Development of new materials for secondary and recycled aggregates in highway infrastructure

Prepared for Department for Trade and Industry (DTI), Waste and Resources Action Programme (WRAP)

K E Hassan, L Elghali and C R Sowerby

TRL Report TRL598

First Published 2004
ISSN 0968-4107

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

CONTENTS

Executive Summary

This work forms part of the DTI/WRAP sponsored Aggregates Research Programme to support the development of construction markets for secondary and recycled aggregates. The project aims to promote the wider and more efficient use of secondary and recycled aggregates in various applications in highway infrastructure. The objectives of this report are to:

- Examine current UK and international experiences of the use of secondary and recycled materials in highway infrastructure.
- Review existing markets for secondary and recycled aggregates and assess potential new material streams and high-value applications.
- Identify technical, environmental and regulatory barriers associated with the high-value use of alternative materials.
- Assess material life and potential future recycling of alternative materials.
- Recommend future work to overcome the identified barriers and support the development of new materials/ applications.

The report reviews the use of secondary and recycled aggregates in highway infrastructure, with emphasis on high-value applications in road construction. The work was conducted within the context of the Specifications for Highway Works (SHW) which forms the basis of road specification in the UK, highlighting potential new applications, not currently included in SHW, to support the optimised use of alternative materials.

The availability of materials is discussed in terms of arisings, stockpiles and locations. Informal consultations were also carried out with materials producers in the UK to identify their views about existing and potential markets and barriers to reaching these potential markets. An examination of international experiences has been carried out to highlight the innovative research, techniques and programmes that could be introduced to the UK. Information on the high-value applications of secondary and recycled materials in highway infrastructure has been obtained from Europe, USA and other countries.

By comparing UK and international experiences, a number of materials have been identified for which use could be extended to higher-value applications. These include construction and demolition wastes, incinerator bottom ash, glass, plastic, and tyre rubber as alternative aggregates. The review also highlights the potential for developing new applications of hydraulic bound materials and roller-compacted concrete using fly ash and slag.

Assessment of the technical, environmental, and regulatory barriers to the use of the new materials/ applications is discussed in the report. The assessment addresses the relevant technical issues and highlights any lack of knowledge on performance characteristics that can have an impact on the potential use of new materials. The environmental and regulatory risks are discussed within the context of leaching and contamination, potential to generate dust, health and safety, and the waste management licensing regime. The material lifetime is discussed within the context of whole life costing considering the economic cost of alternative materials, material performance and potential for future recycling.

Finally, the report concludes with a comprehensive set of recommendations highlighting the need for future work to overcome the barriers identified and to support the development of new materials/applications in high-value applications in highway infrastructure.

1 Introduction

The increased use of secondary and recycled aggregate in civil engineering contributes to sustainable development in construction by reducing the amounts of landfill and minimising the extraction of natural resources. Aggregate is consumed in large quantities in construction with some positive indications of increased use of alternative aggregate. Statistical data on the annual production of primary aggregate, including crushed rock, sand and gravel, indicated a significant reduction from over 300 million tonnes (Mt) in 1989 to 260Mt in 1994 and 215Mt in 1996. This has been followed by a fairly stable production rate of about 220Mt up to 2000 (British Geological Survey, 2001). On the other hand, the amount of secondary aggregate used in construction increased from 32Mt in 1989 to 46Mt in 1999 (Barritt, 2000). These figures indicate the acceptance of recycling and the use of alternative materials in the construction industry.

However it is apparent that recycling and the use of alternative materials are not being carried out to the fullest extent possible. The use of a further 3Mt of recycled aggregate per year will be required to meet the national targets of 55Mt by 2006. There are many factors that inhibit the wider utilisation of recycling and alternative materials. Research on the use of waste and recycled aggregates covering a wide variety of materials in different applications, has indicated promising but, sometimes, contradictory results. This is mainly due to the variability in the recycled material's properties, the perception of new materials and applications in the construction industry and other economic, technical, environmental, and regulatory barriers.

More sustainable construction will not be achieved simply by increasing the amount of recycling but more importantly by the efficient and best use of alternative materials. Unfortunately, in many instances the use of secondary and recycled aggregate is associated with low-value applications, such as general fill. Figure 1.1 shows the results of a recent survey conducted by the Waste and Resources Action Programme (WRAP) on the end use of secondary and recycled aggregates (Barritt, 2003). It can be seen that the majority of alternative aggregate is used in fill applications, whereas only a limited amount is used in asphalt and concrete applications.

