides. Here, however, the avoidance of closures at peak times does minimise the disruption to most road users during the course of any work. With overnight closures, there will be a limit to the area that can be paved in that time and longer lengths would not change the practicalities.

2.2.9.3 Echelon paving
Constructing two or more pavement lanes in echelon is potentially the optimum method for ensuring continuity of the asphalt layer and avoiding longitudinal joints and the associated compaction issues across the longitudinal joint, by ensuring that the full width of the road surface is laid and compacted at the same temperature and environmental conditions. The SHW (HA et al., 2009) permits the utilisation of two or more pavers operating in echelon, where this is practicable, and in sufficient proximity for adjacent widths to be fully compacted by continuous rolling. The continuous rolling process ensures a high density is achieved at the joint.

Paving in echelon effectively eliminates the formation of exposed pavement edges other than day joints. Minimising exposed pavement edges ensures that there is less opportunity for ingress of detritus or moisture into the pavement structure, and also reduces the problems associated with paving when the mat/joint temperatures have dropped below desirable compaction conditions because the existing edge will not cool the newly laid material, at least at its edge. This approach leads to uniformity and consistency in the paving operation and contributes to enhanced asphalt durability.

Cutting back and trimming or reheating of the unconfined low-density lane edge is not required when two or more pavers operate in echelon, thereby reducing the amount of waste material, the cost and the time incurred during these additional processes. However, paving in echelon requires the simultaneous closure of two or more lanes, increasing the disruption to traffic and motorist delay costs. Some of these delay costs could be counteracted by the potential reduction in construction time and whole-life maintenance costs associated with high-quality longitudinal joints. However, the simultaneous closure of two or more lanes can cause politically unacceptable delays or restrictions to motorists and, hence, echelon paving is probably only feasible on a very limited number of jobs in the UK.

Paving in echelon can be combined with other longitudinal joint formation techniques to limit the number of joints produced and disruption to motorists – for example, two lanes of a three-lane carriageway can be paved in echelon leaving one lane open.
2.2.9.4 Paving against a cold joint

Longitudinal joints may be formed by heating the joint with an approved joint heater when the adjacent width is being laid, but without cutting back or coating with binder. The purpose of the joint reheater system is to reheat the initially paved surface (cold lane) and bring it up to a plastic state prior to the new, adjacent hot mat being laid. This reheating permits better consolidation of the mat at the joint, thus making the joint denser and less permeable. The process ensures that both the hot and cold lanes are at similar temperatures, which can aid in ensuring continuity of compaction across the joint and minimising the density gradient across the joint.

The heater must raise the temperature of the full depth of surface course to within the specified range of minimum rolling temperature and maximum temperature at any stage for the material, for a width not less than 75 mm according to the 900 Series of the SHW (HA et al., 2009). The contractor must have equipment available, for use in the event of a heater breakdown, to form joints by the edge cutting method.

The reheating method requires additional plant (the reheater) and a secondary process to form the longitudinal joint. The process of reheating a joint is likely to be both time and energy consuming, resulting in increased costs to the contractor and possible increased traffic delays. The process can also prematurely age the reheated asphalt if not carried out in a controlled manner.

2.2.9.5 Paving against a free edge

Maintaining consistent density across the joint is generally considered a key factor in maintaining durability (Toepel, 2003). The unconfined edge of the cold lane tends to have a lower density, implying less durability, than the centre of the lane. The hot lane tends to have a higher density because the cold lane confines its edge during the paving process (Kandhal and Rao, 1994). Pavements with joint distress show greater variation in the measured density than pavements without joint distress, both at the joint and in the mat (Sebaaly and Barrantes, 2004). The difference in temperature and plasticity of the asphalt mat in the hot lane means that it will not usually bond well with the older, cold lane and a longitudinal crack may occur between the asphalt lifts, increasing the roughness of the joint with potential implications for the life of the pavement. These distresses could contribute to further deterioration of the pavement because they allow moisture to penetrate into the pavement structure (Figure 2.5).

One key to the construction of a durable longitudinal joint is proper compaction of the free edge of the first lane (cold lane) of the pavement to be placed. The mixture placed by the paver will have a slope on its outside edge. The amount of slope, typically about 60 °, depends on the type of end plate on the paver screed. This wedge of material does not receive the same amount of compaction as the rest of the mixture due to its shape and position (i.e. it does not make contact with the roller) and its ability to move horizontally.

The conventional method for longitudinal joint construction and compaction against a free edge is the industry standard butt-type joint. After the first (cold) lane is placed and a tack coat is applied at the free edge of the lane, the longitudinal joint is constructed by slightly overlapping the hot lane over the cold lane. The first pass with the compacting device runs 100 mm to 150 mm away from the joint on the hot lane, pushing the asphalt laterally towards the joint. The second pass of the compaction process overlaps onto the cold side by approximately 150 mm, pinching the material into the joint. This technique achieves a high density at the joint and reduces the density gradient across the joint (Kandhal and Rao, 1994). The butt joint is a well-established construction technique that does not require any new equipment.

However, the densities in the joint area are typically lower than those in the surrounding mat and this method has a history of ravelling at the joint (Kandhal and Rao, 1994).

If the proper amount of mixture is placed in the correct place at the longitudinal joint, no raking of the material at the joint should be necessary. The amount of mixture overlapped from the second lane to the first lane is critical in the construction of a durable longitudinal joint. If an excessive amount of mixture is placed over the edge of the first lane, it will have to be removed by raking the joint or it will be crushed by the rollers. If too little mixture is placed over the edge of the first lane, a depression or dip will occur on the second lane (hot lane) side of the joint. If the joint is raked flat, the rollers will not be able to compress the material at the uncompacted side of the joint because it is at the same level as the compacted mat of the first lane. This results in low density on the second lane side of the joint. In either case, the joint will not perform well under traffic. The proper amount of overlap for typical asphalt is about 25 mm to 40 mm.

Finally, the location of the rollers during the compaction of the mixture at the joint is important in the construction of a durable longitudinal joint. The most efficient location at which to place the rollers, either pneumatic tyre or steel wheel, is on the hot side of the joint with about 150 mm of the drum extending over the top of the joint onto the first, compacted lane. This type of rolling pattern will result in higher compactive effort being applied to the mixture at the longitudinal joint and, thus, achieve higher density at the joint. Additionally, by rolling from the second lane side, the hot mixture is being compacted at the same time as the mixture at the joint, resulting in a more efficient overall compaction operation. Rolling with the roller predominantly on the hot lane can limit the longitudinal movement of material across the lane and away from the joint.
2.2.9.6 Cutting back free edges

The SHW (HA et al., 2009) allows for the unconfined edge of the cold lane to be cut back to sufficiently compacted material, thereby removing the unconfined and low-density pavement edge. The exposed edges should be carefully cut back (Figure 2.6) and trimmed to firm material in the compacted lane, or for a minimum equal to the layer thickness, whichever is the greater, and all loose material arising from this operation must be removed from the pavement before the cut edge is painted. Care has to be taken to ensure that, subsequent to cutting back the unconfined edge, the longitudinal joint remains within the lane edge markings.

After cutting back and trimming, the exposed vertical edges of the longitudinal lane joints must be thoroughly cleaned of all adherent material. The face (generally close to vertical, but consideration has been given to form sloping joints at an angle of 45 °C or 60 °) should be completely coated with a suitable material (hot bitumen, cold-applied polymer-modified intermediate or premium-grade bitumen emulsion, or polymer-modified adhesive bitumen strip with a minimum thickness of 2 mm) before the adjacent width is laid. The coating of the vertical face should be completed just ahead of the spreading unit laying the adjacent lane.

Existing asphalt surfacing against which new surfacing is to be laid also needs to be cut back as necessary to remove all loose or weathered material, finishing with a vertical edge. Immediately prior to the laying of new material, one of the following should be applied over the complete face with a thin uniform coating of 40/60 or 70/100 paving-grade bitumen or else an approved joint seal.

The cutting method generally results in an increase in density at the joint because the low-density edge of the mat is cut and discarded. Although the densities of both lanes are more uniform, causing the density gradient to be lower, this method does not significantly improve the tensile strength across the joint (Kandhal and Rao, 1994).

On completion, the joints must present the same texture as the remainder of the surface. The quality of the joint with the cutting wheel is dependent upon the skill of the operator. The cutting method, when combined with a suitable joint sealant, provides durable joints for asphalt pavements. The method also allows for a clean-looking joint, which, when combined with good workmanship, provides for a uniform pavement surface.

Cutting back the poorly compacted free edge requires a secondary process and appropriate plant (and experienced cutting wheel operators) that increases construction time and requires the disposal of the cut-away material. The increased construction time and discarded material increase the cost of the pavement. The cutting process is very messy because the cutting wheel throws material out and necessitates sweeping before the second lane is paved. It is also difficult to maintain a straight cutting line and a wavy and unattractive joint can result.

Transverse joints must be formed at right angles to the longitudinal joints and should consist of a vertical edge. The vertical edge is achieved by cutting back the exposed edge material of the transverse joints equal to the layer thickness, or to suitably compacted material. Arisings from this operation must be removed from the pavement and the underlying surface cleaned. The exposed joint edges must then be cleaned and painted with hot bitumen immediately before the laying of the lane continues.

The DE (2008b) requires exposed vertical edges of the transverse joints of all layers to be cut back for at least 300 mm and trimmed. The SHW (HA et al., 2009) only requires that a cut equal to the layer thickness is required. Arisings from this operation must be removed from the pavement and the underlying surface cleaned.

2.2.9.7 Influence of density

The density measured at a longitudinal joint will typically not be equal to the density obtained in the mainline pavement mixture even if all of the proper construction procedures are used (Benson and Scherocman, 2006). In general, the density of the asphalt will be less on the side of the joint that was laid first (cold lane) compared with the side laid second (hot lane). This difference is primarily due to the unsupported edge of the first lane placed not being able to fully resist horizontal movement during its compaction, whereas that free edge of the cold lane is able to resist any horizontal movement of the hot lane during the latter’s compaction.
The density variation at the joint between the hot and cold lanes reduces the tensile strength of the pavement and leads to both longitudinal cracking and a high air voids content, which, in turn, leads to raveling of the pavement along the longitudinal joint. The performance of the longitudinal joint appears to be influenced by the overall density achieved at the longitudinal joint (Sebaaly and Barrantes, 2004), based on field trials undertaken in three US states. The best performing joints demonstrate a density at the joint that is within 2% of the mat density. Joints in binder courses and bases have to be compacted so that the air voids content measured on core pairs whose centres are not more than 100 mm from the final joint is not greater than 2% above the maximum permitted limit for core pairs in the body of the mat.

2.2.10 Time of construction

Working at night has the advantage that there may be fewer disruptions because of less traffic. However, the organisation for the work tends to be more complex than for working during the day because:

- it is dark, so artificial lighting is needed with the associated limitations;
- night tends to be colder than day, so operatives may be slower at some tasks;
- it is outside normal working hours, so it is more difficult to obtain replacements for anything that becomes lost or damaged; and
- night work is often associated with tight deadlines for re-opening the following morning.

The sources of artificial light are improving. Traditional, static lighting columns have been used but they have to be moved as the work progresses along the road. However, there are systems that can be attached to the plant that produce very good light (Nicholls et al., 2007a). The advantage is that the light is where it is needed for the work; the disadvantage is that there is limited visibility away from where the work is currently taking place. Nevertheless, even with powerful artificial lighting, the visibility still tends to be poorer than in daylight although certain things, like undulations, are shown up more clearly.

Because of these factors, planning to ensure that there is continuity in the supply of material and that there is sufficient availability of equipment and manpower to both undertake the work efficiently and allow for any breakdowns that have a reasonable probability of occurring becomes more important.

Winter conditions impose narrower margins on the suitable time available for laying asphalt successfully whilst, at the same time, reducing the efficiency of operatives who need to keep warm as well as perform their allotted tasks. Therefore, it is necessary:

- to provide appropriate resources to allow operatives to keep warm; and
- to ensure that the number of operatives is consistent with the conditions and expected output.

More specific issues are that there is less time available for compaction because of the lower temperature and there is the possibility of ice and frost. The reduction in compaction time due to low temperature is often not as great as it is for strong winds, so that wintry conditions when it is very still can still provide a reasonable time for compaction. However, the presence of frozen conditions is more serious because they could result in water being trapped between pavement layers.

2.3 Outside constraints affecting durability

2.3.1 General

Whatever stratagems are taken to increase the environmental sustainability of asphalt used for highway, airfield or other paved areas, they will not be successful unless other constraints that could also affect pavement durability are considered. These constraints include the foundation on which the asphalt is laid, the drainage that controls the water in, over and through it, the traffic loading applied to it during its serviceable life and the geometry that determines whether that traffic is turning or climbing. The latter two are generally considered in the design of a pavement as input parameters, but the former two are often overlooked because they are assumed to be “somebody else’s responsibility”. In order to maximise the sustainability of asphalt, particularly its durability, the constraints on the pavement need to be included in a holistic approach.

2.3.2 Foundations

The foundation of a pavement is crucial because the whole of the remaining structure sits on it, and any failure in the foundation will disrupt all the layers above. Furthermore, any maintenance needed on the foundation can only be undertaken after the overlying layers are removed. The traditional foundation onto which a new asphalt pavement is constructed should have been designed to have the capability to spread the expected loads adequately whilst many evolved roads have developed the necessary strength with the increasing loads from decades of carrying traffic. Advice on the design and construction of foundations is not covered here.

However, even if the foundations are adequate when constructed, there is always the possibility of the pavement being disturbed by excavations that have been poorly back-filled (often associated with work on utilities) and/or affected by defective drainage and/or subject to inadequate maintenance of perfectly sound drainage systems (Farrington, 2000), a simple example being shown in Figure 2.7. The result can be that the foundation becomes wet and its inherent strength is reduced. Experience suggests that all these types of defects (with the exception of back-filling on motorways, where the cables and pipe-work of undertakers are not permitted) will occur within two or three decades of construction.

Whilst the foundation of the pavement is important, the foundation for each asphalt layer, or substrate, is also important. Each layer needs to have internal cohesion (so that it is not liable to break up) with no detritus or dampness on it. If the lack of cohesion is relatively limited, the application of a bond coat can help to bond the existing material together as well to the new layer, but its long-term effectiveness will be suspect. Detritus and dampness also inhibit the formation bond between layers, which is essential for overall durability.

Overlaying a jointed concrete pavement (JCP) is always problematic because reflective cracks will always come...
through. There are various treatments to extend the time before reflective cracks come through, but they can only delay the inevitable. For the longer term, the important thing is to ensure that the reflective cracks, when they do emerge, do not ravel back leading to a poor ride quality and allowing water to enter the structure. One approach is to pre-cut the reflection cracks, but that requires precise positioning – a slight error will lead to a thin section of material between the reflection crack and the saw-cut, which will be soon removed. A second problem with overlaying a JCP is that the joint seals must be in good condition because they cannot be maintained without disrupting the overlying asphalt. Furthermore, the action of joints can be disrupted if aggregate particles from the asphalt get into the joint when it has expanded. The alternative is to crack and seat the concrete (see Section 3.2).

2.3.3 Drainage

2.3.3.1 Need for drainage

The bitumen film on aggregate particles will always be displaced by water if it reaches the interface. However, the UK has a temperate climate and it is impossible to keep all moisture away from asphalt surfacings. Therefore, although the amount of water entering the pavement structure can be reduced by sealing shoulders, cracks, joints and other crevices within the pavement structure, a drainage system is needed to limit the time that water remains in contact with the asphalt. The principal issues have been identified (Nicholls et al., 2008) as follows:

- Drainage of the structure is essential.
- Drainage will only remove water from the pavement if adequately maintained.
- Water in asphalt with a high air voids content may lead to a reduction in stiffness.
- Water between layers will always result in deterioration.
- Water will always find its way between unbonded layers.
- Water ingress from the side can cause problems.

Experience has shown that, when water is trapped in the region of layer interfaces and longitudinal construction joints, stripping often occurs. The process of stripping involves the separation of bitumen film from the aggregate. The propensity to strip is related to the types of aggregate and bitumen used, the thickness of bitumen on the aggregate particles and the air voids content found in the mixture. The destructive combination of traffic and water should not be underestimated. It has been observed that, when a pavement is filled with water, every heavy load passing over it produces a pore pressure wave that moves along at the speed of the vehicle (Cedergren, 1988). In certain instances, “violent water actions” can scour bitumen from aggregate and even erode cavities under concrete pavements.

2.3.3.2 Approach

The conventional approach has been for asphalt to be regarded as relatively impermeable to water, which therefore flows to the edges, from where it is channelled away in a variety of ways. However, environmental and sustainability drivers encouraged the use of PA for the surface course and have now moved to pervious pavements. In these types of structure, water moves through the asphalt, so the emphasis must be on removing it as quickly and completely as practical after the rain stops. However, whenever using these types of design, the aggregate/binder combination must not be moisture sensitive.

For PA surface courses, there is a need to design the drainage to remove the water from both the binder course, which should be impermeable, and from the surface for when the material becomes clogged up. There are designs for use with PA (Nicholls and Carswell, 2001) that can be used for different circumstances. The use of pervious pavements for source control of the water creates issues about the performance in respect of the hydraulic, structural and water quality (Pratt et al., 2002) performance as well as durability issues. The structural limitations currently restrict their use to parking areas and minor roads, but the whole design has to be considered in terms of ensuring that the water gets away, even if after being held up to slow the release, without removing fines or stripping the binder.

2.3.3.3 Maintenance

In-service problems with drainage systems around the world appear to be similar, regardless of locality. Siltation (Figure 2.8), excessive deformation, crushing of drainage pipes and post-construction damage from driven posts

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8 PA can be cleaned to reduce the extent to which it is clogged up, but some loss in performance is inevitable.

9 Source control is a mechanism to allow water from a storm to be released in a controlled manner over a much longer period than the storm lasts in order to minimise the possibility of overloading the drainage system.
and utilities are commonly encountered. However, post-construction and maintenance inspections are not a top priority for most highway agencies (Hoppe, 1998); drainage-related problems are usually dealt with as they arise in a reactive fashion, although a more proactive maintenance effort would be beneficial. It was stated that part of the problem stems from the lack of sufficient funding allocated for maintenance and inspection activities. A summary of the findings are:

- **Design:** Systems commonly include longitudinal edge drains, transverse drains and drainage layers, with French drains – often as a combined surface and ground water filter drain – being popular. Combined drainage systems are used, but recent UK and US practice is to construct separate systems. A number of countries use granular drainage layers. Proper sizing of pipes to allow self-cleaning and accessibility for maintenance is seen as a critical factor whilst pipe layouts need to be designed at gradients to allow self-cleaning and an adequate distribution of manholes are needed for maintenance.

- **Construction:** Siltation and blockage are major recurring problems. Siltation needs to be minimised during construction through site layouts that allow effective surface runoff whilst the ends of drainage pipes can be blocked during construction. Mechanical damage to pipes and outlets by construction equipment often occurs whilst delayed drainage installation techniques are commonly employed to reduce damage from construction traffic. Poor geometric alignment can be produced by either poor design or poor construction practice. Geotextiles need to be protected from UV radiation and breakage or rupture.

- **Aftercare:** Video surveys or flow and mechanical mandrel tests are performed before accepting sub-surface drainage works in several countries. Drainage systems should be checked by visually observing outlets after a period of intense rain, with severity being inversely proportional to the rate of flow. High-pressure water cleaning, video and bore scope surveys can be performed. Problems include siltation, root infestation, deposits of calcite, breakage and utility damage. Maintenance tends to be reactive, with the common activities including sealing of pavement joints and cleaning debris found at inlets and from drainage ditches.

### 2.4 Long-life pavements

The design life of pavements has been changed by the realisation that cracks start at the top of the pavement and go down rather than the reverse. The previous assumption was based on classical analysis that relied on homogeneity of the materials. In practice, the surface layer is generally the only location where the binder is exposed to oxidation, so that the surface becomes more brittle than the rest and, hence, more susceptible to cracking. Under classical analysis, the structural pavement was generally designed for a design life of 40 years with strengthening after about 20 years. Under the revised approach (Nunn et al., 1997), a well-constructed pavement built above a threshold strength was considered to have a very long life. The threshold strength is, in effect, a minimum thickness. Such structures are known as “long-life pavements” in Europe, or “perpetual pavements” in the US (although it is, perhaps, rather optimistic to define anything as “perpetual”). Deterioration in these pavements is assumed to be confined to the uppermost layers of asphalt and manifests itself as surface cracking or deformation.

The designation of long-life pavement is applied because of the make-up of the structural layers. There are current attempts to develop a long-life surfacing material based on high-strength concrete and epoxy resin asphalt, but these mixtures are likely to be relatively expensive and limited to use on specialised and high-profile jobs.

Therefore, the main interest in asphalt durability is that of surface course materials. Not only are these materials exposed to the climate and traffic, but they require replacement on major, well-built roads or the only layers at all on minor roads with limited construction. This concentration on the surface course is also practical in that any maintenance must start at the top. Therefore, some advice on the durability of different surfacing mixtures is given in Section 2.5.

### 2.5 Service life of some asphalt mixtures

#### 2.5.1 Thin surfacings

- **2.5.1.1 Current findings**

Thin surfacing systems can be divided into the following categories, not all of which are hot mixed asphalt:

- **Paver-laid surface dressing (PLSD) or ultra-thin-layer asphalt concrete (UTLAC):** Ultra-thin surfacings developed in France.

- **Thin asphalt concrete (TAC) or béton bitumineux très mince (BBTM):** Generally with polymer-modified binder (PMB).

- **Thin stone mastic asphalt (TSMA) or stone mastic asphalt (SMA):** Generally paving-grade bitumen with fibres.

- **Multiple surface dressing (MSD):** Binder and aggregate applied separately.

- **Micro-surfacing (MS):** Thick slurry surfacing, generally with PMB.

The durability of thin surfacings has been extensively monitored (Nicholls et al., 2002; Nicholls and Carswell, 2004; Nicholls et al., 2007a). From the data collected, the visual condition is extrapolated (the first system only came to the UK in 1991, making the population age skewed) to drop to “Acceptable”, as defined in Appendix R of TRL Report TRL176 (Nicholls, 1997a), after:

- 12 years for PLSD systems with 0/14 mm grading, reducing with smaller aggregate sizes and associated layer thicknesses;
- 12 to 13 years for TAC systems with 0/14 and 0/10 mm gradings;
- 15 years for TSMA systems with 0/14 mm grading and possibly more with 0/10 mm;
- 5 years for MSD systems; and
- indeterminate period for MS systems due to insufficient data to estimate the typical service life. Furthermore, the performance of MS systems depends on the traffic loading of the site.

No consistent difference in the durability was demonstrated with regard to aggregate size, which may be affected by the
influence of layer thickness. However, the service lives of each type of system vary considerably and service lives on individual sites can be significantly greater or lesser than their estimated service lives listed above.

However, evidence from Germany, with smaller aggregate sizes, higher binder contents and lower air voids contents in the mixtures, has demonstrated they have durable surfacings with expected service lives in a heavily trafficked environment of at least 16 years.

With regard to quantitative measurements, a consistent reduction in skid resistance through polishing under traffic was not apparent after 14 years in service. Statistical analysis of the data showed that there are significant differences in adjusted mean summer SCRIM coefficient between sites with varying aggregate size, PSV category and system type. The system type was the variable seen to be least important in determining the differences.

For the texture depths measured using SCRIMtex, statistical analysis has shown that there were significant differences between sites with differing age, PSV category (although there is no physical reason for PSV to be significant) and system type. However, despite the statistical relationship, the results showed no substantial change in texture depth with time except, possibly, for 0/10 mm TAC, which showed the largest increase with time and the greatest correlation.

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

The monitoring involved collecting data on a series of sites with a variety of thin surfacings across England and Wales for nine years to investigate the durability of the various thin surfacing systems. These data extended the data held by TRL from the initial approval of systems when they were first introduced into the UK. The data include the following parameters:

- The visual conditions of the surfacings, as assessed by an Inspection Panel with members from across the industry, were measured in accordance with Appendix R of TRL Report TRL176 (Nicholls, 1997a).
- The type of system that was applied (SMA or BBTM).
- The proprietary system of thin surfacing that was applied.
- The category of road onto which the thin surfacing was laid.
- The nominal maximum aggregate size.
- The binder content of the mixture.
- The age at which the site was monitored.

The visual condition is the parameter that is monitored, whilst the age is assumed to be the most significant parameter because any site can be monitored through its decline from new until it becomes unserviceable, however long that takes. Multiple regression analysis, as opposed to linear regression analysis, has shown that the binder content is the most significant parameter with the others having a secondary influence. The complete ranking of parameters and the way they were found to affect the durability is:

1) Surfacings deteriorate with increased age.
2) Surfacings deteriorate faster with less binder.
3) Whilst the actual surfacing system was important, no guidance can be extracted because the system names are deliberately being kept anonymous.
4) SMA surfacings deteriorate faster than BBTM surfacings.
5) Surfacings deteriorate faster with smaller nominal aggregate sizes.
6) Surfacings deteriorate faster on more major roads.

These rankings are not unsurprising other than that the sites with BBTM were in better condition than those with SMA, where the reverse was found in previous analysis (Nicholls et al., 2007a). The binder content, which is generally higher in SMA than BBTM systems, is taken account of separately so that any difference is due to the binder type, PMB being better than paving-grade bitumen and fibres. The previously reported marginally better performance of SMA over BBTM reflects the increased binder content being more important than the improved binder type.

The overall conclusions of the analysis were:
- The binder content is the most significant factor after age in the deterioration of thin surfacings.
- The supplier and, to a lesser extent, the binder type, the aggregate size and the category of road also influence the rate of deterioration.
- After allowing for the different binder content and binder type, SMA surfacings deteriorate marginally slower than BBTM surfacings.

These findings could be expected to be repeated for other asphalt mixture types, but similar data sets are not available.

2.5.1.3 Overlaying concrete
The application of thin surfacing systems directly over joints in concrete pavements is not considered a suitable treatment because cracking will normally occur within two years and require reactive ongoing maintenance. The saw-cut and seal (SCS) technique has shown to be very effective in reducing the occurrence of reflection cracking and is an appropriate treatment for JPCs in a generally good condition. However, the performance with overlay thicknesses of less than 50 mm has not been satisfactory and it is recommended that this is the minimum thickness for this technique to be applied, and preferably at least 70 mm (Coley and Carswell, 2006).

2.5.1.4 Case study: A96, Munich eastbound autobahn
The A96 is the autobahn in Germany that goes from Munich eastwards to Bad Wurzach near the Swiss border. Two sections of interest are the Oberpaffenhofen to Wörthsee section and the Bad Wörishofen to Mindeleim section. The 40 mm thick surfacing of the Oberpaffenhofen to Wörthsee section was constructed in 1989 with 0/11 mm SMA using 6% PMB, although lane 1 was resurfaced with 0/5 mm asphalt in 2005. The 8/11 mm coarse aggregate was granite whilst smaller sizes were gravel and the filler was limestone. The 30 mm thick surfacing of the Bad Wörishofen to Mindeleim section was constructed with 0/8 mm SMA using 7.3% 70/100 pen bitumen and 0.9% of a 5:1 combination of Trinidad Lake
asphalt (TLA) to fibre. The 2/8 mm coarse aggregate was granite, the 0/2 mm fine aggregate was gravel and the filler was limestone. The mixture had an air voids content of 3.1%.

A group of 12 asphalt technologists from the UK visited Munich in 2008 and inspected a series of sites of varying ages on three autobahns around Munich, some of which had been seen during a preliminary visit in 2007, including the two sections described above. The inspections were organised with the help of the state highways authority, Bayerisches Staatsministerium des Inneren. The 19-year-old Oberpfaffenhofen to Wörthsee section was assessed as “Good” to “Moderate” whilst the 15-year-old Bad Wörishofen to Mindeleim section was assessed as “Moderate” to “Acceptable” with some loss of aggregate and cracking.

The results of the inspections of the Bavarian SMA sites were plotted with the averaged UK results (Nicholls et al., 2007a) and are shown in Figure 2.9. All the points are on or above the trend line derived from the UK TSMA systems. These sites show the advantage of low air voids contents on the durability of SMA mixtures. However, it is appreciated that the relatively high texture depths specified on high-speed trunk roads in the UK preclude the use of mixtures with the low air voids contents specified for German autobahns. Nevertheless, the consensus of the UK delegation on the technical visit was that it would be appropriate to review the current balance between safety (with better skid resistance and spray reduction from high texture) and sustainability (from enhanced durability and noise reduction from low texture and use of smaller aggregate sizes), with greater emphasis on the latter.

2.5.2 Hot rolled asphalt

2.5.2.1 Durability on A26 trials at Burton-on-Trent

Data sets have not been gathered on other materials to the same extent, but a more limited data set is available on HRA from trials on the A38 at Burton-on-Trent (Nicholls, 2005). The trials included three categories of HRA: high stability with a binder content of 6.9%; medium stability with a binder content of 7.2%; and low stability with a binder content of 8.1%. The durability of these trial HRA mixtures was better overall than the typical durability of thin surfacing systems. The exceptions were the low stability HRAs that had less durability than the typical TAC and TSMA mixtures.

As such, the durability of the low-stability HRA mixtures, with one exception, was inferior to that of the medium- and high-stability HRA mixtures, whose performances were similar. However, the unmodified sections were among the best performing of the medium- and high-stability mixtures for durability, indicating that modification does not significantly improve the durability.

Whilst modification may not have improved the durability, it does improve other properties. The deformations, as measured in 2003, were substantially lower with PMBs than with paving-grade bitumen. For the medium- and high-stability mixtures, the deformation of the asphalt containing PMB was about half of that using paving-grade 40/60 pen bitumen. The reduction was even more significant in the low-stability mixture.

As with the thin surfacings, multiple regression analysis shows that the binder content is more significant than whether the binder is a PMB, which indicates that the use of PMBs has little impact on durability. Whilst this finding implies that there is no advantage in modifying the binder just for durability, it also implies that modifying a binder in order to enhance another property of the asphalt mixture does not compromise its durability.

The analysis showed that the binder content is the more significant parameter but, unlike with thin surfacings, the higher binder content/lower stability HRA mixtures have less durability. The less significant parameter of whether the binder was modified showed a marginal benefit for PMBs.

2.5.2.2 Case study: M25, Swanley to Sevenoaks

The M25 is an orbital motorway 188 km (117 miles) in circumference and circles London. The road was constructed in stages between 1975 and 1986, and was officially opened in October 1986. One of the last sections to be constructed was the section between Swanley and Sevenoaks. This case

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**Figure 2.9** Results from Bavaria compared with average visual assessment rankings for different surfacing types
study looks at the construction of this section and attempts to highlight the benefits of the innovative construction techniques that were employed to minimise the number of longitudinal joints in the pavement. The M25 now carries traffic in excess of 150,000 vehicles per day and this is testimony to good pavement construction.

The contract to construct the M25 between Swanley to Sevenoaks went approximately from Junction 3 to Junction 5 and included a 14 km long six-lane motorway, a roundabout at Badger’s Mount, connecting roads to the A224 and A21 and 14 bridges. The scheme’s designer was Kent County Council and the main contractor was John Laing Construction Limited. The asphalt surfacing was subcontracted to Associated Asphalt Limited (AA). The scheme cost £38.5 million (at 1986 prices).

A total of 400,000 t of asphalt were manufactured by AA using an ASTEC mobile drum mixing plant (Figure 2.10) with a daily capacity of almost 5,000 t. Such a large quantity required AA to have the right rolling equipment and batching plant to ensure a continuously reliable supply of material over the 30-week programme. AA had to have batching plants with high production and reliably consistent levels. The batching plant used was an ASTEC Super Six Pack® mobile asphalt plant capable of producing 400 t/h. It was acquired from the US and had to undergo some modifications to enable it to be used in the UK.

The courses to be rolled were 125 mm thickness of HRA lower roadbase, 205 mm of DBM upper road base in two layers of 100 mm and 105 mm and a 40 mm HRA wearing course (Figure 2.11).

Paving was carried out by two pavers working in echelon (Figure 2.12) set at widths of 7.75 m and 7.5 m, respectively, permitting the roadbase courses for the three-lane carriageway and the hard shoulder to be laid together as a 15.25 m wide mat. The wearing course layers were laid in lane widths with longitudinal joints between each.

AA operated Dynapac CC-42 series rollers, which could be programmed to repeat compaction performance and were claimed by the manufacturers to eliminate compaction error. Dynapac CC-42 rollers had not previously been used in the UK.

The durability of the M25 Swanley to Sevenoaks pavement can be assessed by reviewing the maintenance work that has been carried out over this section in relation to that on other sections of the M25. Details of maintenance work carried out on this section were obtained from the managing agent. The main points are:

- There has been no major maintenance in recent times and it appears that the surface course is the original HRA that was placed in 1986.
- The two surface course joints, under the lane lines, are in good condition and show little sign of deterioration. There is no sign of reflective cracking through the surface course above any joints in the lower layers.
- The ride quality is good and the section has performed well, and as the material was laid in 1986 it compares favourably with other sections on the network.

Construction of the M25 Swanley to Sevenoaks scheme was the first project in the UK (1986) to adopt the technique of asphalt paving in echelon. The decision to pave in echelon was adopted at the time because construction had to be completed in a 30-week period and echelon paving seemed suitable. Twenty years on, this section of the M25 is still in a sound condition as a result of the construction methods and
techniques that were employed at the time. The lessons that could be learned from this scheme are as follows:

1) Echelon paving minimised the amount of material wasted compared with traditional paving, which would require joint cutting. At the end of the contract, less than 100 t of material was recorded as wasted or unused. This amount represents less than 0.0003% of the total material that was used on site.

2) Echelon paving eliminated concerns about attaining adequate compaction at the joints.

3) Paving in echelon ensured that only one longitudinal joint was developed throughout the whole scheme. Traditional paving methods would have led to the development of three longitudinal joints. Joints are areas where weaknesses occur and close attention to their construction and frequency can enhance asphalt pavement durability.

4) Good quality control adopted during the paving stage reduced the number of stoppages during the paving process. This reduction had the advantage of eliminating errors associated with resetting the pavers after each stoppage and thus resulted in consistent paving and attainment of good ride quality.

5) Paving in echelon meant that, at the end of each shift, there were no exposed pavement edges. The absence of exposed faces ensured that there were fewer opportunities for ingress of detritus or moisture into the pavement structure and also eliminated the problems associated with paving when the mat/joint temperatures have dropped. This approach leads to uniformity and consistency in the paving operations and contributes to enhanced asphalt durability.