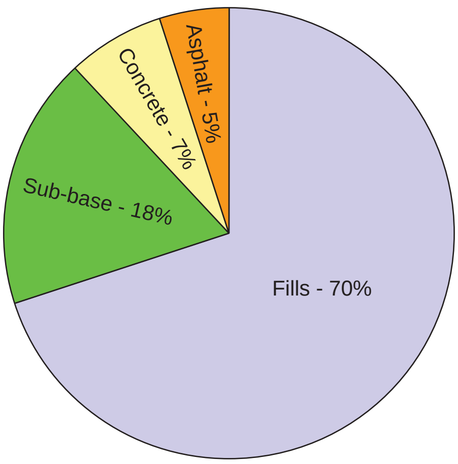

Figure 1.1 End use of secondary and recycled aggregates (Barritt, 2003)

Highway infrastructure represents a wide market for the utilisation of secondary and recycled aggregates, with potential for added values in various applications. Within the highway infrastructure, road construction has the highest demand for aggregates, which accounts for about one third of total aggregate production. It is estimated that the construction of each mile of a motorway uses a minimum of 20,000 tonnes of aggregate (Sherwood, 2001). This report discusses the various pavement layers of road construction and the quality requirements of each layer, which increase from the bottom upwards. The use of alternative aggregates in layers above the sub-base is therefore relatively limited as the specification requirement increases. Those layers placed above the sub-base, including cementitious and bituminous composites, representing the main structural layers of pavements, are considered in this report as high-value applications of alternative aggregate materials.

The properties of secondary and recycled aggregate are different, in many ways, from those of primary aggregate and this could lead to varying properties when incorporated in asphalt or concrete composites. In many cases, specifications that use recipe mixtures and prescribed materials prevent the wider utilisation of recycled materials. The mechanical properties of recycled aggregates are generally lower than primary aggregates and therefore limit their uses, sometimes, to low-value applications. However, it is now generally accepted that it is not the mechanical properties but rather a combination of surface texture, mineralogy and particle shape of aggregates and optimisation of the design that influence the composite performance (Hassan *et al*., 1998). Therefore the inclusion of end-performance specifications, within the current standards, should enhance the wider use of recycled materials in many high value applications. The report discusses the extent to which secondary and recycled aggregates can be used in highway infrastructure.

An examination of international and UK experiences on the use of secondary and recycled aggregates in highway infrastructure has been carried out. Information on the optimised use of these materials has been obtained from different sources including a number of European countries and the USA. Informal consultation with the Road and Hydraulic Engineering Division of the Directorate General of Public Works and Water Management (DWW) in the Netherlands was also made. The outcomes of a literature review and the consultation are presented to highlight the innovative research, techniques and programmes that could be introduced to the UK.

By reviewing the requirements and specifications for alternative materials in highway infrastructure and examining the UK and international experiences, a number of new materials and applications have been identified. The availability of these materials is discussed in terms of arisings, stockpiles and locations. Informal consultations were also carried out with materials producers in the UK to identify their views about existing and potential markets and barriers to reaching them. Innovative research on the high-value utilisation of the identified alternative materials is recommended within the context of technical barriers. The environmental and regulatory issues restricting the potential use of new materials are also discussed.

The report also provides an examination of material lifetime covering whole life costing (WLC) and considers the economic cost of the material, material performance and future recyclability. WLC is a process that aims to look at 'every cost incurred in respect of a facility or product from inception to disposal', i.e. the total costs associated with the procurement, use during service-life and disposal at the end of life. The report explains how WLC methods can be used in relation to secondary and recycled material selection although limited technical data restricts the prediction of lifetime and recyclability. The need for further studies on material development and performance characteristics that are required to be implemented, to assess the WLC of new materials using secondary and recycled aggregates, are highlighted.

Finally, the report provides a comprehensive set of recommendations for future work that is required to develop a better understanding of material behaviour and performance and to overcome the identified barriers towards the optimised use of secondary and recycled aggregates in highway infrastructure.

2 Applications in highway infrastructure

Aggregates are used in large quantities in highway construction and there is a great potential to replace primary aggregates with secondary and recycled materials. Highway construction includes various applications in pavements, earthworks, drainage and structures such as bridges.

New construction and maintenance of the trunk road and motorway network in England are based upon the requirements and specifications given in documentation produced by the Highways Agency. This consists primarily of the Manual of Contract Documents for Highway Works (MCHW), the Design Manual for Roads and Bridges (DMRB), and the Trunk Road Maintenance Manual (TRMM). The MCHW incorporates a number of volumes used to govern the design and construction of roads. These include the Specification for Highway Works (SHW), the associated Notes for Guidance and Highway Construction Details (HCD). The specification requirements for roads are broadly similar to those of runway and taxiway (airfields) and track ballast and ancillary (rail) applications.

The following sections review the current SHW and related documents on the use of recycled aggregates in highway infrastructure and highlight new applications of the materials, with more emphasis on high-value applications in road construction.

2.1 Road construction

Road construction represents the major market for the utilisation of secondary and recycled materials in highway infrastructure. Traditional pavement designs focus on the use of conventional materials. There is however a tendency to move to end-performance specifications, which will enable a wider range of alternative materials to be used in pavements. Road construction involves a number of pavement layers with the specification of each layer becoming less stringent from the top surface downwards. The requirements for the performance and/or permitted constituents for a given layer tend to be higher than those of the layer beneath. Pavements constructed from asphalt and concrete are classified as flexible and rigid pavements, respectively. There are, however, two more categories, known as flexible composite and rigid composite, with asphalt surfacing in the upper layers supported on a rigid base of cement-bound material or pavement quality concrete, respectively. Figure 2.1 shows the different pavement types, illustrating that the main differences are within the top layers (above sub-base).