6) The scheme used experienced equipment operators who were well versed in paving and compaction techniques. This approach meant there was less likelihood of operator error or inexperience, which therefore led to construction of a good-quality pavement.

7) It is essential that considerable time is spent planning and evaluating the right equipment for a particular job. Planning for these works was meticulously undertaken and considered equipment types, construction methods and construction resources. This time was well spent because it translated into good construction work.

2.5.2.3 Case study: M6, Staffordshire

In 1984, substantial lengths of the M6 between Junctions 10A and 11 were rebuilt by Tarmac Limited National Contracting in severe winter conditions, yet the asphalt surface course lasted 21 years and the structural layers of the pavement are still sound (Farrington, 2009).

The previous carriageway base was a composite construction of lean-mix concrete overlaid with 100 mm of asphalt, which had full-depth transverse reflective cracks at regular intervals. It was decided to retain parts of the concrete, but elsewhere both the cracked lean mix and asphalt were excavated in 1 m widths and the lean mix replaced with fully compacted asphalt before being overlaid with 160 mm of DBM50 binder course and 50 mm of surface course.

The amount of reflective cracking had increased substantially by the time work started, giving concern about the effectiveness of overlaying the composite construction rather than a total reconstruct. Areas with the worst cracking were planed out to inspect the lean mix, showing that the planned crack treatment would significantly extend the contract period with the possibility of further delays if the job was affected by bad weather.

Instead, therefore, the exposed lean mix was swept, the crack locations were marked on the adjacent safety fence, a 60 mm thickness of 0/10 HRA “fine binder” course was machine laid, the crack locations were marked out and sheets of steel fabric were laid to bridge them. These areas were then overlaid with 200 mm of DBM in two layers with a 50 mm layer of new surface course. The asphalt was laid with insulated paver hoppers and, when suspect areas had to be re-rolled, the surfacing was preheated using infra-red heaters.

The works were subject to periods of snow and severe cold with asphalt being laid at temperatures down to -7 °C. Snow did stop the asphalt paving although an unsuccessful attempt was made to restart the work with use of an infra-red heater on part of the snow-bound site. However, excavation of the old pavement where it was to be totally reconstructed, crushing and screening of the excavated material and the placing of it as the capping layer were not stopped.

Therefore, the asphalt was laid when the areas were free of snow and, in shallow excavations, sheltered from the wind. The contractor had erected a large, heated marquee as an overnight shelter for the asphalt plant and, importantly, had insulated all paver hoppers. It then attempted to lay the DBM
2 DURABILITY

Despite temperatures being well below the specified minimum, the level tolerances and degree of compaction of these layers were closely monitored and the work proved to be entirely satisfactory.

The performance of the pavement has demonstrated that it is possible to lay asphalt layers successfully in very cold temperatures, provided there are adequate site controls in place to ensure frequent checking of compaction and laying tolerances and that areas requiring re-rolling are preheated.

2.5.3 Porous asphalt

PA was monitored by TRL for many years (Nicholls, 1997b) but was never used widely in the UK. For those trial sections that remained in service until no longer serviceable, a value of their ultimate life is available whilst a value for spray-reducing life is available for trial sections whose spray properties were monitored. Obviously, the data are subjective in that any life depends on when surfacings are deemed no longer serviceable (or spray-reducing). However, with these qualifications, cumulative distributions of ultimate life and spray-reducing life of the trial sections are given in Figure 2.13.

The service life of PA in the road trials appears to have been governed by progressive binder hardening until the binder was no longer able to accommodate the strains induced by traffic. Brittle fracture generally began during winter and, if the surfacing survived a cold winter, it usually remained serviceable during the following warmer months. An indication of imminent failure was often provided by the onset of fretting, particularly during the winter, which was usually accompanied by an increase in texture depth. Sometimes at this stage, core samples were taken from the surfacing and the condition of the binder used to establish a failure criterion.

The penetration of the binder from the sections of PA in the 1984 and 1987 Burton trials was monitored using samples taken from the mixing plant tanks and after recovery from the surfacings when laid together with recovered binder from cores taken at various intervals during the life of the surfacings (Daines, 1992). The results of binder recoveries are subject to several sources of error such as variation within the surfacings (sampling errors) and errors introduced by dissolution, recovery and testing. The errors are particularly evident for PMBs when the polymer is less than 100% soluble in the solvent used to extract it. Also, there was evidence of polymer instability in sections from both trials. Nonetheless, the following general trends were evident from the results:

- There was general hardening with time; between mixing and laying, a typical reduction in penetration of 30% was observed, although there were wide variations.
- The hardening proceeded at about 20% reduction in penetration per year.
- The critical binder penetration was judged to be about 15 x 0.1 mm with the softening point generally close to 70 °C, after which failure generally occurred when sub-zero temperatures were next encountered.
- The higher binder content materials showed a slightly lower hardening rate and, hence, increased longevity.
- The presence of hydrated lime tended to lower the hardening rate.

The effect that the penetration grade of the bitumen has on progress to failure is illustrated in Figure 2.14, using the current bitumen grades, for paving-grade bitumen at binder contents of about 4%. The predicted ultimate life of PA with 70/100 pen bitumen is six years, and that with 160/220 pen bitumen is ten years. However, stiffer binders are needed for heavily trafficked roads in order to avoid early closing-up of the PA and, hence, loss of the desired spray- and noise-reducing properties. It should be noted that PA with PMB has been shown to be serviceable at lower recovered penetration values (Carswell et al., 2005).
Based on this information and some assumptions about the relative performance of other surfacing types, estimates of typical service lives are given in Table 2.1. These are based on the assumption that the surfacing was laid on a good-quality substrate, is reasonably heavily trafficked and will be replaced when it reaches an "Acceptable" visual condition. However, these figures should be treated with care because the actual service life achieved will be dependent on a myriad of other factors such as the inherent suitability of the site and the care and attention in the design, mixing and application of the asphalt.

Table 2.1 Typical service life of surfacings

<table>
<thead>
<tr>
<th>Type</th>
<th>Category</th>
<th>Expected life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin surfacing</td>
<td>BBTM</td>
<td>11 to 15 years</td>
</tr>
<tr>
<td></td>
<td>SMA</td>
<td>10 to 16 years</td>
</tr>
<tr>
<td></td>
<td>UTLAC</td>
<td>8 to 11 years</td>
</tr>
<tr>
<td></td>
<td>MSD</td>
<td>4 to 8 years</td>
</tr>
<tr>
<td></td>
<td>MS</td>
<td>2 to 6 years</td>
</tr>
<tr>
<td>HRA</td>
<td>High and medium stability</td>
<td>14 to 24 years</td>
</tr>
<tr>
<td></td>
<td>Low stability</td>
<td>8 to 13 years</td>
</tr>
<tr>
<td>Asphalt concrete</td>
<td>DBM</td>
<td>10 to 16 years</td>
</tr>
<tr>
<td></td>
<td>Open-graded macadam</td>
<td>6 to 10 years</td>
</tr>
<tr>
<td></td>
<td>Marshall asphalt</td>
<td>15 to 25 years</td>
</tr>
<tr>
<td>PA</td>
<td></td>
<td>7 to 10 years</td>
</tr>
<tr>
<td>Surface dressing</td>
<td>Racked-in or double</td>
<td>4 to 8 years</td>
</tr>
<tr>
<td></td>
<td>Single</td>
<td>3 to 5 years</td>
</tr>
</tbody>
</table>

2.5.4 Overall comparison

Figure 2.14 Predicted penetration of paving-grade binder recovered from PA
3 Recycling

3.1 Introduction
Achieving sustainability in construction is one of the key objectives of the HA, requiring the optimum use of (and, where appropriate, the reuse of) materials to conserve resources and minimise the environmental impact of abstraction, production and construction processes. Recycling of asphalt and concrete materials for use in base layers and binder course layers, or for lower-grade applications, is well established.

Recycling can be considered in two distinct forms:

- **Closed loop**: Where the material removed is used for the same application. That is, a material removed from a bound base layer is recycled into a new bound base layer. This approach maintains the value of the material, particularly for surface course layers where premium aggregates are present.
- **Open loop**: Where material removed is used for an alternative application. For example, a material removed from a bound base layer is recycled into an unbound granular sub-base layer.

Both of these forms of recycling can apply to both hot- and cold-mix recycling. Furthermore, this recycling can be, and has been, undertaken on asphalt in layers of the pavement.

However, there is another type of recycling that can be used as part of construction with asphalt. This type of recycling is where an existing concrete pavements is recycled in situ to become the base for a new asphalt surface and binder courses.

3.2 Crack and seat

3.2.1 Description
The performance of an overlay to a JCP or hydraulically bound mixture (HBM) base is greatly affected by the action of reflection cracks. Reflection cracks are transverse and/or longitudinal cracks that occur in the overlay above the joints or cracks in the concrete (or HBM) layer due to its thermal expansion and contraction.

The objective of the C&S technique is to induce fine cracks into unreinforced or reinforced JCPs or cement-bound bases, before overlaying with new asphalt surfacing. This approach should then encourage the seasonal thermal movement in the concrete materials to occur at the induced cracks. These cracks are at a closer spacing than the normal shrinkage cracks or joints, thus the thermal movements at individual cracks should be much smaller and the occurrence of transverse reflection cracks in the asphalt overlay should be minimised. There are different variations of C&S techniques for use in different situations, including crack, seat and overlay (CSO), saw-cut and seal (SCS) and saw-cut, crack and seat (SCCS). Trials have demonstrated that C&S is a cost-effective pavement maintenance option.

The C&S and overlay treatment has been shown to perform considerably better than control sections with the same overlay thickness. At all the sites where cracks have been observed in the asphalt overlay, the visual condition surveys have indicated that the C&S trial sections are performing better than their equivalent control sections. The C&S process has reduced both the occurrence and severity of reflection cracking. At one site, C&S has been seen to outperform control sections with greater thicknesses of overlay. Therefore, the treatment inhibits reflection cracking above joints and pre-existing cracks in unreinforced concrete pavements and HBM bases. The closely related technique of SCCS is showing similar promise for the treatment of reinforced concrete pavements.

The C&S technique can be considered a form of recycling. The alternative of breaking out to reconstruct the pavement will increase transport, processing energy, costs and the use of raw materials. Some of the benefits that accrue are a reduction in:

- the contract period, with consequent reductions in costs, traffic delays and emissions;
- energy consumption during construction compared with traditional reconstruction or repair;
- use of primary aggregates; and
- the volume of materials taken to landfill.

These benefits make the process a cost-effective maintenance option. Hence, the use of C&S supports the UK government’s aims of sustainable construction by retaining the existing pavement as the main structural layer.

3.2.2 History of crack and seat and UK trials
A technique that had been used on JCP roads in the US and in other countries within Europe was to crack or break the concrete slabs, then seat them with a heavy roller before overlaying with asphalt material. However, this approach had not been used on roads with continuous laid bases constructed from HBMs. As a result of promising results received from overseas experience, it was decided that the technique of C&S should be investigated for its suitability in the UK.

In the UK, the performance of both reinforced and unreinforced JCP roads depends, in part, on the condition and performance of the dowel bars between slabs. Corrosion of the bars through ingress of de-icing agents often inhibits thermal movement, which can cause spalling at the joints and lead to mid-bay cracking. Poor load transfer at the joints increases the stresses on the foundation under the action of traffic and this overloading can result in differential movement, settlement of the slabs and pumping of fines from the underlying foundation materials. To improve the serviceability, it is common practice to overlay the pavement with asphalt after carrying out repairs to the concrete.

Although the overlay strengthens the pavement, it is often carried out to reduce water ingress and road noise, and improve ride quality. However, thermal movements within the concrete frequently cause transverse reflection cracks to develop in the new surfacing above the joints (Figure 3.1). To minimise transverse cracking, the present advice (Coley and Carswell, 2006) is that, unless cracked and seated, at least 180 mm of asphalt material is normally required following rehabilitation of any failed joints or slabs in the concrete. However, schemes have shown that even 180 mm of asphalt may exhibit reflection cracking within only four years of overlaying a JCP. Whilst a thinner overlay may be used in conjunction with SCS, this treatment is not suitable for concrete pavements with poorly performing joints according to Clause 713 of the SHW (HA et al., 2009).
Where the concrete is deemed to be in a good condition, an overlay of 70 mm or greater would be recommended with a SCS treatment applied to the finished asphalt surface (Coley and Carswell, 2006). The SCS treatment effectively controls the occurrence of reflection cracking above the joints in the concrete whilst still maintaining a seal at the asphalt surface.

An investigation of the suitability of C&S in the UK was undertaken by constructing full-scale road trials. These were designed to contain cracked and seated sections produced by different equipment incorporating differing crack spacings and crack patterns. Typical guillotine equipment now recommended for C&S is shown in Figure 3.2.

The degree of compaction required to seat pavements was explored by using different types of compaction plant. Following C&S, sections were overlaid with various thicknesses of asphalt. Trials were constructed on lean concrete bases (following removal of the existing asphalt) as well as JCPs. All the asphalt overlays considered in the trials consisted of HRA surface course on varying thicknesses of HRA binder course.

The performance of the cracked and seated trial sections was compared with that of control sections. No treatment of joints, cracks or failed slabs was carried out in the control sections prior to overlay. The in-service performance monitoring included:

- detailed visual condition surveys and coring of the pavement to investigate reflection cracking and slab thickness; and
- falling weight deflectometer measurements, traffic-speed surveys and measurements of the transverse profile in order to assess the deflection and permanent deformation of the pavements.

It was apparent from the first few years of monitoring of the road trials that the technique was proving to be highly effective in controlling reflection cracking when compared with the control areas. The reflection cracking in the control areas was demonstrated to occur in the surfacing at the road surface and propagate downwards. A procedure for the rehabilitation of JCPs and HBM bases was produced and continually updated. A protocol was developed to monitor the sites to assess their construction and performance. Following revisions arising from site experience, the procedure became a draft specification and was mounted on the HA’s “Speclib” database of draft specification clauses.

Several trial sites for C&S were constructed in the UK between 1991 and 1999 (Coley and Carswell, 2006). The earlier sites were full-scale experimental trials and the later supplementary trials were constructed using designs and specifications developed in the earlier research.

The success of the trials demonstrated that 150 mm of asphalt overlay could effectively inhibit reflection cracking and, therefore, this thickness of material was adopted as a minimum requirement in the C&S design method.

By the late 1990s, the C&S technique was being used on a large proportion of the major maintenance schemes requiring a structural overlay to a JCP. By this time, the use of HRA surfacing courses had been superseded by proprietary surfacing course systems that demonstrated considerable benefits over the previous material. In addition, the binder courses of these schemes normally comprised heavy-duty macadam (HDM), dense bitumen macadam (DBM) or high-modulus base rather than the HRA used in the original road trials.

The success of the C&S technique led to the development in the late 1990s of a similar method for the rehabilitation of jointed reinforced concrete pavements. SCCS is carried out in a similar manner to C&S except for the fact that the pavement is first transversely sawn at a predetermined spacing to a depth that just severs the longitudinal steel reinforcement. The first road trial for SCCS was constructed in 1999, leading to a design method and specification that have since been used on a number of major rehabilitation schemes.

### 3.2.3 Cost and environmental benefits

The C&S technique has been particularly cost effective on contracts on HA roads, with contracts being completed in one-third of the time and at one-third of the cost of traditional reconstruction. Substantial savings in time and cost have been made compared with rehabilitation of the concrete (requiring full-depth replacement of failed joints and slabs) and overlaying with at least 180 mm of asphalt. As an example, a costing exercise carried out after the original trial on the M5 at Taunton estimated that C&S could provide a material cost saving of about 40% when compared with traditional techniques (Potter et al., 2000).

As the existing pavement is left in place, the C&S technique supports the UK government’s aims of sustainable
construction. The reduction in contract period reduces traffic delays and, therefore, the cost to the travelling public. Energy consumption during construction is reduced compared with traditional reconstruction or repair. Use of primary aggregates is also reduced together with a reduction in materials taken to landfill tip.

The estimated cost and output rates for a theoretical scheme are given in Table 3.1. It shows the potential costs and output rates for the rehabilitation of one carriageway of a 1 km long section of a two-lane dual carriageway. Full-depth reconstruction (FDR), 180 mm overlay with joint and slab repairs and CSO are compared. The concrete repair and thick overlay option shown assumes 2.5% full-depth repairs, 2.5% joint replacements and 2.5% thin bond repairs. Each scheme will be different depending upon the state of the concrete pavement, but the total amount of repairs is considered to be typical.

The majority of C&S schemes to date have been carried out on two- or three-lane dual carriageways. If similar costs are applied to the 2.65 Mm² of pavement maintained to 2002, using CSO, then the potential total costs can be calculated as follows:

- Cost of full reconstruction = £113.4M.
- Cost of concrete repair and thick overlay = £94.7M.
- Cost of C&S and thinner overlay = £56.7M.

FDR tends to be discounted on cost and environmental grounds on maintenance schemes for JCPs so the savings should be compared with the concrete repairs and thick overlay alternative. Hence, the estimated construction savings for C&S schemes to 2002 is £94.7M - £56.7M = £38M.

In addition, the reduction in duration of works arising from using C&S leads to significant savings in reduced delay costs. Comparing C&S with concrete repair and thick overlay, the savings per day due to reduced delay costs are about £8k/day (range £7k–£11k) using QUADRO3 reference tables present in Annex 5.5.2 of Volume 1 of the Trunk road maintenance manual (Department for Transport, 1996). This assumes that the majority of schemes are two- or three-lane dual carriageways and works at any given time are about 3 km in length, full contra-flow operating, and carrying approximately 50,000 vehicles per day, of which 10% are HGVs.

If it is assumed that concrete repair works and overlay will take approximately 14 days/km for a two-lane dual carriageway and C&S will take four days (Table 3.1), then the savings due to reduced traffic delays (SRTD) on the schemes to date can be calculated from the following:

- Area maintained using C&S = 2.65 Mm². This area is equivalent to almost 360 dual carriageway sections of 1 km length.
- SRTD = 360 x 10 (days) x £8k (per day) = £28.8M.

Thus, the estimated total cost savings on C&S schemes to date is £38M (construction costs) + £28.8M (traffic delays) = £66.8M.

If it is assumed that there are about 37,000 lane km of JCP roads in the UK, of which about 15% are continuously reinforced concrete pavement, this assumption leaves 31,450 lane km for potential maintenance by C&S. Thus there is a total area of about 116 Mm² of such roads with only 2.65 Mm² being maintained thus far, leaving almost 113 Mm² of concrete pavement that potentially could be maintained by C&S in the future.

Using the above figures, the future benefits of using C&S could amount to savings of £2.85 billion.

### Table 3.1 Comparative costs for one carriageway of a 1 km long, two-lane dual carriageway with 5 m long, 250 mm thick slabs and 24-hour working*

<table>
<thead>
<tr>
<th>Maintenance technique</th>
<th>Cost (£)</th>
<th>Construction duration (h)</th>
<th>Total duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(1) Full-depth reconstruction</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td>316,720</td>
<td>400.0</td>
<td>Total: 25.0</td>
</tr>
<tr>
<td><strong>(2) Concrete repair and overlay</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FDR (2.5% of slabs)</td>
<td>16,580</td>
<td>66.7</td>
<td>Construction 4.2</td>
</tr>
<tr>
<td>Joint repairs (2.5% of joints)</td>
<td>4,280</td>
<td>5.0</td>
<td>Construction 0.3</td>
</tr>
<tr>
<td>Joint sealing</td>
<td>12,764</td>
<td>34.8</td>
<td>Construction 2.2</td>
</tr>
<tr>
<td>Thin bond repairs (2.5%)</td>
<td>56,943</td>
<td>185.0</td>
<td>Construction 11.6</td>
</tr>
<tr>
<td>180 mm overlay</td>
<td>173,900</td>
<td>43.5</td>
<td>Construction 2.7</td>
</tr>
<tr>
<td>Total:</td>
<td>264,467</td>
<td>228.5</td>
<td>Total: 14.3</td>
</tr>
<tr>
<td><strong>(3) Crack, seat and overlay</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C&amp;S</td>
<td>8,140</td>
<td>16</td>
<td>Construction 1.0</td>
</tr>
<tr>
<td>150 mm overlay</td>
<td>150,220</td>
<td>46.3</td>
<td>Construction 2.9</td>
</tr>
<tr>
<td>Total:</td>
<td>158,360</td>
<td></td>
<td>Total: 3.9</td>
</tr>
</tbody>
</table>

* 24-hour working assumes 16 h/day.
3.3 Cold recycling

3.3.1 Description
Recycling of existing pavement materials has become an increasingly important factor in the UK for maintenance of highways. Use of the "linear quarry" concept of using the existing highway as a source of road-stone aggregates has gained considerable favour in recent years following the introduction of the first nationally consistent guidelines in TRL Report TRL386 (Milton and Earland, 1999). Since that time, sustainability and environmental issues have continued to receive more attention and this has resulted in the demand to consider recycling in the maintenance of a larger proportion of the primary and secondary road network. In construction and maintenance, the way in which materials are specified is changing to allow for innovation and alternatives to the use of primary aggregates newly extracted from a quarry. Specifications and guidance has been developed based upon performance rather than on the use of standard materials made to strict recipes. This guidance allows a greater range of materials to be incorporated into the pavement, including alternative and secondary materials (Chapter 4) when these materials can provide the desired performance properties. TRL Report TRL611 (Merrill et al., 2004) gives full details of the guidance and specification for cold recycled materials for the maintenance of road pavements, and allows the use of in situ and ex situ techniques as the material is assessed on performance rather than method of production.

Materials are generally classified into families based on the binders used. Four basic cold recycled material families are classified as follows:

- **Quick visco-elastic**: A bituminous binder with cement and possibly containing another pozzolanic binder.
- **Slow visco-elastic**: A bituminous binder without cement but possibly containing other pozzolanic binders.
- **Quick hydraulic**: A hydraulic binder with cement.
- **Slow hydraulic**: A hydraulic binder without cement.

The performance is based on one-year properties of stiffness for visco-elastic and compressive strength for HBM. Early-life strength is another aspect that needs to be considered and can be demonstrated by trafficking.

The use of cold recycled materials is currently permitted for use on the HA network for designs up to 30 msa (HA et al., 2006), which is based on the use and experience of these materials to date. However, higher levels of design traffic may be permitted with a departure from standard, which would extend current experience and may permit routine designs at higher levels of traffic. A case study on the A38 trunk road in south Devon using a quick visco-elastic ex situ recycling is described in Section 4.2.3.3, where the design traffic was about 38 msa.

3.3.2 Case study: A46 Shottery to Bishopston
The use of C&S on a lean concrete layer and cold recycling of the asphalt for use as a base layer have been combined at a site on the A46 in Warwickshire.

The scheme consisted of 2 km of the A46 (the Stratford Northern Bypass), between the roundabout with the A422 at Shottery (south end of site) and the roundabout with the A3400 at Bishopston (north end of site). This section of road is a two-lane single carriageway and is approximately 12 m wide. The condition of the pavement had resulted in ongoing annual emergency and routine maintenance that could only be rectified by structural maintenance. The original proposal was to plane off the existing asphalt, crack and seat the lean concrete layer and overlay with hot-mix asphalt. Cemex Construction proposed reusing some of the planed-off asphalt into a new ex situ cold recycled base layer (known as ViaFoam). This was accepted and was the first use of the two techniques together in the UK. The design (figure 3.3) thus entailed planing out the asphalt and 40 mm of the existing lean concrete base, C&S treatment of the lean concrete and laying 140 mm cold recycled ViaFoam base, 70 mm hot-mix binder course and 30 mm of thin surface course.

The works were carried out in three phases between January and February 2006. They were inspected visually in September 2008 and were considered to be performing well with no signs of any deterioration. A full description of the works and the detailed design are given elsewhere (Hewitt et al., 2008). An estimate of the carbon dioxide equivalent emissions showed that considerable savings could be made (Table 3.2).

3.4 Hot recycling

3.4.1 General
Recycling RA into base and binder course mixtures has become almost routine whilst its inclusion in surface course has been much more limited. This bias is demonstrated by PD 6691 (BSI, 2007b) where the recommended upper limit is 10% for surface course mixtures but 50% for mixtures in other layers. Therefore, this section will concentrate on recycling RA into surface course mixtures.

3.4.2 Recycling into thin surfacing systems
Thin surface course systems were first introduced to the UK from France and Germany in the early 1990s because of their ease and speed of construction, resistance to deformation and improved ride quality, and noise and spray reduction. These materials have seen their popularity and use increase to the extent that they are now the principal option for surfacing on trunk roads in England. However, they incorporate premium-quality, high-PSV aggregates throughout the layer, thereby increasing demand for these aggregates. A 2008 report to the Mineral Industry Research Organisation (Capita Symonds, 2008) indicated crushed rock reserves of 39 years, although this did not take into account the demand for specialist products such as high-PSV (skid-resistant) materials, which cannot be substituted by more general-purpose aggregates from other sources.
Therefore, the need to make best use of the high-PSV aggregate in surfacing materials is becoming increasingly important. The alternatives would be either transporting material from well-sourced to less well sourced areas or increasing imports from elsewhere. The cost and environmental impact related to those choices justifies the conservation of the already used materials; that is, recycling. Recycling of surface course RA is generally common, but in lower-level applications such as binder, base and sub-base layers. Recycling into the same layer has not yet become standard practice and requires better controls for ownership, storage and treatment of planings and adaptations to asphalt plants to increase their capability to add RA in increasing quantities.

A study into recycling of thin asphalt surfacings back into surface course layers established its feasibility (Carswell et al., 2005), and further research has led to the development of best practice guidance (Carswell et al., 2010). Trials have demonstrated comparable performance after six years of service with RA contents of up to 30%. Resurfacing schemes have been carried out on the M4 in South Wales and the M25 in Reigate incorporating up to 25% of the existing asphalt surfacing into the new surface course layer.

Table 3.2 Summary of the carbon dioxide equivalent emissions estimation exercise

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-depth replacement of the bound layers in hot-mix asphalt</td>
<td>C&amp;S with conventional hot-mix overlay</td>
<td>C&amp;S with ViaFoam cold-mix ex situ recycling</td>
</tr>
<tr>
<td>Construction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 mm surface course</td>
<td>30 mm surface course</td>
<td>30 mm surface course</td>
</tr>
<tr>
<td>60 mm binder course</td>
<td>60 mm binder course</td>
<td>60 mm DBM binder course</td>
</tr>
<tr>
<td>250 mm HDM base</td>
<td>150 mm HDM base</td>
<td>150 mm CRBM base</td>
</tr>
<tr>
<td>300 mm granular sub-base</td>
<td>C&amp;S of CBM</td>
<td>C&amp;S of CBM</td>
</tr>
<tr>
<td>Total arisings</td>
<td>30,612 t</td>
<td>14,577 t</td>
</tr>
<tr>
<td>Arisings haul distance</td>
<td>40 km (to stockpile/waste management)</td>
<td>40 km (to stockpile/waste management)</td>
</tr>
<tr>
<td>Reduction in CO₂ equivalent emissions when compared with Case 1</td>
<td>–</td>
<td>484 t</td>
</tr>
</tbody>
</table>

Figure 3.3 Design for A46 Shottery
3.4.3 Case study: M4 Cardiff surface course recycling

PA with 20 mm maximum size aggregate was laid at a nominal 50 mm depth on 4.7 km of the M4 from Junction 32 to Junction 33 in 1994 using Craig-yr-Hesg coarse aggregate and a PMB. Major maintenance was required in 2006 and the tender specification from the Welsh Assembly required at least 25% of the surface course mixture to be RA from the planings. This work was undertaken in July and August 2006 (Nicholls et al., 2007b).

The selected surfacing material was a proprietary TAC system consisting of 80% aggregate in the 6/18 mm fraction. The PA planings were screened to remove both the undersize (0/6 mm) and oversize (>18 mm) with the three fractions being stockpiled separately. Only the 6/18 mm fraction was recycled in order to reduce the influence of the greater water content that would be required and the detritus that would be expected in the finer fractions.

The site was assessed visually by the HA/TRL Inspection Panel in 2009, after three years of service, and both sections were considered to be "Good".

3.4.4 Case study: M25 Reigate surface course recycling

Similar to the M4 Cardiff, this scheme involved planing out an existing PA surfacing and replacing it with a thin surfacing incorporating 23% RA from the existing material. The material was transported to an asphalt plant at Hayes for processing, with the undersize and oversize aggregate fractions removed, to enable the RA to be incorporated into a new thin surfacing system. The resurfacing works took place at night during August 2007 under lane closures with the carriageway re-opened to traffic during the day. Initial trial mixtures were undertaken to establish the best method of adding the RA to the mixture whilst still being able to maintain sufficient temperature within the mixed material for transportation and laying on site. The impact of this scheme in terms of energy use, as shown in Table 3.3, demonstrated the savings for this particular scheme.

### Table 3.3 Impact of M25 surface course recycling scheme

<table>
<thead>
<tr>
<th>Impact of the scheme</th>
<th>Energy used (GI)</th>
<th>CO$_2$ generated (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3,235.32</td>
<td>220.02</td>
</tr>
<tr>
<td>of which:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>attributable to Masterpave-R mixture (total of 3,096 t used at 22.3% RA content)</td>
<td>2,828.46</td>
<td>191.97</td>
</tr>
<tr>
<td>attributable to Masterpave mixture used in first section (total of 447 t used)</td>
<td>406.86</td>
<td>28.05</td>
</tr>
<tr>
<td>Equivalent to approximately, per tonne of asphalt laid</td>
<td>0.913</td>
<td>0.0621</td>
</tr>
<tr>
<td>Impact of the alternative &quot;what if&quot; scenario (only Masterpave used, total of 3,543 t)</td>
<td>3,488.05</td>
<td>236.32</td>
</tr>
<tr>
<td>Equivalent to approximately, per tonne of Masterpave</td>
<td>0.984</td>
<td>0.067</td>
</tr>
</tbody>
</table>

Source: TRL Published Project Report P99304 (Schiavi et al., 2007).
4 Secondary materials

4.1 Introduction
The following is the general order of priority for the sustainable choice of materials for highway works (Reid et al., 2008):
• Reuse existing highway materials at the same level or at as high a level as reasonably practical.
• Use imported recycled or secondary materials10 as much as reasonably practical.
• Use primary materials.

This chapter deals with the second of these bullet points, Chapter 3 having dealt with the first point.
Traditionally, asphalt has been manufactured with primary coarse aggregates, quarry fines as added filler and hot asphalt. In recent years, however, a range of other materials have been investigated for use as added filler, fine aggregate and coarse aggregate, and the development of cold recycling techniques has opened up the possibilities considerably. The materials that are either already used or have potential for widespread use in the UK are discussed in this chapter.

4.2 Filler
4.2.1 General
The purpose of added filler is to extend the grading of the fine and coarse aggregate to ensure that a dense, low-permeability mat with low air voids is formed when it is mixed with hot bitumen and compacted. The grading requirements for added filler in asphalt are given in Table 24 of BS EN 13043:2002 (CEN, 2004) with a maximum aggregate size of 2 mm and the target grading having to be no lower than 85% at the 0.125 mm sieve size and no lower than 70% at the 0.125 mm sieve size; the producer is allowed a production tolerance of ± 10% on the target.
Other tests that may be required for added filler are described in Chapter 5 of BS EN 13043 (CEN, 2004). These include properties of the filler itself and of mixtures of the filler with bitumen, such as the delta ring and ball test to BS EN 13179-1 (CEN, 2000). Any materials that are proposed for use as added filler must be tested in accordance with this standard and compared with standard materials to see if they confer any advantageous or disadvantageous properties. The consistency of the material must also be assessed to ensure that it does not vary significantly and affect the properties of the asphalt. In other words, use as added filler cannot be seen as a cheap way of getting rid of unwanted material; a consistent, quality-controlled material with reliable properties is required.
The amount of added filler will vary depending on the type of asphalt being produced, but in most cases will not be more than 4%. The amount of secondary material that can be used in this way is thus limited at any one asphalt plant. However, given the very large volumes of asphalt that are produced annually in the UK – the Mineral Products Association (2008) reports 25.7 Mt for 2007 – an addition rate of 4% would indicate a potential usage of 1.03 Mt/year of secondary materials.

4.2.2 Quarry fines
Quarry fines are sometimes not regarded as secondary materials as they are not exempt from the aggregates levy. However, as they arise as a by-product from the production of aggregates and are not produced as an end in themselves, it is appropriate to consider them as secondary materials for the purposes of this chapter.
Limestone is the most commonly used material as added filler for asphalt mixtures, with Portland cement and hydrated lime (which are not quarry fines) being used for some specialist applications. Limestone is used because the material is available in sufficient quantities at most batching plants in the form of fines from the quarrying of limestone for coarse aggregate (Nicholls et al., 2007c). However, there is generally no requirement to restrict the type of filler for most generic types of asphalt, so other types of quarry fines can also be used. Fines from the quarrying of sandstone for high skid resistant aggregate in South Wales are used as filler, with about half the total fines produced being used in this way (Lamb, 2005).
Quarry fines can range from about 4 mm down to clay size, so in most cases some pretreatment is required to meet the grading requirements of Table 24 of BS EN 13043 (CEN, 2004). In some quarries, the filler is separated by washing and filtering, leaving clean sand-sized material that can be used in construction applications; this increases the cost but ensures that both the filler and the larger fine aggregate fractions can be used. Untreated and treated quarry fines from a sandstone quarry in South Wales are shown in Figure 4.1. Alternatively, a smaller amount of the all-in quarry fines11 can be mixed with the fine aggregate to provide a mixture that lies within the allowable grading envelope. Fines produced from the quarrying of hard rock are generally very consistent in grading due to the uniformity of the production process, and hence are well suited for use as added filler.
Quarry fines are currently extensively used as added filler. If this option was not available because of the use of secondary materials, such as those discussed in the following sections, alternative uses would have to be found for the quarry fines. Whilst various alternative applications have been investigated (Lamb, 2005; Tarmac Limited, 2007), there is a risk that large quantities would either be used as inappropriate landscaping and restoration fill in worked-out quarries or would have to be landfilled. The annual production of quarry fines is estimated to be about 41 Mt, which is much greater than the potential market of about 1 Mt for added filler. However, this is a high-value application, which should be encouraged.

4.2.3 Pulverised fuel ash
4.2.3.1 Description
Pulverised fuel ash (PPA), or coal fly ash as it is sometimes called, is a fine, grey particulate material left behind by the burning of coal in power stations (Figure 4.2). About 5 Mt are produced annually in England (Capita Symonds, 2007). PFA consists principally of glass spheres together with some crystalline matter and a varying amount of carbon. It possesses pozzolanic properties that make it suitable as an ingredient in concrete and HBMs. It is also used as added...