2.1.1 Surface course materials

The surface layer of a pavement carries and transfers traffic loads to the underlying layers while providing protection against water penetration and providing adequate skidding resistance and a good ride quality. The

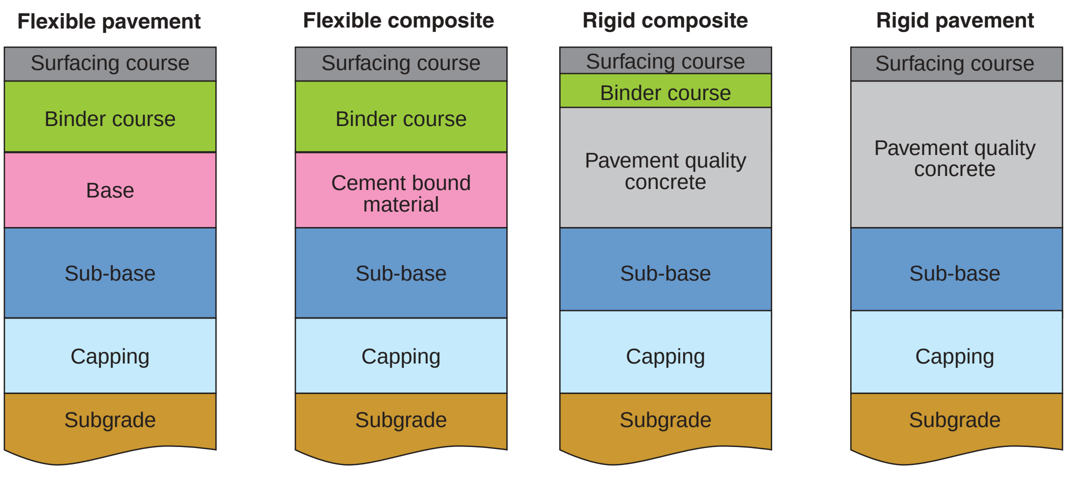

Figure 2.1 Typical types of pavement in road construction (not to scale)

surfacing layer is directly subjected to varying traffic and weather conditions and specifications impose more stringent requirements on this layer than lower layers of the road pavement.

2.1.1.1 Surfacing and binder course materials

The requirements of surfacing materials are mainly based on frictional properties and durability as specified in Clause 901 of SHW (Highways Agency *et al.*). Surfacing materials include rolled asphalt, macadam and thin surfacing and the selection is based on the amount of traffic, with conventional recipe mixtures for lightly trafficked areas, to end-product performance approved through the British Board of Agrément (BBA) Highway Authority Product Approval Scheme (HAPAS) for more heavily trafficked areas. The aggregate requirements are given in terms of grading and mechanical properties. *In situ* recycling is permitted. Secondary aggregates permitted are blast furnace and steel slag aggregates, recycled bituminous materials (maximum 10% for rolled asphalt and macadam wearing courses) and recycled coarse aggregate.

In addition to aggregate, filler is also used with rolled asphalt to stiffen and strengthen the bitumen and lower its temperature susceptibility to deformation. Limestone dust is the most commonly used filler with potential for other inert mineral powders with adequate fineness. The use of power station fly ash in hot rolled asphalt has indicated improved workability and a reduction in energy requirement, without affecting the engineering and performance properties.

TRL Road Note 39 (Nicholls, 1997) provides guidance on the design and construction of surface dressing, and the requirements are based either on a recipe specification (Clause 919) or an end-performance specification (Clause 922). The material is mainly characterised by its skid resistance, and resistance against water penetration and disintegration of the road surface. Both blast furnace and steel slags are permitted for use as surface dressing aggregates provided that they meet with the specified requirements of skid resistance and durability.

2.1.1.2 Pavement quality concrete

Current practice in the UK is to cover concrete pavement with a thin-layer asphalt surfacing material. The use of a thin, low-noise surfacing allows the requirements for aggregate used in pavement quality concrete (PQC) to be less stringent with more recycling opportunities. The requirements of concrete pavements are currently specified in terms of minimum cement content and maximum water/cement ratio to achieve a desired compressive strength. However, as the structural performance of concrete pavements is more related to the flexural strength, there are other properties of aggregates than mechanical properties to be considered. Current research at TRL is investigating the effect of different aggregate types on the flexural and compressive strength of concrete, which could be implemented in the development of new pavement designs based on flexural strength. Such specifications will give more consideration to the surface texture of the aggregates and properties at the interface with the cementitious matrix. They could allow the wider utilisation of alternative aggregate in pavement quality concrete.

Aggregate represents the highest proportion of the concrete constituents, more than 75% by volume, and the specification permits the use of natural and recycled aggregates. The requirements of recycled aggregate are given in Clause 1001 (Highways Agency *et al.*) and can be summarised as:

- Recycled concrete aggregate that complies with the quality and grading requirements of BS 882 (1992), with a draft specification of similar requirements to include Incinerator Bottom Ash (IBA).
- Crushed air-cooled blast furnace slag complying with BS 1047 (1983), with grading to Table 1 of BS 1047.
- Pulverised fuel ash to BS 3892: Part 2 (1996).
- China clay waste and slate waste are also permitted if the material complies with the specification requirements, but these materials are not named in the specification.