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10 Secondary materials are component materials that were originally by-products of other industrial processes, although they can have a value once a use is found for them.
11 All-in aggregate contains all the available fractions; in this case, the filler and fine aggregate fractions.
INCREASING THE ENVIRONMENTAL SUSTAINABILITY OF ASPHALT

filler in asphalt, especially in cold recycled mixtures, which are mixed either in situ or ex situ at temporary batching plants near the site. PFA is widely available throughout the UK (Capita Symonds, 2007), so can readily be delivered to sites wherever it is required. Whereas quarry fines are advantageously located for many batching plants for hot asphalt, PFA is more convenient for on-site operations such as cold recycling.

PFA has a suitable grading for use as added filler, is generally very consistent in quality and is widely used in small quantities. When used in asphalt on its own, it is inert and effectively replaces quarry fines as added filler. It can also be used in combination with binders such as cement or lime to bestow specific technical properties on the asphalt, particularly when used with foamed bitumen in cold recycled materials. Pozzolanic reactions between the PFA and cement or lime increase the stiffness of the mixture, enabling it to accommodate higher traffic loadings or thinner layers to be used (Merrill et al., 2004). Use with cement creates a high-stiffness material that has to be placed and compacted within a few hours, whereas use with lime creates material that can potentially be stored for several days before use and has lower stiffness, though still considerably higher than could be achieved with foamed bitumen and PFA alone (although PFA is not generally used on its own unless added solely for increasing the fines content; lime or cement are needed to effect a pozzolanic reaction). This ability to store the product for a period of time before use can be very valuable for plants that recycle arisings for highway works, where small quantities are often required at a number of locations over a period of time. Two case studies illustrating the use of PFA in different applications are given below.

In order to avoid categorisation as waste, PFA should be handled in accordance with the proposed Quality Protocol for PFA being developed by the Environment Agency (EA) and Waste Resources Action Programme (WRAP). Use in asphalt and other bound forms is not considered to present any significant danger to the environment (WRAP and EA, undated a).

4.2.3.2 Case study: F M Conway’s reprocessing facility, Dartford

F M Conway is a major civil engineering company specialising in term maintenance contracts for highway maintenance for London Boroughs and County Councils in the South East. It produces large quantities of concrete, asphalt, soil and gully waste as part of its operations. In response to the shortage of natural aggregates in the South East, the increasing use of recycled aggregates, the development of national specifications that permit the use of recycled aggregates in high-value applications such as asphalt and concrete, and the likely future difficulties in disposing of materials to landfill, it decided to invest in a comprehensive package of treatment plants to produce high-value products. This investment includes a plant to produce cold recycled bituminous materials using foamed bitumen as a binder and recycled asphalt from F M Conway’s highway maintenance arisings. The product is known as Foamway. PFA is used as added filler with either cement or lime to produce two products:

• Structural grade
• Storage grade

Structural-grade Foamway uses cement and PFA and can be designed to produce pressure values (as a surrogate for stiffness) ranging from 2,500 to 6,000 MPa. It is designed to be laid within hours of manufacture and can be used as a base or binder course in road pavements for traffic loadings up to 30 msa. The use of cold recycled bitumen bound material is permitted under Clause 948 of the SHW (HA et al., 2009). Storage-grade Foamway using PFA and lime can be kept for up to one month under sheeted conditions. It is ideal for footways and lightly trafficked applications.

13 The case study is available at www.aggregain.org.uk/recycling_infrastructure/case_studies/f_m_conways.html
4.2.3.3 Case study: Ex-situ recycling of a trunk road on the A38, South Devon

A section of the A38 on the southern side of Dartmoor, adjacent to Ashburton, was recycled. It is one of the most heavily trafficked roads in Devon, taking most of the traffic between Exeter and Plymouth, the two largest centres in the South West. Typically, the two-way annual average daily traffic volume is around 39,000 vehicles, with around 14% being heavy goods vehicles (HGVs). The road was identified as needing major structural maintenance in 2004 following increasing amounts of patching.

Ex-situ recycling in the form of Foamix® (Figure 4.3) was selected in preference to conventional reconstruction for financial reasons and environmental benefits such as reduced pollution and congestion. The structural layers of the existing pavement were recycled to produce the Foamix®, which is a cold-lay asphalt with a binder consisting predominantly of foamed bitumen. This is a high-volume, low-viscosity fluid with a low surface tension, which enables a wide range of moist, cold recycled aggregates to be coated with bitumen. The significant reduction in truck movements on the A38 and waste disposal costs enhanced the sustainability benefits of this solution. The work was carried out in the winter of 2005–2006 to minimise disruption to holiday traffic.

PFA and cement were added to the mixture to provide the increased stiffness required to cope with the very high traffic flows. PFA was used because of its pozzolanic properties when mixed with cement, not simply as added filler. The constituents of the mixture are shown in Table 4.1.

---

**Table 4.1 Constituents of the Foamix® mixture for the A38**

<table>
<thead>
<tr>
<th>Material</th>
<th>Proportion by mass (%)</th>
<th>Compliance criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycled aggregate from the A38</td>
<td>88</td>
<td>Zone A (TRL611)</td>
</tr>
<tr>
<td>PFA</td>
<td>5</td>
<td>Incorporated in the end performance requirements</td>
</tr>
<tr>
<td>Bitumen (100/150 pen)</td>
<td>3</td>
<td>(3 ± 0.50)%</td>
</tr>
<tr>
<td>Cement (CEM 1)</td>
<td>1.5</td>
<td>(1.5 ± 0.3)%</td>
</tr>
</tbody>
</table>

---

4.2.4 Cement kiln dust

CKD is a fine powder that is a by-product of the manufacture of cement. It consists of very fine particulates that are trapped in the air pollution control systems of rotary kilns used to manufacture cement. The particles are a mixture of unburnt constituents from the original materials used to manufacture the cement – limestone and shale, partially combusted by-products and fly ash from the fuel. Despite the name, it does not contain cement and, although it displays some of the same properties as cement such as pozzolanic behaviour, it is a completely different material with a much higher content of chemically active compounds. It generally has a high pH value of 12 or greater due to the presence of free (quick) lime (CaO) (Table 4.2) together with other alkalis, sulphates, chlorides and possibly significant amounts of trace elements. The amount of these components can vary significantly depending on the nature of the fuel, particularly any additives. Significant amounts of CKD are produced annually in the UK and most of this is disposed of to landfill. CKD is classified as a non-hazardous waste in the UK and its use is, therefore, subject to the UK Waste Permitting Regulations.

A considerable amount of research has been carried out on the use of CKD in various applications, including concrete, HBM and asphalt. The high free lime content of CKD is considered to yield advantages in terms of improved adhesion and/or reducing the binder demand. A review of the research relating to asphalt and trials with samples of CKD from three sources in the UK is reported by Nicholls et al. (2007c). The CKD was found to vary significantly in terms of physical and chemical properties between the three sources. The grading analyses of the three samples compared with limestone quarry fines, cement and the BS EN 13042 limits, together with a range of chemical properties, are shown in Table 4.2.

Laboratory trials were undertaken using five different asphalt mixtures that were regarded as representative of those generally used in the UK. Each mixture was manufactured both with CKD and limestone quarry fines filler at a rate of 4% and then tested for a range of properties. The tests demonstrated that use of CKD filler has marginal effects on asphalt properties with, if anything, a small overall improvement. Further tests were undertaken on the influence of CKD on the workability and water sensitivity. The workability tests found that, whilst one source of CKD did not significantly affect the workability, the other two tested did result in less workable mixtures that would require an increase in mixing temperatures, a major disadvantage in economic and sustainability terms. Furthermore, only one of the three sources tested (Source A) satisfied the requirements for grading and loose bulk density in BS EN 13043 (CEN, 2004).

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Figure 4.3 Foamix® being laid on the A38

The case study is available at www.aggregain.org.uk/case_studies/a38_exsitu.htm
Additional work found that the water sensitivity is reduced by replacement of limestone filler with CKD, and that the improvement is more marked for mixtures with lower binder contents. The improvement could be up to four times on the SATS conditioning test and 15% on the HAPAS water sensitivity test. The greatest improvement was for the CKD from Source A. These results showed better adhesion than those from the previous study and could form the required driver to counter the need for higher mixing temperatures.

A pilot-scale trial laying of mixtures for two layers (binder course and surface course), both with and without CKD filler without changing the mixing temperatures, was carried out (Figure 4.4). The materials used were a 0/20 mm HDM binder course and a 0/14 mm proprietary thin surface course system. The trial demonstrated that asphalt mixtures can be produced and laid to produce a satisfactory mat. However, the surface course material, when CKD was included, achieved a higher air voids content than the control. This enhancement indicates that the use of CKD as the filler without increasing the mixing temperature does increase the probability of the compaction being less effective with some, but not all, mixtures.

The trials have shown that CKD can be used as the filler in asphalt mixtures. However, the properties of the CKD, and hence its effect on the mixtures, have been shown to vary considerably depending on the source. The consistency of the material from a single source would need to be investigated before it could be considered for regular use as added filler. It would also be necessary to agree a protocol with the EA or the equivalent authorities in Scotland and Northern Ireland to demonstrate that the CKD had been fully recovered by incorporation into asphalt and was no longer a waste. There are thus considerable potential barriers to the more widespread use of CKD as added filler in the UK. If the temperature of the asphalt mixture had to be raised to increase the workability of the mixture, this increase would negate the sustainability gains of using it.

### 4.3 Coarse and fine aggregate

#### 4.3.1 General

Secondary and recycled aggregates have been used to replace some or all of the coarse and fine fractions of the aggregate in asphalt mixtures. The use of some of these materials is well established because of the specific technical advantages that they possess, such as the use of steel slag in the surface course and surface dressing because of its high skid resistance. Other uses have developed more recently in response to the presence of materials in specific geographic areas, such as slate in North Wales and china clay sand in the South West of England. Enabling the use of these local materials in high-value applications brings sustainability benefits in terms of reduced transport and the preservation of primary aggregates. Other applications have been based on a combination of the development of new techniques, such as cold recycling and a desire to utilise particular materials for high-value applications, seeing them as a resource rather than a waste. An example of this approach is the use of incinerator bottom ash (IBA) with foamed bitumen binder.

**Table 4.2 Grading analyses and chemical properties of cement kiln dust**

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>CKD</th>
<th>Limestone</th>
<th>Cement</th>
<th>BS EN 13043 limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source A</td>
<td>Source B</td>
<td>Source C</td>
<td>Proportion passing (%)</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>0.125</td>
<td>94.4</td>
<td>92.6</td>
<td>99.2</td>
<td>99.2</td>
</tr>
<tr>
<td>0.063</td>
<td>71.8</td>
<td>48.7</td>
<td>88.7</td>
<td>98.2</td>
</tr>
<tr>
<td>pH value</td>
<td>12.5</td>
<td>12.6</td>
<td>12.7</td>
<td>9.9</td>
</tr>
<tr>
<td>Free lime (%)</td>
<td>6.9</td>
<td>4.5</td>
<td>5.0</td>
<td>0.14</td>
</tr>
<tr>
<td>Water solubility (%)</td>
<td>8.5</td>
<td>5.1</td>
<td>2.2</td>
<td>&lt; 1.0</td>
</tr>
</tbody>
</table>

nd = Not determined.

**Figure 4.4** Pilot trial: binder course (left) and surface course (right) containing CKD filler being laid (Source: Nicholls et al., 2007c)
Table 4.3 Restrictions on coarse aggregates for bituminous mixtures in the SHW

<table>
<thead>
<tr>
<th>SHW Clause</th>
<th>Application</th>
<th>Permitted constituents</th>
</tr>
</thead>
<tbody>
<tr>
<td>918.6</td>
<td>Surface skurry incorporating MS</td>
<td>Crushed rock, slag, gravel, calcined bauxite</td>
</tr>
<tr>
<td>919.5</td>
<td>Surface dressing: recipe specification</td>
<td>Crushed rock, slag, gravel, calcined bauxite</td>
</tr>
<tr>
<td>922.8</td>
<td>Surface dressing: design, application and end product performance</td>
<td>Crushed rock, slag, gravel, calcined bauxite</td>
</tr>
<tr>
<td>942.5</td>
<td>Thin surface course systems</td>
<td>Crushed rock, steel slag</td>
</tr>
<tr>
<td>943</td>
<td>HRA surface course and binder course (performance-related design mixtures)</td>
<td>Crushed rock, steel slag</td>
</tr>
</tbody>
</table>

Source: HA et al., 2009.

Whilst the use of these materials can bring sustainability benefits in terms of beneficial use of the materials, reduced transport distance and preservation of primary aggregates, they must also deliver satisfactory performance and durability when used in asphalt. For materials with established uses, such as slags, specific requirements are set out in the relevant standards and specifications, including BS EN 13043 (CEN, 2004) and the SHW (HA et al., 2009). For more innovative materials, the engineering benefits may need to be established for specific applications. It is particularly important that materials formed at very high temperatures, such as slags and ashes, are properly weathered before use. Failure to do so may result in swelling reactions in use, with break-up of the asphalt as a result. There may also be adverse chemical reactions between the binder and the secondary aggregates. Most producers of these materials employ quality control schemes to ensure the materials are properly weathered before use and can provide guidance on how they should be used.

A number of secondary aggregates that can be used in asphalt are classed as waste by the EA. This means they have to be subject to a recovery process, conform to relevant standards and specifications and have certainty of use before they can be regarded as fully recovered and no longer waste. To aid in determining when these materials have been fully recovered, the EA and WRAP are developing a series of Quality Protocols. Quality Protocols for steel slag and ICB are currently in production. However, BFS has been reclassified as a by-product rather than waste and is not subject to Waste Permitting Regulations. Use of secondary aggregates in asphalt is unlikely to lead to environmental harm provided they have been produced in accordance with an appropriate quality control system (a requirement for all aggregates under harmonised European standards) and are used in accordance with the relevant standards and specifications. However, where a Quality Protocol is available it should be followed by producers to ensure that there is no question of the material being regarded as waste.

BS EN 13043 (CEN, 2004) specifies the properties of aggregates obtained by processing natural or recycled or manufactured materials for use in bituminous materials. There is thus no discrimination against recycled or manufactured aggregates in the standard, though specific tests are included for some secondary materials, such as tests for constituents that affect the volume stability of BFS and steel slag. The standard includes a note that secondary materials from unfamiliar sources should be tested for release of dangerous substances (Essential Requirement 3 under the Construction Products Directive) before use.

Clause 901.3 of the SHW (HA et al., 2009) states, “Natural, recycled unbound and manufactured (artificial) aggregates shall be clean, hard and durable and shall comply with BS EN 13043.” The suitability of aggregates for specific applications is determined by whether they meet the performance requirements for the application, not by the origin of the aggregate. Recycled and secondary aggregates may, however, have specific requirements related to their origin. Clause 901.3 goes on to say, “Where recycled coarse aggregate or RCA is used in bituminous mixtures, it shall have been tested in accordance with Clause 710 and the content of other materials (Class X) including wood, plastic and metal shall not exceed 1% by mass.” The use of china clay sand and crushed slate aggregate is covered in Clauses 901.4 and 901.5, respectively. Requirements for volume stability of BFS are given in Clauses 901.12 and 901.13 and for steel slag in Clause 901.14.

As well as the specific requirements for individual materials, aggregates for use in bituminous mixtures have to satisfy other requirements related to particle strength and soundness. Clause 901.6 states, “The resistance to fragmentation category of the coarse aggregate as defined in Clause 4.2.2 of BS EN 13043 (CEN, 2004) shall be LA30 or better for natural aggregates and LA50 or better for blast furnace slag.” This will rule out weak materials such as colliery spoil. There are also requirements for a magnesium sulphate soundness category of MS25 or less, particularly if the water absorption is greater than WA242. Many recycled and secondary aggregates are likely to have water absorption values greater than 2, so it is likely that suitable values of magnesium sulphate soundness will have to be demonstrated if they are to be acceptable. The requirements for water absorption do not apply to BFS, presumably because there is sufficient experience with the material to allay any concerns about its durability.

For aggregates proposed for use in surface course or surface dressing, there are further requirements for PSV and aggregate abrasion value (AAV). The required PSV depends on the location where the material will be used, but there is a general requirement for the AAV to conform to category AAV10. For a few applications, there are specific restrictions on the permitted constituents (these are summarised in Table 4.3). For all other applications, only performance criteria are given in the SHW (HA et al., 2009), in addition to the general criteria given above.

Whilst the use of a wide range of recycled and secondary aggregates is permitted under the standards and specifications, in practice the number of materials that are...
widely used is relatively limited. The main ones currently
used and some with potential for greater use in the future
are described in the following sections. BFS, steel slag (well
weathered), china clay sand and slate aggregate can meet
the SHW and have been specifically named in the 900 Series
(HA et al., 2009). Recycled glass, IBA, RCA and phosphoric
slag can comply as components of recycled aggregates within
bituminous layers (HA et al., 2004).

4.3.2 Blast furnace slag
Annual BFS production in the UK is currently around 3 Mt.
About 75% of this is turned into ground granulated blast
furnace slag (GGBFS), with the remaining 25% being used
as bound and unbound aggregates for a range of uses,
including coarse aggregate in asphalt in base, binder course
and surface course (WRAP and EA, undated b). Currently,
demand for BFS as aggregate exceeds supply in the UK, and
it is being imported from Europe to meet demand (WRAP
and EA, undated b). This demand is because it is a well-
established aggregate that has properties suitable for high-
value applications such as concrete and asphalt. In asphalt, it
is suitable for use in base, binder course, surface course and
chippings.