2.1.2 Base materials

The base is the main structural layer of flexible and flexible composite pavement construction. Its function is to spread the surface loads and reduce the stresses thereby ensuring that the bearing capacity of the subgrade is not exceeded. In rigid and rigid composite pavements, the concrete slab with its high load bearing capacity undertakes the function of the base layer. In a flexible composite construction the surfacing bituminous layers are supported on a cemented or pavement quality concrete base, whereas an asphalt base material is used with flexible pavement.

2.1.2.1 Asphalt base materials

Rolled asphalt and macadam are commonly used as base materials. The requirements of aggregates are similar to those for asphalt surfacing materials in terms of grading and mechanical properties given in Clause 901 (Highways Agency *et al.*). Permitted aggregates include blast furnace and steel slags, reclaimed asphalt materials and recycled coarse aggregate, similar to that of asphalt surfacing materials. In addition, the specification also allows the use of china clay sand and slate waste, and increases the maximum allowable amount of reclaimed asphalt to 50%.

2.1.2.2 Cement-bound base materials

Generally there are five categories of cement-bound materials (CBM1 – CBM5) mainly characterised by aggregate grading and 7-day mean compressive strength, Clauses 1035-1038 (Highways Agency *et al.*, 2001). The average compressive strength increases from 4.5MPa for CBM1 to 20MPa for CMB5. Only CBM3, CBM4 and CBM5 are permitted in the construction of the base. The specification allows the use of a variety of recycled and secondary materials provided that they satisfy the grading and strength requirements, for example crushed concrete, blast furnace slag and PFA.

Another form of cement-bound material is wet lean concrete as defined in Clause 1030 (Highways Agency *et al.*, 2001). This has a lower strength requirement than pavement quality concrete. The secondary aggregates permitted are recycled concrete aggregate with the quality and grading requirements of BS 882 (1992), crushed air-cooled blast furnace slag to BS 1047 (1983), and pulverised fuel ash to BS 3892: Part 2 (1996). For standard mixtures (termed ST1, ST2, and ST3, with compressive strength of 20MPa or less) bituminous planings, demolition wastes, steel slag, colliery spoil, spent oil shale, furnace bottom ash, china clay waste and slate waste are permitted if the material complies with the specifications but these materials are not named in the specification.

2.1.3 Sub-base construction materials

The sub-base is a platform layer upon which the main structure of the pavement is laid. It also provides protection to the subgrade by spreading wheel loads during construction and as an insulating layer against freezing, as the subgrade can be weakened by the action of frost. Unlike structural pavement layers, the sub-base thickness is dependent on the bearing capacity of the subgrade, rather than traffic intensity. Sub-base could be constructed of granular or bound materials, but only cement bound sub-bases are permitted under rigid (concrete) or rigid composite pavements.

2.1.3.1 Granular sub-base materials

Granular sub-base materials are classified in Clauses 803, 804 and 806 of the SHW (Highways Agency *et al.*) with the requirements and permitted aggregates given for granular sub-base material Type 1, Type 2 and Type 4, respectively.

Type 1 granular sub-base materials include crushed rock as natural aggregate with crushed concrete, crushed slag, well burnt non-plastic shale and recycled aggregate as secondary aggregates. Type 2 granular sub-base materials include the same secondary aggregates as in Type 1 and also natural sand and gravel. Type 4 sub-base materials, however, do not include natural aggregates but asphalt road planings or granulated asphalt. The requirements of granular sub-base materials are given in the forms of grading and physical properties with limitations on sulphate content and frost resistance (frost heave). Sulphate limitation is specified for aggregates other than slag when placed within 500 mm of cement bound materials or concrete products.

2.1.3.2 Cement/slag bound sub-base materials

Cement bound materials may be used as an alternative to unbound granular materials under flexible construction and are the only permitted materials under rigid and rigid composite construction. Cement bound materials and wet lean concrete of the highest quality are mainly used in road base applications, as discussed before. However for sub-base applications, CBM3, CBM2 and 2A, CBM1 and 1A and weak wet lean concrete mixtures are commonly used. This means a wider range of secondary aggregates with lower quality may be used. These include crushed concrete, blast furnace slag, PFA, recycled coarse aggregate, bituminous planings, demolition wastes, steel slag, colliery spoil, spent oil shale, furnace bottom ash, china clay waste and slate waste.

With the development of cement replacement materials, slag bound material was also included in Clause 805 of the SHW. Slag bound material (SMB) is a mixture of aggregate bound by granulated blast furnace slag (GBS) and an activator, usually lime. The secondary aggregates used are mainly crushed concrete and crushed blast furnace slag. Two types of SMB are classified: Type B2 for road pavements and Type B3 for footways. These should comply with draft BS EN 14227: Part 2 (2001), except for those changes given in Clause 805 of the SHW (Highways Agency *et al.,* 2001).

2.2 Earthworks

Earthworks make up the foundation on which the pavement layers are constructed. This may be existing *in situ* material or fill material which has been imported to build up the surface level or to replace existing subgrade material that is unsuitable for use. The design and construction of earthworks is described in the Advice Note HA44 (DMRB 4.1.1) (Highways Agency *et al.*).