The nature and properties of BFS aggregates are described
by Dunster (2001) and Coventry et al. (1999). It is a by-
product of the manufacture of iron by chemical reduction in
a blast furnace and is made up primarily of the silicates and
alumina-silicates of calcium and magnesium together with
other compounds of sulphur, iron, manganese and other trace
elements. It bonds well with bituminous binders and has a
moderately high PSV in the range 53 to 57 (Dunster, 2001),
so is well suited for use as coarse aggregate in asphalt and has
been widely used.

BFS can be subject to two types of unsoundness that affect
its suitability for use as an aggregate:

- “Falling” or “lime disintegration” (dicalcium silicate
unsoundness)
- Iron unsoundness

Dicalcium silicate unsoundness results from inversion of the
metastable “K” form of the dicalcium silicate to the “γ”
form. Iron unsoundness results from the hydrolysis of iron
and manganese sulphides; BFS generally contains about
1% sulphur, largely in the form of sulphides (Dunster, 2001;
Coventry et al., 1999). Both forms of unsoundness can result
in disintegration of the lumps of aggregate, tests for which
are given in BS EN 1744-1 (CEN, 1998). The SHW (HA et al.,
2009) requires that BFS for use in highway works is free from
unsoundness.

Problems with unsoundness should not occur with material
from current production, which will be produced under a
quality control system and tested by the producer. However,
problems can arise with old “bank slags”16 that are of unknown
history and may have been dumped for a long time. Bank
slags should only be used if their history is known and they
have been recovered by a reputable supplier.

4.3.3 Steel slag
4.3.3.1 Description
There are two main forms of steel slag in the UK, basic oxygen
steel (BOS) slag and electric arc furnace (EAF) slag, which arise
from different production methods for steel. The arisings
of BOS slag in England in 2005 totalled 500,000 t, of which
250,000 t was used as aggregate (Capita Symonds, 2007).
This compares with 670,000 t in 2001 (Office of the Deputy
Prime Minister, 2002), and further decline is likely with the
continued contraction of the steel industry. All of the BOS
steel slag in England is produced in the North East and the
material is used mostly in this area. Arisings in South Wales
were 330,000 t in 2001 (Office of the Deputy Prime Minister,
2002). The Llanwern works at Newport has now closed but
some steel slag is still produced at the Port Talbot works.
Although arisings are declining, there is still a substantial
stockpile of BOS in both Wales and the North East areas.

In 2007, the arisings of EAF slag were 260,000 t, all of
which was used as aggregate (Capita Symonds, 2007). Most
of the material (220,000 t) is produced in Yorkshire and the
Humber, with a small amount (40,000 t) produced in Kent.

Steel slag is a high-density aggregate with a high crushing
strength. It is denser and stronger than BFS. When used in
asphalt surfacing, it delivers a high resistance to abrasion
and polishing under heavy traffic, and hence is widely used
in surface course mixtures, especially thin surfacing systems
(Roe, 2003). The HA has accepted that steel slag is equivalent
to a natural aggregate with a measured PSV of 60.

Steel slag contains free lime (CaO) and magnesia (MgO)
and has to be weathered under controlled conditions to allow
these minerals to hydrate before use as aggregate. Failure to
weather steel slag properly can lead to expansive reactions
during service (Dunster, 2001). A test for the volume stability
of steel slag is given in BS EN 1744-1 (CEN, 1998) and there
is a limit on the expansion of the slag (category V10) as
determined by this test in Clause 901.14 of the SHW (HA et
al., 2009).

All current steel slag arisings are weathered and processed
under controlled conditions by the producers and are tested
to ensure conformity with the requirements of the SHW. As
with BFS, problems are more likely to arise with old bank slags
of unknown history, and material from such sources should be
avoided unless the quality can be guaranteed by the producer
and the relevant test results are available.

4.3.3.2 Case study: Use of basic oxygen steel slag as a
surface course aggregate in England
BOS slag is available from steel works in South Wales,
Humberside, Lincolnshire and Teesside. Since 1999, work
has been undertaken to investigate the use of this material
as a road surface course aggregate. Five trial sections were
laid on Local Authority roads in 1999 and 2000, including
some heavily trafficked dual carriageways. They have been
monitored by TRL on an annual basis, and the skid resistance
compared with that of adjacent control sections and with HA
standards for skid resistance (Roe, 2003; 2005). The results
indicate that the BOS slag performs well in comparison with
natural aggregates in a wide range of situations provided it is
not subject to excessive stress.

16 Bank slags are piles of past arisings from steel manufacture of unknown
date and quality.
The initial work (Roe, 2003) found that, for BOS slag aggregate, the measured PSV did not sufficiently characterise the material and it had the potential to provide better skid resistance than indicated by the standard laboratory test. Site measurement using the sideway-force coefficient routine investigation machine (SCRIM) provides a better indication of the actual skid resistance. Based on the evidence from initial on-road studies over a period of three years, the HA permitted the use of BOS slag in surface courses in thin surfacing systems where an aggregate with a PSV of 60 would normally be used without the need for PSV tests, with the proviso that its performance continued to be monitored. Details of the monitoring results after five years are given in Roe (2005) and show that the material continues to perform satisfactorily. Monitoring has continued on an annual basis to 2009 and continues to show that the material performs well if used in the correct situations.

4.3.4 Ferro-silicate slag (zinc slag)
Until early 2003, the Britannia Zinc Limited (BZL) works was the UK’s only primary zinc smelter and had been at the site at Avonmouth, near the Severn Estuary, for 50 years. BZL produced on average 90,000 t/year of zinc and 35,000 t/year of lead, and 80,000 t/year of ferro-silicate Imperial smelting furnace (ISF) slag as a residue. ISF slag is a granulated, glassy material that has the appearance of dark coloured sand. It typically has a particle size distribution between coarse and fine sand, but it has a higher specific gravity than sand due to its metal content. There are still significant quantities of this material, 2,000,000 t stockpiled and landfilled, available at the Avonmouth site. However, this material is probably only economically viable for use in the South West of England and South Wales.

Zinc slag contains a number of heavy metals in high concentrations, including cadmium and arsenic (Dijkink, 1994). It is considered that the environmental implications of any secondary aggregates containing heavy metals such as cadmium and arsenic will probably inhibit their use in asphalt. However, zinc slag has been used in a trial asphalt pavement at the Avonmouth site and showed satisfactory performance (Dunster et al., 2005). The ISF slag was used in a DBM mixture and replaced 30% of the coarse aggregate. The trial pavement has been trafficked continuously since being placed. Performance of the trial section was similar to that of the control section. Leaching tests indicated no significant release of metals; levels were similar for the trial and the control materials.

ISF slag is classified as hazardous waste in the European waste catalogue. This classification means that test evidence such as that produced by this project would need to be presented to the EA before their wider adoption as aggregates and any exemptions from waste management requirements could be considered on a local basis. However, a report (Dunster et al., 2005) provides a good body of evidence for this purpose.

4.3.5 Slate aggregate
Crushed slate aggregate, the surplus material from the production of slate roofing tiles, is available in large quantities of approximately 6.3 Mt/year arisings and 466 Mt currently in stockpiles. However, the availability of the material is relatively localised to North Wales, which has restricted its use. With exemption from the aggregate levy, transport of the material is becoming commercially feasible and it is widely used for a variety of unbound applications in the North Wales area. Crushed slate produces aggregate with high particle strength but with one dimension much less than the other two, leading to tabular and flaky particles with a high flakiness index. Under normal specifications this flakiness would limit its use as it makes the material difficult to compact, either as an unbound material or as an asphalt or concrete mixture. However, local contractors have developed techniques that enable them to achieve adequate compaction of mixtures with crushed slate as the coarse aggregate.

Clause 901.5 of the SHW (HA et al., 2009) was amended to permit the use of this locally abundant material as coarse aggregate in base and binder course provided it complies with the relevant standards and specifications, with the exception of requirements for flakiness index. However, crushed slate aggregate must not be mixed with aggregate of other geological types, as this would produce an aggregate with properties unlike either normal aggregate or crushed slate aggregate.

Small quantities of crushed slate are also available in the Lake District and South West England. These can be used as aggregate in base and binder course. However, it is important to ensure that the contractor knows how to handle the mixture to achieve the required performance levels.

4.3.6 Recycled glass
The use of crushed glass from civic amenity sites as a replacement for primary aggregate in base and binder course was pioneered in the late 1990s and has become a widely accepted method, particularly in urban areas where waste glass is an abundant waste stream. A survey of arisings in England in 2005 (Capita Symonds, 2007) found that 115,000 t of waste glass was used in asphalt. This represented 79% of the waste glass used as aggregate identified by the survey; most of this was produced by a small number of operators. Most of the major UK asphalt producers can produce asphalt with glass as a proportion of the coarse aggregate.

Proper crushing can virtually eliminate sharp edges and the corresponding safety hazards associated with the product. A major concern about using glass in asphalt is the adhesion between the bituminous binder and the smooth glass surface (Hassan et al., 2004). Trials in the UK (Nicholls and Lay, 2002) have demonstrated no significant stripping on mixtures with 30% replacement of primary aggregate by glass after three years in service. Glass cannot be used in the surface course because of the potential for polishing that would reduce the skid resistance, but it is widely used in binder course, especially by Local Authorities who view this as a sustainable use of a waste material. In overall sustainability terms, it is better to melt down glass for reuse in new glass. However, whilst this is feasible for clear glass and to some extent for brown glass in the UK, there is no facility for melting down
and recycling green glass, which is imported into the UK in large quantities. Use as aggregate in asphalt is, therefore, a sustainable, high-value use for this material.

4.3.7 Incinerator bottom ash

4.3.7.1 Description

IBA is the residue of the combustion of municipal solid waste in incinerator plant (energy from waste) facilities. Several individual ash streams are produced including grate ash, siftings, boiler ash, scrubber ash and precipitator ash. The incineration residues mainly contain clinker, glass, ceramics, metal and unburnt organic matter. In the UK, current processing of the material involves only mechanical treatment without chemical processing or washing. This treatment includes extracting metal, screening, removal of unburnt organic matters and natural drying (York, 2000). Storage of IBA for up to three months under controlled conditions is recommended to allow swelling, hydration, carbonation and oxidation ageing to occur, to improve the chemical integrity and structural durability of the ash. Current production of processed IBA accounts for about 725,000 t/year, of which about 400,000 t/year is used as aggregate (Capita Symonds, 2007). This value is expected to rise in future years as more Local Authorities turn to energy from waste as a means of meeting targets for reduction of municipal waste to landfill.

IBA is suitable as coarse aggregate in base and binder course, either in new hot asphalt or in a cold mixture with foamed bitumen as the binder. In most cases, it has been used as a partial replacement for primary aggregates at levels of up to 30% (Reid and Chandler, 2001). However, it can also be used at up to 100% of the coarse aggregate in cold mixtures with foamed bitumen (Reid et al., 2006). This use can be particularly advantageous for Local Authorities that have opted for energy from waste as an option for dealing with their municipal waste, as it demonstrates a high-value use for the by-product IBA.

As for steel slag, IBA has to be thoroughly weathered before use or it will be liable to expansive reactions. This weathering requires facilities for storing the IBA securely and collecting the leachate, which may be polluting during this phase. IBA is a controlled waste and hence subject to Waste Permitting Regulations. The EA and WRAP are currently working on a Quality Protocol that will define when IBA has been recovered. It is recommended that all clients ensure that their producers and contractors follow this protocol when it is published. As with all recycled and secondary materials, clients should only purchase from suppliers who can demonstrate that the materials are produced under a quality control system and meet the requirements of the relevant standards and specifications.

4.3.7.2 Case study: Use of IBA in cold foamed bitumen at Bar End household waste recycling centre, Winchester (from Reid et al., 2006)

Hampshire County Council (HCC) wished to build a new household waste recycling centre (HWRC) to serve Winchester on a previously developed site at Bar End. The use of recycled aggregates in the construction of the HWRC and access road has been maximised by the client insisting on the use of recycled materials. HCC wanted the project to be an example of how the council should work on future developments.

Involvement of Foster Yeoman (FY) and Onyx through other HCC initiatives led to the use of processed IBA as coarse aggregate in the base and binder layers of the 300 m long access road using Foamix®. Foamix® is a term commonly used to describe cold-lay asphalt with a binder consisting predominantly of foamed bitumen. IBA was selected because HCC has developed energy from waste plants at three locations for dealing with its municipal waste and the council wished to develop applications for the 100,000 t of IBA that the plants produce annually.

The method statement for the use of IBA in Foamix® was written in conjunction with FY and was based on the experience of HCC and FY with Foamix® in a number of highway maintenance and new works projects. Foamed bitumen is produced by the injection of 1% to 2% cold water with air into hot penetration-grade bitumen. This process produces a high-volume, low-viscosity fluid with low surface tension. These properties enable the foamed bitumen to coat a wide range of moist, cold recycled aggregates. Foamed bitumen can be used for in situ and ex situ recycling, which allows the use of other recycled or secondary materials as the coarse aggregate – in this case, IBA. The design was based on guidance on the use of foamed bitumen in the SHW (HA et al., 2009) and design guidance for cold recycled bituminous materials produced by TRL as TRL Report TRL611 (Merrill et al., 2004).

The technical benefits of using IBA in Foamix® were identified by FY as being an easy material to handle with consistent properties. A programme of testing for the Foamix® was prepared to demonstrate that its performance was satisfactory. A total of 1,200 t of IBA was used. The Foamix® was placed in two layers in November 2004 with a conventional surface course and the site was opened in December 2005. The trial demonstrated that IBA can be successfully used as coarse aggregate in cold foamed bitumen mixtures for base and binder course (Figure 4.5).

Figure 4.5 Cold foamed bitumen base with IBA as the coarse aggregate, Bar End, Winchester

Chorus:

“The rolling English drunkard made the rolling English road”

G K Chesterton
4.3.8 Recycled concrete aggregate
Recycled concrete aggregate (RCA) is defined in BS 8500-1:2002 as “recycled aggregate principally comprising of crushed concrete”. RCA is differentiated from recycled aggregates on the basis of composition: RCA must contain no more than 5% brick or masonry, 5% asphalt, 0.5% lightweight material and 1% foreign material. Thus, it has to come from very pure sources such as demolition of concrete bridges or structures, railway sleepers, concrete pipes or damaged/surplus material from precast concrete manufacture. It can also be obtained from concrete roads and runways, so long as it is not mixed with asphalt or excavated soil arisings.

Whilst RCA has been widely used as an unbound fill material, and a lot of work has been done to assess its suitability for reuse as aggregate in new concrete, it has not been widely used in asphalt. However, there is some experience with recycling lean concrete pavements using cold recycling techniques. This experience was applied on a 1.85 km section of the A9 near Aviemore in the Scottish Highlands (WRAP, 2004a). The surface course was planed off and the existing lean concrete and part of the underlying granular sub-base was pulverised prior to being bound by foamed bitumen and compacted as the base. This layer was then overlaid with a conventional DBM binder course and HRA surface course. Stiffness measurements indicated good performance over a period of two years and the road has continued to perform well.

It is likely that use of RCA in asphalt will continue to be dominated by in situ and ex situ cold recycling of existing concrete pavements rather than use as coarse aggregate in new pavements.

4.3.9 China clay sand
China clay sand is a residue from the extraction of china clay and is available in large quantities in Cornwall, with approximately 19.6 Mt/year arisings and 150 Mt of available stockpiles (Capita Symonds, 2007). Approximately 2.6 Mt/year is used as aggregate, so supply considerably exceeds demand. China clay sand is mainly composed of quartz and fine particles of mica and only needs to undergo the same basic grading and washing as other primary aggregate, before being used. Technically, china clay sand is an inert material and suitable to replace primary aggregate in all bound and unbound applications. Its use in base and binder course is specifically permitted under Clause 901.4 of the SHW (HA et al., 2009). The main problem with the wider utilisation of the material is transport, because it is produced and used in a localised area with poor transport links and long distances to markets.

4.3.10 Foundry sand
Spent foundry sand arises from the metal castings industry mainly in the Midlands, London, North East and North West of England (Capita Symonds, 2007). Total arisings in England in 2005 were estimated to be about 1.0 Mt, of which about half was thought to be used, mainly in block making with some in asphalt. The sand is a single-size material, which is suitable for use as fine aggregate in asphalt. However, it should be noted that foundry sand may contain small amounts of phenols and other organic chemicals, which are added to help the sand cohere in the moulding process. These chemicals are toxic and would be released as vapours in an asphalt plant. It is thus important to ensure that any foundry sand proposed for use in asphalt is free from contamination.

Foundry sand has been used by Tarmac Quarry Products Limited in Poole to partially replace the fine aggregate in asphalt (WRAP, 2004b). Laboratory evaluation confirmed the density, grading and compactibility for use to replace some of the fine aggregate. The quality of the products has not been affected by using foundry sand, with no problems reported after eight years in service.