The bearing capacity of the subgrade influences the design and thickness of the road structure above it. The bearing capacity of earthwork materials is usually measured using the California Bearing Ratio (CBR), as detailed in BS1377: Part 4 and Part 9 (1990). The CBR test empirically relates the material strength of the test specimen to that of a good quality crushed rock, which is considered to have a bearing capacity of 100%.

In terms of the layered approach to flexible road construction, the majority of earthworks materials can be split into capping and general fill classifications within the SHW. In addition earthworks materials can also be used in a variety of other applications such as fill to structures and reinforced earth. These latter applications have various additional suitability and acceptability criteria. However, in general terms, the aim of the SHW is to ensure that the widest possible range of suitable earthwork materials may be used in as many different applications as possible.

2.2.1 Capping layer construction

The capping layer is a subgrade improvement layer. It performs three functions. In the short term, it acts as a working platform for construction of the sub-base and provides protection for weak subgrades. In the longer term, capping acts as a structural layer within the pavement. Thirdly, during construction, capping protects the subgrade from damage due to wet weather and over-stressing. In general terms, capping can both enhance the load-bearing capacity and reduce the thickness of the sub-base required for given subgrade conditions.

The capping layer may be constructed from a wide range of locally available, low cost granular materials or by *in situ* stabilisation of the subgrade with lime and/or cement. As an improvement layer, capping is typically used on subgrades with predicted long-term bearing capacities below specified values. For instance, when bearing capacities are predicted to have a CBR value less than 5%, a capping layer of at least 350 mm is normally specified in HA44 (DMRB 4.1.1). For bearing capacities between 5% and 15%, depending on economic considerations and pavement design, either a capping layer or thicker sub-base design may be used.

2.2.1.1 Granular capping materials

Granular capping materials can be used either as unbound or cement stabilised materials. Specific requirements for these materials are usually given in terms of their grading, physical, chemical and compositional properties, see Clause 613 in the SHW. Whilst the SHW does not specifically specify a strength requirement, HD25 (DMRB 7.2.2) indicates that materials permitted for capping have been chosen to meet the requirements for a formation with a CBR in excess of 15%.

Generally, the requirements for capping materials are not particularly onerous, and are classified on the basis of particle size distribution, moisture content and 10% fines value (Table 6/1, Clause 613, SHW). This allows the potential use of many natural, recycled and alternative materials. The SHW classifies the following granular material classes for capping:

- Class 6E: Selected granular material for stabilisation with cement, which may be any material or combination of materials, other than unburnt colliery spoil.
- Class 6F1: Selected granular material (fine grading) which may be any material or combination of materials, other than unburnt colliery spoil.
- Class 6F2 Selected granular material (coarse grading) which may be any material or combination of materials, other than unburnt colliery spoil.
- Class 6F3 Selected granular material which may be recycled bituminous planings and granulated asphalt, excluding material containing tar or tar-bitumen binders.
- Class 6R Selected granular material for stabilisation with cement which could be any material or combination of materials, other than unburnt colliery spoil.

2.2.1.2 In situ stabilised capping materials

In situ stabilised capping materials have the advantage of utilising the existing subgrade making use of lime and/or cement as the binder, as described in HA74 (DMRB 4.1.6). Compared to imported aggregates, *in situ* stabilisation offers potential cost savings.

Lime (quicklime or hydrated lime) can be used effectively when subgrade materials possess pozzolanic properties, which is associated with a clay component. When mixing occurs, there are immediate improvements in the material properties and stabilisation; the process also produces strength gains in the longer term.

Cement can be used either in conjunction with lime or on its own as it possesses hydraulic properties which provide strength to the stabilised subgrade. The use of and design of lime and or cement stabilised capping is dependent on the particular properties of the subgrade and the required strength characteristics.

Different types of cement-stabilised (Clause 614) and lime-stabilised (Clause 615) capping material are classified in the SHW (Highways Agency *et al.*) as follows:

- Class 9A: Selected well-graded granular material (Class 6E) for stabilisation with cement.
- Class 9B: Selected silty cohesive material (Class 7F) for stabilisation with cement.
- Class 9C: Selected conditioned pulverised fuel ash cohesive material (Class 7G) for stabilisation with cement.
- Class 9D: Selected cohesive material (Class 7E) for stabilisation with lime.

2.2.2 General fill material

The design and construction of highway earthworks involves utilising the lowest cost solutions to achieve acceptable performance. For example, if the existing level of the ground over which a new road is to be built is not as required, the level will be increased or decreased. This process is known as ‘cut and fill’. As far as possible, the road designer will try to balance volumes of cut and fill by reusing cut material in other areas. This task is often complicated and may not always be achieved in practice. As a result, both site-won and imported fill may be required in very large quantities. The major requirement is that these materials are easy to transport, lay and compact. The required properties for these materials are not particularly onerous, mainly being particle size distribution, plasticity, and moisture content. Once placed and compacted, the main short-term requirement is that they are stable and strong enough to allow the construction of the upper layers to take place. In the longer term, the materials should have sufficient durability to meet the requirements of the application. Many recycled or secondary materials have been used as general fill.

The different types of general fill are specified within the SHW as follows:

- Class 1: General granular fills (1A, 1B and 1C).
- Class 2: General cohesive fills (2A, 2B, 2C, 2D, 2E).
- Class 3: General chalk fill.