Whilst the foundry industry is continuing to decline, the increased cost of disposal is causing producers to look for options such as asphalt for the spent sand as an alternative to landfill. This is likely to remain a niche market, with specialist producers using small amounts of materials where they are locally available.
5 Life-cycle environmental impacts

5.1 General
The use of more recycled and secondary materials to produce durable asphalt for highway construction has benefits in terms of finite resource preservation. These benefits are especially the case for surface course materials that require high-PSV aggregate, which has a limited number of available sources in the UK (see Section 3.4). Some areas of the UK already have fairly limited indigenous sources of high-PSV aggregate, such as the South East, and this problem will be exacerbated should preservation efforts not be made. Depletion of finite resources of aggregates will eventually cause a more dispersed network of sources and require greater transport distances to be covered from quarry to batching plant and then on to the construction site, with higher resultant emissions. In terms of finite resource preservation in the surface course, it is also pertinent to consider the type of asphalt alongside its durability and recyclability. If one type of asphalt is used to the exclusion of others, such as thin surfacings of a particular aggregate size, then certain fractions of aggregate will either be surplus or have to be crushed further. This specialisation will make aggregate processing inefficient and speed up the depletion of reserves.

Whilst these types of finite resource preservation are fairly straightforward to gauge, and longer-life pavements, which incorporate greater quantities of recycled or secondary material, are almost undoubtedly positive in this measure, other environmental impacts are not always so straightforward to assess. In terms of environmental impacts that result from emissions (such as climate change, eutrophication, acidification or summer smog production), there are often some trade-offs in the highway maintenance system in terms of benefits and burdens, which mean that the overall picture is not always clear cut. It is necessary to apply techniques that consider impacts across the lifetime of a highway material (such as life-cycle assessment and carbon footprinting) to determine the true picture in terms of overall environmental impact. This chapter considers the incorporation of recycled, secondary and more durable materials in terms of life-cycle environmental impacts, in particular the climate change impacts (“carbon footprint”), and draws on relevant examples from past works where appropriate.

5.2 Effect of recycling
Chapter 3 considered recycling. For this section, “recycling” is taken to mean closed-loop recycling, i.e. where a material gets recycled to its original use, as opposed to open-loop recycling (sometimes called “down cycling”), where waste materials arising are reprocessed and incorporated into products that were not the original use. Open-loop recycling is considered in Section 5.3. Both closed-loop and open-loop recycling are available to asphalt.

On the whole, recycling has an environmental benefit that is principally achieved by conserving embodied energy and using recycled rather than virgin materials. Energy is conserved in recycled products by using closed-loop recycling because the energy required to reprocess a waste material back to a state where it can be reused for its original purpose is usually less than the original “embodied” energy17. The net energy saving usually corresponds to a reduction in environmental impacts because it requires less consumption of resources (e.g. fuels) and, therefore, a lower production of harmful emissions (carbon dioxide \([\text{CO}_2]\), nitrogen oxide \([\text{NO}_x]\), \(= \text{NO} + \text{NO}_2\) and sulphur oxide \([\text{SO}_x] = \text{SO}_2 + \text{SO}_3\) amongst others). However, a net energy saving can only give a broad indication since different energy sources for the reprocessing may cause emissions levels to vary in quantity and type. Any use of alternative materials in reprocessing compared with production would also cause other environmental impacts to change. An indication of embodied energy savings achieved by the closed-loop recycling of different materials is indicated in Figure 5.1.

![Figure 5.1 Indicative energy consumption for virgin production against reprocessing for a range of materials (Adapted from Morris, 2005)](image)

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17 Embodied energy is defined as the primary energy that was used in the work of making a product.
The benefits of closed-loop recycling for asphalt were investigated in TRL Published Project Report PPR304 (Schiavi et al., 2007), as previously mentioned in Section 3.4.4. This project investigated the carbon implications of reclaiming asphalt planings from a worn surface layer of PA, incorporating the RA directly into a Masterpave-R mixture (mixed off-site) and resurfacing the same stretch of road. This practice had clear benefits (as shown in Table 3.3) relative to using primary aggregates, with the energy usage being 7% lower than it would be otherwise.

The critical factor in the study that made the Masterpave-R scenario favourable was the replacement of primary aggregate by RA and a marginal reduction in the amount of bitumen used. This creates a similar scenario for asphalt to that displayed for the materials in Figure 5.1. Material replacement was not the only factor because using RA in the mixture required a slightly higher heating and mixing energy at the asphalt plant (10% more for the job overall). Transport was also an important factor, particularly utilisation of backhauling in the recycling scenario, with this aspect being explored in more detail in Section 5.4. This example illustrates that realising the benefits of using recycled materials can be a delicate balancing act between several factors and assessment on a life-cycle basis is necessary to see the full picture.

Many of the disbenefits of hot-mix recycling can be countered by using cold-mix in situ recycling. The benefits of primary material replacement are still obtained, but the residual bitumen in RA is likely to be less active, hence the benefit here lies in replacing primary aggregate only. However, an in situ method cuts out journeys from site to the asphalt plant and “cold” recycling requires far less heating and mixing. TRL investigated the benefits of cold recycling in 2006 and indicative savings of the carbon footprint of the cold mixture over the hot mixture were in the region of 80% to 90%.

Above all, the most important factor for closed-loop recycling is the ability of the reclaimed material to be recycled. Should the reclaimed material contain impurities or volatile materials, or be mismanaged once taken up, then the benefits may be lost as fractions of the reclaimed material have to be diverted to lower-grade uses or landfill.

5.3 Effect of secondary materials

The potential for the use of secondary materials as constituents in asphalt was comprehensively discussed in Chapter 4. One class of secondary materials are by-products of industrial processes, which, if not utilised in an appropriate application, would be disposed of to landfill. Secondary materials can also be "reprocessed" materials, which derive from primary uses elsewhere and have been reprocessed to the point where they can be used again in open-loop recycling.

Beyond use in construction applications, other potential applications of the first class of secondary materials are limited. Hence, the environmental benefit of utilising secondary materials as a substitute for virgin materials in highway construction applications is fairly easy to realise, providing that the following assumptions are true:

- The transport undertaken from source to use is not excessive (ideally not exceeding that which would normally be undertaken by virgin materials).
- Any required material crushing is comparable to that required by a virgin aggregate.
- All of the impacts of the industrial process that produces the primary and secondary material are allocated to the primary material only (and none to the secondary material), although allocation is a contentious issue in life-cycle analysis, particularly where the use of secondary materials is concerned.

The environmental gains associated with utilising secondary materials to replace virgin aggregates are mostly realised in terms of resource conservation. However, when the assumptions listed above are correct, energy and savings to the carbon footprint are likely to be realised as well.

Two types of secondary materials, GGBFS and PFA, offer far greater environmental gains should they be used as binding materials as an alternative to traditional Portland cement. The embodied energy of Portland cement is in the region of 4.6 GJ/t (Hammond and Jones, 2008). Using a substitute material not only conserves the virgin resources used to make cement, but also reduces many of the environmental impacts that would be associated with this energy use, which are far in excess of the transport, drying and crushing required to prepare the secondary materials for use.

Hence, where utilisation of secondary materials is concerned, the picture is fairly unambiguous for the materials discussed because the only alternative to being utilised in a construction application with the consequent environmental benefits is being sent to landfill. Secondary materials that demonstrate good pozzolanic properties should be utilised to substitute for conventional binding material wherever possible.

The second class of secondary materials, described above as "reprocessed" materials, derive from municipal solid waste (MSW). MSW is the multitude of waste materials that arise from households and other sources including streets, public parks and gardens, the management of which falls under the jurisdiction of local government waste management authorities. Increased recycling targets for materials arising from these sources means that alternative, viable applications in which they can be used are always being sought, alongside the more traditional closed-loop options by which they are returned to their original use. As more potential applications for MSW materials are realised, other factors start to influence the choice of application that is actually pursued, including economics, quality of material arising and politics. This pressure results in an interesting conundrum in sustainability terms: determining which recycling route is best for MSW derived materials. TRL Published Project Report PPR395 (Wayman et al., 2009) investigated this for glass. The results of the study are presented in Figure 5.2 with the savings being presented as relative savings compared with the virgin material alternatives.

The benefits of closed-loop recycling of glass into containers over its use as an aggregate were highlighted by this study. However, for sources of mixed-coloured cullet (rather than colour separated), which is often the result of Local Authority collections, using glass used as secondary material for aggregate replacement is still advantageous in terms of environmental benefits, provided that it is not diverted from a recycling facility where it has already been processed for closed-loop recycling.
INCREASING THE ENVIRONMENTAL SUSTAINABILITY OF ASPHALT

INCREASING THE ENVIRONMENTAL SUSTAINABILITY OF ASPHALT

C&S (see Section 3.2) is essentially an example of in situ open-loop recycling of a secondary material. C&S utilises the previous concrete surface course as a binder course/base layer in the resurfaced pavement, which has been overlaid with a new asphalt surface course. In this case, secondary material reprocessing is minimal, requiring just cracking with a guillotine and/or sawing in the case of SCS. Transport is minimised by virtue of the fact that the reprocessing takes place in situ. The benefits of the use of secondary material in this way are demonstrated over the traditional alternative (full-depth replacement of the bound layers) by Table 3.2 in Section 3.3.2.

5.4 Effect of transport

Transport has already been mentioned in relation to recycling and secondary materials; minimising transport often enhances the overall performance of asphalt applications. In situ recycling is obviously the optimum “low transport” scenario but, where material is being down-cycled to lower-grade uses, it is sometimes more advantageous to excavate and transport the material if this means that the recycling loop will instead be closed and material will return to higher-grade uses.

In the aforementioned RA recycling project (Schiavi et al., 2007; see Section 3.4.4), transport was a key factor. Backhauling was utilised in this project to minimise transport impacts between the asphalt plant and the construction site. Wagons filled with Masterpave-R on outward-bound journeys were filled with RA on the return (43% of the time). Overall, utilisation of trucks between asphalt plant and construction site was 71.5%. A theoretical scenario was also investigated in which trucks were 100% utilised (i.e. full outward bound and on return); this yielded the results given in Table 3.3 (Section 3.4.4) compared with the baseline scenario. The overall carbon footprint of using Masterpave-R and maximising backhauling would theoretically be 89% compared with a 100% Masterpave solution.

When recycling RA, transport can be a key factor in determining environmental benefits because it takes place by road whereas primary aggregate transport can often be by more sustainable means, such as rail or waterway. Therefore, it is essential to maximise backhauling in RA recycling projects where off-site asphalt plants are the only option.

The investigation of glass recycling (Wayman et al., 2009) also considered transport “tipping points” for recycling. Tipping points are where the benefits of recycling are negated by excess transport. It is possible to isolate the tipping point for the different environmental impacts of a system as a transport distance; this effect is demonstrated in Figure 5.3, which shows the impacts for glass shipped overseas to be recycled back into bottles.

Figure 5.3 suggests that, in terms of global warming potential, recycling still remains beneficial for shipping distances up to around 8,500 km (one way if no cargo is available to be transported on the return leg). To put this into perspective, the cullet could be shipped to Brazil (Southampton to Natal, Brazil, is 7,100 km) and save approximately 2% of the climate change impacts of glass production in the UK from primary materials only. At this distance, however, four of the other impact categories are between 120% and 140% of glass manufacture from virgin materials. Ozone-layer depletion potential is the impact category with the lowest tolerance to transport distance, exceeding 100% at approximately 700 km. Transporting glass for recycling to aggregate will have a lower transport threshold because the environmental impacts of processing glass to aggregate are lower. The trucking distance threshold, at which point the impacts of processing glass to aggregate become comparable to using virgin aggregate, will be in the region of a 300 km round trip from glass reprocessor to asphalt plant, using the 26 t truck commonly used for this purpose.
5.5 Effect of durability

Whereas recycling and the incorporation of secondary materials into asphalt are concerned with primary material substitution, increasing the durability of asphalt has the potential to reduce, or even avoid, the need to replace materials during the life of a pavement. However, a study of the effect of durability on environmental impacts would need to take account of the whole life of the road. This analysis has not been conducted to date, but is a subject of the 2008–2011 Collaborative Research Programme between TRL, the HA, the Mineral Products Association and the Refined Bitumen Association.

A preliminary assessment of the effect of durability was made in Section 2.5.4, which presented some estimates for the service life for different types of asphalt. The average lifetimes of two typically used surfacings were 13 years for SMA thin surfacing and 19 years for HRA. Over a typical 40-year service life of a road, these estimates would suggest three maintenance interventions to maintain the thin surfaced road and two interventions to maintain the HRA. Hence, using HRA over thin surfacing might avoid the additional environmental impacts of one whole intervention of planing out, sourcing and placing new materials, and the consequent disruption to traffic flows. Very approximately, over the service life of the road, this analysis would suggest that the whole-life environmental impact of using HRA might be one-third lower.

Of course, the overall environmental impact will depend on a number of factors, not least the scale of the intervention required and traffic flows on the road over time. For example, if using HRA in place of thin surfacing requires two extensive maintenance interventions in place of three straightforward ones, then the environmental impact over the surface life may be offset in comparative terms because the overall material requirement is similar. On a busy road, using a very durable material that requires the fewest interventions might be desirable to avoid disrupting traffic flow, which might have the most significant impact. Conversely, overspecifying for a very durable material on a low trafficked road, where a low level of wear is experienced and few interventions are required, may make the environmental impact for this particular road excessive because a less durable material may require the same minimal level of interventions. Therefore, it seems necessary to consider durability carefully alongside predicted traffic flows to make the optimal choice. This factor will be investigated more thoroughly as the previously mentioned Collaborative Research Programme progresses.
6 Discussion

6.1 Durability
In the 19th century, the model road of John Loudon McAdam had to be built up from thin layers of stone, broken into more or less cube-shaped fragments, each one of which was not to weigh more than six ounces if the roads were to last for a long time. In the 21st century, this statement can be translated to show that quality control is important in achieving durable asphalt pavements. Despite the difficulties, the necessary consistent level of care can be, and has been, achieved. The three case studies in Section 2.5 on major schemes have shown that exceptional durability can be achieved; it is important for true sustainability that their example is repeated regularly.

Extending the durability of each layer of asphalt can contribute to the sustainability of the pavement. However, there are many factors that can affect durability including planning of the works, choice of materials, construction practices and workmanship. A major deficiency in any of these aspects can be crucial on the “weakest link” principle. To achieve extended durability, therefore, requires all aspects to be properly addressed.

There is often more than one approach to achieving durability. For example, to minimise the moisture in the mixture, the mixture can either be made relatively impermeable so that water comes into contact with the binder only on the surface or it can be made relatively permeable with adequate drainage paths so that any water can escape easily. Furthermore, durability can be affected by outside practicalities, such as work having to be undertaken at night in small chunks, and this needs to be taken into consideration when planning the works.

Most, but not necessarily all, of the aspects that need to be considered are raised in Road Note RN42 (Nicholls et al., 2008). As has been demonstrated in the case studies, extra care when planning the works can significantly increase the durability of asphalt pavements. The hope is that, in the future, greater care will be applied more generally so that these cases will no longer be exceptions.

6.2 Recycling
Closed-loop recycling, where the material removed is reused for the same application and maintains the same value, should be encouraged, particularly for surface course layers where premium aggregates are present. Cold recycling, with the use of mobile plant, has many advantages in terms of reduced use of raw materials, reduced energy and reduced transport and emissions. An increasing awareness of the carbon footprint of construction activities is likely to see an increase in the use of recycling using cold and warm processes.

Savings in raw materials and transport need to be demonstrated over the lifetime of the pavement, which will include maintenance requirements and the number of necessary interventions.

Surface course recycling, where the existing surfacing contains high-PSV aggregate throughout the layer, is becoming more common and clients more environmentally aware. Comparable performances with control sections have been shown with incorporation of 30% RA in the medium term where the source of the RA is known. The addition of high quantities of RA into new surface course layers is likely to be scheme specific where the source RA is of a known consistent quality and compatible with the proposed new surfacing layer. For other sites, the addition of smaller quantities of up to 10% is likely to become the norm. However, this approach will require that surface course layers are planed off and stored separately from the lower layers.

Where materials cannot be reused for the same application, open-loop recycling should be the next consideration, where the material removed is used for an alternative application. When using alternative materials and innovative treatments such as grids and interlayers, it is necessary to consider their future recyclability. That is, if the material will create issues for future recycling it is a less attractive proposition. C&S of cement-bound layers is a sustainable option compared with the alternative of reconstruction because it maintains the concrete layer in place and is thus a very cost-effective form of recycling.

6.3 Secondary materials
The use of recycled and secondary aggregates, either as filler or coarse aggregate, can contribute to the sustainability of asphalt. The potential for use as added filler is significant, and quarry fines and PFA are widely used for this purpose in hot and cold asphalt. PFA can also act as a hydraulic binder when activated by cement, lime or other cementitious agents, particularly in cold recycled asphalt mixtures. The use of CKD may also yield advantages in certain cases. However, further work is required to quantify the advantages and to ensure that the material is consistent. Use of CKD would also displace the quarry fines and PFA that are normally used as added filler. However, it may be easier to find alternative applications for these materials than for CKD.

In terms of coarse aggregate, the potential for sustainability gains is more limited. BF’s and steel slag are high-quality aggregates that provide added value when used in asphalt. However, these materials are only available in limited quantities and have been fully utilised in asphalt and concrete manufacture for many years. With the continuing decline of the iron and steel industry and closure of more plants, the quantities available for use in asphalt are likely to decline. This may lead to greater import of these materials, and alternatives such as phosphoric slag. However, the greater transport associated with this will reduce or negate the sustainability benefits.

One of the main benefits from using recycled and secondary materials is to make use of locally available materials. The SHW (HA et al., 2009) has been amended to permit use of china clay sand and crushed slate aggregate, which fall into this category. These are used in the local areas, but these are a long way from the main construction markets and the materials may not be economic to transport beyond the local areas. Supply continues to outstrip demand and this is unlikely to change in the short to medium term. If the material was transported over much greater distances to meet demand in other areas, this would defeat the point if suitable aggregates are already available in these areas.

It is expected that foundry sand and recycled glass will continue to be used in asphalt where there is a local supply.
The amounts of both that can be used are limited, though there may be some increase on present levels. There is greater potential for the use of IBA, particularly if more Local Authorities opt for energy from waste to deal with their municipal waste. The use of IBA will be greatly helped by the development of a Quality Protocol by WRAP and the EA, as this will give clients much greater confidence in the material as a product.

Overall, it is likely that primary aggregates will continue to be the main aggregates used in new hot asphalt and in many cases they will be the most sustainable choice. One of the key principles for building a sustainable road (Reid et al., 2008) is “Do not be afraid to use primary aggregates.” If using primary aggregates involves the shortest transport distances and guarantees a more durable pavement, this will be the most sustainable option. The greatest sustainability gains for asphalt are likely to be:

- in the continued use of quarry fines and PFA as added filler;
- in the continued use of locally available materials as coarse aggregate; and
- by maximising the use of RA and low-energy techniques.

### 6.4 Life-cycle impacts

The environmental sustainability of asphalt should be assessed on a life-cycle basis. Making assessments on this basis allows the contribution of different factors within a given asphalt maintenance intervention or maintenance schedule to be identified. Past studies have shown that primary material substitution using closed-loop and open-loop recycling (incorporating secondary materials) can be beneficial in environmental terms, not least because these processes can be used to preserve resources of high-PSV aggregate. Closed-loop systems, which preserve the use of materials in higher-grade uses, are usually more beneficial than open-loop systems. Transport can be an important factor in determining whether a given system is environmentally favourable. For this reason, *in situ* recycling or optimal transport (maximising backhauling or alternative modes to road transport) should be used wherever possible. Cold recycling is also beneficial, certainly in terms of the environmental credentials of the life-cycle of asphalt up until it is installed, provided equivalent durability can be attained.

Material durability is potentially the most important factor in determining carbon footprints on a whole-life basis because of the potential for reducing the frequency of maintenance interventions, with or without the use of recycled or secondary materials. The effect of durability is also the greatest unknown. Research is ongoing that will determine how durability affects the “whole-life carbon footprint” alongside traffic flow considerations.
7 Conclusions

There are many factors that can affect durability, with any of them capable of being the “weakest link” for any site. As a result, all aspects need to be properly addressed, although there is often more than one way to treat each of them. However, some aspects are dependent on outside practicalities, which cannot always be controlled, and the approach should therefore be to take more care with the other aspects. Extra care with any of the aspects can significantly increase the durability of asphalt pavements. The hope is that, in the future, greater care will be applied more generally so that the case studies cited will no longer be exceptions.

Recycling of materials is important for the conservation of natural resources and gives potential for reduced energy consumption in construction processes. Reuse of material for the same application is preferred because this approach maintains the value of the material, which is particularly important for premium aggregates used in surface course layers. Cold recycling offers benefits in materials, cost, time and carbon savings. C&S treatments to concrete pavements can be considered as a recycling option if the alternative is to reconstruct the pavement. Overlay treatments to cracked and seated concrete inhibit reflection cracking and provide improvements over untreated concrete.

The use of recycled and secondary aggregates, either as filler or coarse aggregate, can contribute to the sustainability of asphalt. The potential for use as added filler is significant whereas the potential for sustainability gains is more limited for coarse aggregate. The reason for using recycled and secondary materials is to make use of locally available materials. However, it is likely that primary aggregates will continue to be the main aggregates used in new hot asphalt and in many cases they will be the most sustainable choice. Nevertheless, the greatest sustainability gains for asphalt are likely to be in the continued use of quarry fines and PFA as added filler and locally available materials as coarse aggregate and by maximising the use of RA and low-energy techniques.

The environmental sustainability of asphalt applications should be assessed on a life-cycle basis. Closed-loop systems, which preserve the use of materials in their current higher-grade use, are usually more beneficial than open-loop systems. Transport can be an important factor in determining whether a given system is environmentally favourable. Material durability is potentially the most important factor in determining carbon footprints on a whole-life basis.

Overall, asphalt is a remarkable material that can be durable, is 100% recyclable and can incorporate secondary materials. However, it can be made more durable, more of it can be recycled and a greater quantity of appropriate secondary materials can be incorporated. The result will improve the sustainability, reduce the carbon footprint and enhance other life-cycle benefits. However, care and attention is needed in the design, construction and maintenance of the material if these aims are to be fully achieved.
Acknowledgements

The work described in this Insight Report was carried out in the Infrastructure and C4S Divisions of the Transport Research Laboratory. The authors are grateful to R Woodward who carried out the technical review and auditing of this report. Acknowledgement is also given to Michael McHale, Richard Griffiths and Benjamin Olobo for the preparatory work they undertook on Road Note RN42, which was incorporated into Chapter 2.

References


Carswell, I, J C Nicholls, I Widyatmoko, J Harris and R Taylor (2010). Best practice guide for recycling into surface course. TRL Road Note RN43. Crowthorne: Transport Research Laboratory.


REFERENCES


## Glossary

<table>
<thead>
<tr>
<th>Abbr.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>Associated Asphalt Limited (now part of Aggregate Industries Limited)</td>
</tr>
<tr>
<td>AAV</td>
<td>aggregate abrasion value</td>
</tr>
<tr>
<td>BBA</td>
<td>British Board of Agrément</td>
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<tr>
<td>BBTM</td>
<td>béton bitumineux très mince (type of thin surfacing, otherwise known as TAC)</td>
</tr>
<tr>
<td>BFS</td>
<td>blast furnace slag (a secondary component material)</td>
</tr>
<tr>
<td>BOS</td>
<td>basic oxygen steel (slag) (a secondary component material)</td>
</tr>
<tr>
<td>BSI</td>
<td>British Standards Institution</td>
</tr>
<tr>
<td>C&amp;S</td>
<td>crack and seat (of concrete base prior to overlaying by asphalt)</td>
</tr>
<tr>
<td>CBM</td>
<td>cement-bound material</td>
</tr>
<tr>
<td>CEN</td>
<td>Comité Européen de Normalisation (European Committee for Standardisation)</td>
</tr>
<tr>
<td>CKD</td>
<td>cement kiln dust (a secondary component material)</td>
</tr>
<tr>
<td>CRBM</td>
<td>cold recycled bound material</td>
</tr>
<tr>
<td>CSO</td>
<td>crack, seat and overlay (of concrete base prior to overlaying by asphalt)</td>
</tr>
<tr>
<td>DBM</td>
<td>dense bitumen macadam (type of asphalt mixture)</td>
</tr>
<tr>
<td>DBM50</td>
<td>DBM with 40/16 pen bitumen</td>
</tr>
<tr>
<td>DE</td>
<td>Defence Estates (part of Ministry of Defence)</td>
</tr>
<tr>
<td>Defra</td>
<td>Department of the Environment, Farming and Rural Affairs</td>
</tr>
<tr>
<td>EA</td>
<td>Environment Agency</td>
</tr>
<tr>
<td>EAF</td>
<td>electric arc furnace (slag) (a secondary component material)</td>
</tr>
<tr>
<td>EME2</td>
<td>Category 2 enrobé à module élevé (type of asphalt mixture)</td>
</tr>
<tr>
<td>FDR</td>
<td>full-depth reconstruction</td>
</tr>
<tr>
<td>FY</td>
<td>Foster Yeoman (now part of Aggregate Industries Limited)</td>
</tr>
<tr>
<td>GGBFS</td>
<td>ground granulated blast furnace slag (a secondary component material)</td>
</tr>
<tr>
<td>HA</td>
<td>Highways Agency</td>
</tr>
<tr>
<td>HAPAS</td>
<td>Highway Authorities’ Product Approval Scheme</td>
</tr>
<tr>
<td>HBM</td>
<td>hydraulically bound mixture</td>
</tr>
<tr>
<td>HCC</td>
<td>Hampshire County Council</td>
</tr>
<tr>
<td>HDM</td>
<td>heavy-duty macadam (type of asphalt mixture)</td>
</tr>
<tr>
<td>HGV</td>
<td>heavy goods vehicle</td>
</tr>
<tr>
<td>HRA</td>
<td>hot rolled asphalt (type of asphalt mixture)</td>
</tr>
<tr>
<td>HWRC</td>
<td>household waste recycling centre</td>
</tr>
<tr>
<td>IBA</td>
<td>incinerator bottom ash (a secondary component material)</td>
</tr>
<tr>
<td>ISF</td>
<td>Imperial smelting furnace (slag) (a secondary component material)</td>
</tr>
<tr>
<td>JCP</td>
<td>jointed concrete pavement</td>
</tr>
<tr>
<td>JRC</td>
<td>jointed reinforced concrete</td>
</tr>
<tr>
<td>MS</td>
<td>micro-surfacing (type of thin surfacing)</td>
</tr>
<tr>
<td>msa</td>
<td>million standard axles</td>
</tr>
<tr>
<td>MSD</td>
<td>multiple surface dressing (type of thin surfacing)</td>
</tr>
<tr>
<td>MSW</td>
<td>municipal solid waste</td>
</tr>
<tr>
<td>MTV</td>
<td>material transfer vehicle (for transferring asphalt from the delivery wagons to the paver in a controlled manner)</td>
</tr>
<tr>
<td>PA</td>
<td>porous asphalt (type of asphalt mixture)</td>
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<tr>
<td>PFA</td>
<td>pulverised fuel ash (a secondary component material)</td>
</tr>
<tr>
<td>PLSD</td>
<td>paver-laid surface dressing (type of thin surfacing)</td>
</tr>
<tr>
<td>PMB</td>
<td>polymer-modified binder</td>
</tr>
<tr>
<td>PSV</td>
<td>polished stone value (of aggregate)</td>
</tr>
<tr>
<td>RA</td>
<td>reclaimed asphalt (also known as recycled asphalt pavement, RAP)</td>
</tr>
<tr>
<td>RCA</td>
<td>recycled concrete aggregate (a secondary component material)</td>
</tr>
<tr>
<td>SATS</td>
<td>saturation ageing tensile stiffness (conditioning test)</td>
</tr>
<tr>
<td>SCS</td>
<td>saw-cut, crack and seat (of concrete base prior to overlaying by asphalt)</td>
</tr>
<tr>
<td>SCD</td>
<td>saw-cut and seal (of concrete base prior to overlaying by asphalt)</td>
</tr>
<tr>
<td>SCRM</td>
<td>sideway-force coefficient routine investigation machine (for measuring skid resistance of a pavement)</td>
</tr>
<tr>
<td>SCRIMt</td>
<td>SCRM with laser texture metre (for measuring skid resistance and texture of a pavement)</td>
</tr>
<tr>
<td>SHW</td>
<td>Specification for Highway Works</td>
</tr>
<tr>
<td>SMA</td>
<td>stone mastic asphalt (type of asphalt mixture, otherwise known as TSMA when used in a proprietary thin surfacing system)</td>
</tr>
<tr>
<td>SRTD</td>
<td>savings due to reduced traffic delays</td>
</tr>
<tr>
<td>TAC</td>
<td>thin asphalt concrete (type of thin surfacing, otherwise known as BBTM)</td>
</tr>
<tr>
<td>TLA</td>
<td>Trinidad Lake asphalt</td>
</tr>
</tbody>
</table>
TRB  Transportation Research Board, US
TSMA  thin stone mastic asphalt (type of thin surfacing, otherwise known as SMA)
UN  United Nations
UTLAC  ultra-thin-layer asphalt concrete (type of asphalt mixture, otherwise known as PLSD)
WRAP  Waste and Resources Action Programme
WSDOT  Wisconsin Department of Transport, US
Improving the stability of slopes using a spaced piling technique

Comprehensive overview of important series of research projects into the remediation of clay slopes

Discrete piles are used to stabilise infrastructure slopes, especially where there is insufficient land to allow construction of large toe berms or regrading of the slope. This Insight Report discusses the findings from a literature review, centrifuge and analytical studies, and two instrumented case history studies of the remediation of clay slopes on the highway network. The implications of the findings are discussed and appropriate design advice recommended.


Driver distraction from in-vehicle sources: a review of TRL research

Brings together the results of recent TRL studies on in-vehicle distraction

In 2007, a workshop was conducted at the Department for Transport, and the conclusion was drawn that driver distraction is a significant factor in accident causation, but is neither completely understood nor documented. This Insight Report describes the results of four recent TRL studies in the field of in-vehicle distraction. The scoping study of driver distraction brought together experts in the field to discuss the concept of driver distraction and reach agreement on a definition.


Speed, flow and density of motorway traffic

It seems intuitively obvious that the more traffic that tries to use a section of road, the slower it must move, but the precise mechanisms behind this relationship are surprisingly elusive. This Insight Report examines the features of some actual data and speed–flow–density relationships, and “classical” models of speed, flow and density in the context of the wealth of detailed traffic data now available.


The management and impact of abnormal loads

Understanding congestion and other impacts caused by movement of abnormal loads

Congestion on Britain’s roads is an increasing problem. The movement of large and heavy abnormal indivisible loads (AILs) through the road network can cause additional delays to other traffic. This Insight Report covers several projects that have investigated the prevalence and congestion impact of AILs and the effect of mitigation measures such as movement by water or by night. It concludes, however, that the overall impact of AILs on network delay is small and mitigation measures will be most effective if selectively targeted.


How can we produce safer new drivers?

Considers the factors associated with the collision risk of new drivers

New drivers, especially young new drivers, are over-represented in road collisions worldwide. This Insight Report reviews evidence for the effectiveness of post-licence driving experience, driver education and training and limiting the exposure of new drivers to risk through graduated driver licensing in lowering new-driver collisions.


A route to low-carbon mobility in developing countries

Explores the relationship between transport and climate change in developing countries

The transport sector worldwide is currently responsible for 13% of global greenhouse gas emissions and 23% of all energy-related carbon dioxide emissions. This Insight Report explores ways in which low-carbon mobility can be achieved in the land passenger transport sectors of developing countries. In doing so, it suggests the type of approaches, strategies and policy measures that can support low-carbon mobility, and also the type of financing, technology transfer and capacity building support that developing countries will require to realise this goal.


Order now from www.trl.co.uk
Focus on asphalt products and surface treatments

Best practice guide for recycling into surface course
The incorporation of suitable reclaimed asphalt in thin surfacing materials is becoming an important issue with the availability of high-quality aggregate resources depleting and with the greater emphasis being placed on sustainability by society. This Road Note is intended to act as a guide to what is considered to be good practice when specifying, designing, producing and applying the approach to enhance sustainability through recycling surfacing materials.

Review of Shell Thiopave™ sulphur-extended asphalt modifier
The cost of sulphur-extended asphalt has now reduced and Shell has produced a pelletised form, Shell Thiopave™. This TRL Report reviews the laboratory tests and site trials that have been undertaken with the product to assess the changes in technical properties that are achieved with mixtures incorporating it at rates of between 20% and 40% by mass of binder.

Design guide for road surface dressing (6th edition)
Surface dressing can be used successfully on all types of roads, and provides a simple but cost-effective form of maintenance. This Road Note is intended to act as a guide for the design of surface dressing for roads throughout the UK. This sixth edition has been comprehensively updated to take account of standards, nomenclature, materials and traffic categories.

Durability of thin asphalt surfacing systems
Thin surfacing systems, as the term is currently understood, were introduced into the UK in 1991. On some sites used for the system to gain Highways Agency approval, the thin surfacing systems are approaching the end of their assumed lives while others have only been in service for just over two years. Therefore, it is opportune to begin to evaluate information collected from these sites to establish a better understanding of their service life. These TRL Reports discuss published information and the data currently available from the trial sites to confirm the suitability of proprietary thin surfacings for use in the UK after various periods of monitoring.

Current Topics in Transport
These issues of Current Topics in Transport include abstracts of reports, conference papers, books and journal articles focusing on the effects of both concrete and bituminous road surfacings, including texture treatments, specifications/testing, skidding resistance, durability, and noise generation from vehicle tyres.

Order now from www.trl.co.uk
Increasing the environmental sustainability of asphalt

There is increasing interest in improving the sustainability of every aspect of life in order to conserve resources and reduce carbon emissions. Great strides have been made to improve the environmental sustainability of asphalt with the industry implementing measures to improve its durability, reuse reclaimed asphalt and incorporate secondary materials. Durability is a major issue for minimising both the environmental impact of and traffic disruption caused by subsequent maintenance, whilst recycling should be the easiest method of improving environmental sustainability. The incorporation of secondary material has great potential, although its recyclability needs to be considered. The effect on the carbon footprint of these effects and other life-cycle impacts should increase the environmental sustainability of asphalt pavements. This Insight Report describes these measures and considers the resulting life-cycle implications.

Other titles in this series

INS001 Improving the stability of slopes using a spaced piling technique. D R Carder. 2009
INS003 Speed, flow and density of motorway traffic. S O Notley, N Bourne and N B Taylor. 2009
INS004 The management and impact of abnormal loads. N B Taylor. 2009
INS005 How can we produce safer new drivers? A review of the effects of experience, training and limiting exposure on the collision risk of new drivers. S Helman, C B Grayson and A M Parkes. 2010
INS006 A route to low-carbon mobility in developing countries. A Binsted and H Dalkmann. 2010