2.2.3 Selected fills

In addition to capping and general fill applications, the SHW makes provision for the use of a wide range of both site-won and imported earthwork materials in more specific applications. These selected fill classes within the SHW have specific material suitability and acceptability requirements (e.g. chemical properties), which are more exacting than those specified for general applications. However, many recycled or secondary materials have the potential to be used as selected fill materials. The different types of selected general fill are given in the SHW.

2.2.4 Unsuitable materials

Unsuitable earthwork materials, classified as Class U1 in Clause 601 of the SHW, may be deemed suitable via a process of ‘improvement’. This process is described in

HA74/00 (DMRB 4.1.6) and typically uses quicklime to improve both cohesive and granular materials. The addition of lime to cohesive and granular materials causes some reduction in moisture and for cohesive materials a significant alteration in engineering properties. Accordingly, Class U1 granular or cohesive materials may, via a process of improvement, be reclassified as Class 1A, 1B, 1C or Class 2A, 2B or 2C respectively. This can have significant cost savings associated with the avoidance of disposal and importation of replacement material.

2.3 Street works

Street works comprise the construction, maintenance and reinstatement of the wide variety of minor roads, footways, footpaths and cycle tracks that are part of both the urban and rural infrastructure. New construction and maintenance in the UK typically follow specifications that are amalgams of national specifications, often principally based on the SHW, and local procedures, typically collated from experiences gained by Local and other Highway Authorities. Materials, methods and procedures discussed in previous sections (Sections 2.1 and 2.2 on road construction and earthworks respectively) are applicable and cover the most pertinent issues related to these two aspects of street works.

Reinstatements are governed by the New Roads and Street Works Act 1991, and the Specification for the Reinstatement of Openings in Highways (SROH) (Department for Transport, 2002). The term reinstatement applies to the restoration of an excavation or trench, which typically contains apparatus providing services such as gas, water, electricity, telecommunications, cable TV, sewers and drains. Generally, narrow trenches are often 200 mm width by 450 mm depth (dimensions typically used by telecom utilities) and the wider trenches are 350 mm width by 800 mm depth (dimensions typically used by electricity and gas utilities). Other categories of openings include deep openings, where the depth of cover over the buried apparatus is greater than 1.5m, and other openings, applying to excavations and trenches with surface areas greater than 2m².

2.3.1 Design

Street works comprising construction, maintenance or reinstatements are designed under either road or footway classifications. For the road classification, the design types include flexible, composite, rigid or modular, and are similar to that shown in Figure 2.1. Five categories of road types are also specified in SROH. Road types 0 to 4 are based on the number of millions of standard axles (msa) carried by the road over a 20-year period. Different engineering requirements are specified for each road type.

Footways, footpaths and cycle tracks are categorised as high duty (dependant on the flow of pedestrians and/or cyclists), high amenity (routes constructed to a high standard with special or decorative surfaces) or other (neither high duty nor high amenity). Details of the design types applied to footways are detailed in SROH (Department for Transport, 2002).

2.3.2 Materials and applications

The unbound and alternative reinstatement material categories detailed in SROH, comprising surround, backfill, sub-base, and base are placed in the excavation following method specifications. Suitability and acceptability for the unbound materials are based on mechanical properties, which reflect the requirements for these applications when used in standard road construction. For the majority of reinstatements, the bituminous bound categories detailed in SROH, comprising the surface and binder courses, are placed according to end performance specifications. The acceptable performance criteria are typically based on achieving an *in situ* air void content of between 2 and 13%.

2.3.2.1 Bituminous surfacing materials

The majority of bituminous bound materials detailed in SROH are the conventional hot-lay bituminous materials covered by BS 4987: Part 1 (2001). Whilst no recycled materials are explicitly specified for use within bituminous hot-lay surfacing materials, their use is not precluded.

Permanent Cold-lay bituminous Surfacing Materials (PCSMs), which can be formulated to give a performance equivalent to hot-laid materials, yet remain workable for several days, may be specified. The overall PCSM formulation, manufacture and placement are limited only by the need to comply with the BBA/HAPAS (www.bbacerts.co.uk) guideline for approval and certification of PCSMs. Approved PCSMs may be used as substitutes for any permitted bituminous bound material.

2.3.2.2 Concrete

Concrete for use in the formation of a road slab is specified as C40 concrete, in accordance with SHW Clause 1001, with an air entraining admixture used in at least the top 50 mm of the road slab. The requirements of recycled aggregates for Clause 1001 are summarised in Section 2.1.1.2.

2.3.2.3 Pavement modules, bedding and grouting

Pavement modules include setts, concrete blocks, brick pavers and paving slabs. Where an interim reinstatement is required, SROH recommends that the existing modules should be reused, including the use of broken modules. Permanent reinstatement of modular surface layers is carried out in accordance with BS 7533: Parts 1 to 7 (BSI, 1997 to 2002).

The specified bedding material is sand or mortar, to match the characteristics of the existing type and thickness. Sand, mortar or other grouting, to match the performance of the existing materials, is applied to gaps between individual modules at the time of permanent reinstatement.

2.3.2.4 Base

Dependent on design, granular sub-base (GSB) materials, in accordance with Clause 803 of the SHW, and cement bound material CBM3, in accordance with Clause 1038 of the SHW, are permitted for use as base in flexible or composite road reinstatements. The curing procedure specified for the CBM3 is dependent on the road type.

2.3.2.5 Sub-base

Granular sub-base (GSB) materials are specified in accordance with Clause 803 of the SHW. The characteristics are in accordance with those specified for the GSB used in standard road construction.

2.3.2.6 Backfill

Five material classes are defined as backfill on the basis of the field identification tests described in Appendix 1 of the SROH. Material acceptability is defined via anticipated strength (CBR). The re-use of excavated materials as backfill material in verges and unmade ground is encouraged as part of a policy of environmentally sustainable construction.

2.3.2.7 Surround

The entire surround effectively forms a foundation structure for the remainder of a reinstatement and must be capable of providing adequate support for all loading imposed on the reinstatement surface, as well as the weight of the reinstatement structure.

2.3.2.8 Alternative reinstatement materials (ARMs)

New or alternative reinstatement materials (ARMs) allow more rapid, reliable and cost-effective reinstatements, with less dependence on the skill and physical effort of the operators.

ARMs are categorised by SROH into two generic groups:

Structural materials for reinstatements (SMRs)

This generic group is intended to include proprietary or alternative bound reinstatement materials that include a cementitious, chemical or hydraulic binder or are inherently self-cementing. SMRs may be used on a trial basis in any combination of the following:

- At any position within the surround to apparatus.
- As a sub-base within any reinstatement.
- As a combined sub-base and base (roadbase) within any reinstatement in Road Types 1, 2, 3 and 4.
- As a combined sub-base and binder course, within any reinstatement in footways, footpaths and cycle tracks.

SMRs shall not be used in place of surface course materials.

SMRs are categorised as follows:

- *Foamed concretes for reinstatements (FCRs).* FCRs conform to Clause 1043 of the SHW and are produced from virgin material to prescribed mix formulations.
- *Flowable SMRs (FSMRs) and non-flowable SMRs (NFSMRs).* These materials comprise any type and/or combination of aggregates and binders. FSMRs are flowable mixtures that should not normally require compaction while NFSMRs are non-flowable mixtures that will normally require compaction on site. Both are capable of achieving strengths equivalent to FCRs but these materials may only be used on a trial basis.

Stabilised materials for fills (SMFs)

This generic group is intended to include materials derived from excavated spoil, virgin, secondary or recycled materials, or any combination, that have been improved by re-processing, re-grading and/or by the inclusion of a cementitious, chemical or hydraulic binder. SMFs are generally non-flowable and shall therefore normally require compaction. SMFs may be used in place of other materials on a trial basis, in the layers appropriate to their strength classification, in any combination of the following:

- At any position within the surround to apparatus.
- As a sub-base within any reinstatement.
- As a combined surround to apparatus and/or backfill and/or sub-base within any reinstatement.

SMFs shall not be used in place of the permanent binder course or surface course.

The overall requirements for SMFs is that each stabilisation method and formulation shall be classified as yielding SMF materials equivalent to one of the five defined classes of backfill material described in SORH.

General considerations for ARMs

ARMs used within 450 mm of the road surface are required to be non-frost susceptible. Following identifications of sites where high sulphate levels are known to occur, Ordinary portland cement-based binders in the ARMs shall be replaced with sulphate resistant portland cement-based binders.

2.3.2.9 Alternative options

The SROH recognises that research into new or improved reinstatement materials may produce materials that perform as well as, or better than, those currently specified. Materials may also be available locally that have not been defined in any national specification, but which, by experience, are known to give acceptable performance in service. To allow the use of such local materials, SROH permits that the materials may be amended or supplemented, subject to agreement. Recycled, secondary or virgin materials, or any combination, are also permitted provided they meet the performance requirements for the relevant material layer.

2.4 Summary

The Specification for Highway Works (SHW), including the May 2001 amendments, permits a wide range of alternative materials for use in the various layers of pavements. However, as the aggregate requirements increase from the foundations to the upper pavement layers, the use of alternative materials is reduced. The tendency to move to end-performance specifications will enable a wider range of recycled materials to be used in pavement construction.

The SHW currently has no specific provision for the use of glass, plastic waste, tyre rubber, and incinerator bottom ash (a draft specification has been produced by the Highways Agency). The use of recycled asphalt pavement is restricted to asphalt bound materials and cement bound materials. There is also a lack of specification on the use of other hydraulic bound materials than cement, such as fly ash and slag bound materials, for base layers. UK and international experiences on the use of these materials/ applications will be discussed in the following sections.

3 Examination of UK experience

3.1 Availability of materials

Some alternative aggregates are in limited supply and therefore cannot compete with primary aggregates due to an inability to meet demand. The location of the material also greatly influences the decision whether or not to use alternative aggregates. In some cases, alternative aggregates could be available in large quantities but uneconomic to use due to high transport costs away from localised sources. Ellis (2003) provides comprehensive information on the quantities, locations, and uses of alternative materials in the UK, based on the data obtained from the Office of the Deputy Prime Minister (ODPM, 2001) surveys and other sources. A summary of this information is given in Table 3.1.

Within the above materials construction and demolition wastes (CDW) represents the largest amount of materials arising and is mainly located in urban areas. Plants producing incinerator bottom ash (IBA) are similarly located in urban areas, making them suitable ‘urban quarries’ with the opportunity to minimise transport of ash to landfill and of primary aggregate into congested urban areas.

Glass, plastic, and tyre rubber are relatively new potential alternative aggregates in the construction industry and are currently produced in much smaller quantities, compared to CDW, and distributed across the UK. There is however a potential for increased recycling of these materials and a growing interest to develop appropriate markets, especially for glass cullet produced from crushing waste glass collected in municipal and industrial waste streams. Care should be taken when recycling these materials as higher value utilisation could exist in other applications than civil engineering. The use of the materials in the construction industry should be either in high-value applications where the material is competing with conventional materials, or where the materials have no other use and are currently landfilled.

Wastes from power stations and steel works are available at various locations across the UK. The use of furnace bottom ash and blastfurnace slag as aggregate replacement is well established. There are restrictions and limitations on the use of steel slag in cementitious composites due to problems associated with expansion and dimensional stability but it is well established as an asphalt surface course aggregate (Roe, 2003). Fly ash and blastfurnace and steel slag are produced at the rate of approximately 10Mt/a, and have been considered in this report for new high-value applications in road construction, such as hydraulic bound material and roller compacted concrete.

Table 3.1 shows that significant quantities, arisings and stockpiles, of china clay and slate wastes are also available in the UK. Technically, these materials are potentially suitable for many applications as primary aggregates and are permitted by the SHW. There might be some specific technical issues with grading and particle shape of the material, which could be overcome with the appropriate mixture design in bound applications. The materials, however, are mainly produced and used in localised areas, so transport cost presents the main barrier. Overcoming this barrier may result in a wider use of the materials.

Based on the above discussion, the main materials that are identified as having either a potential for increased use or higher value use, in highway infrastructure are:

- Construction and demolition wastes.
- Incinerator bottom ash.
- Glass.
- Plastic.
- Tyre rubber.
- Power station fly ash.
- Slags.

Table 3.1 Alternative material arisings, stockpiles and locations in the UK (million tonnes / annum) (Ellis, 2003)

Material	*Arising Mt/a*	*%*	*StockpileMt*	*Location*
Blastfurnace and steel slag	4+1	3.2	*	N and E England, S Wales
China clay by-products	22.6	14.7	600	Cornwall, Devon
Coal and other mining waste (colliery spoil)	7.5	4.9	15	Coalfields, mineral workings
Construction and demolition wastes	94	61.0	0	Principally urban areas
Crushed brick	5	3.2	*	Demolition sites
Foundry sands	0.9	0.6	0	West Midlands and Yorkshire
Glass cullet	2.2	1.4	0	Municipal waste. Currently 1.6Mt mainly green landfilled
Municipal solid waste IBA	1.35	0.9	0	Generally urban areas
Power station fly ash (PFA)	4.9	3.2	55	Coal-fired power stations
Scrap tyres	0.4	0.3	*	
Slate waste	6.3	4.1	466	Wales, Scotland, Pennines
Spent oil shale	0	0.0	100	West Lothian
Spent railway track ballast	1.3	0.8	*	
Waste plastic	2.8	1.8	0	
Total	154	100	1236	

** Not determined*

3.2 Material application

The following sections review the current UK experience on the use of alternative aggregates in different applications of road construction, with more emphasis on high-value applications in asphalt and concrete composites. Case studies on the use of various materials in different applications are given in Appendix A.

3.2.1 Surface and binder courses

Surface course is used in all types of road pavements and is a high-value application for secondary and recycled aggregates. Work by TRL on field trials showed that recycled surface courses performed equally as well as new material and met the composition requirements of the relevant specifications (Edwards and Mayhew, 1989). It has also been shown that contractors can successfully produce recycled hot rolled asphalt surface course containing up to 80% of the original surfacing using the Remix process and off-site recycled bituminous binder and base courses. Five major resurfacing schemes were constructed in 1990 and 1991, which utilised the Remix recycling process (Earland, 1996).

TRL work has assessed the in-service performance of three trials of recycled asphalt binder course produced in off-site mixing plants. The test sections on the A20 were built in 1986 and contained up to 60% reclaimed material in the base and binder course (Cornelius and Edwards, 1991). Those on the A500 and A23 were built in 1992 and 1993 respectively, and contain up to 30% of reclaimed asphalt material. The trials of recycled base and binder course asphalt were constructed on trunk roads and subjected to typical traffic and climatic conditions. The laboratory trials at the time of construction showed that the recycled materials had stiffness moduli and creep stiffness that were equivalent to the conventional materials laid alongside, apart from an asphalt planings section that performed less well in creep tests. The in-service monitoring of the three sites found that the recycled materials had continued to perform in a similar manner to their respective control sections in all the parameters measured (Megan and Potter, 2000).

Crushed glass has also been used in the construction of asphalt layers. The material is relatively durable but has the disadvantage of weak bond strength with bitumen. There are potential uses for crushed glass, but there is an imbalance for green glass, for which there is little use in the UK despite significant quantities imported as wine bottles. RMC Aggregates (UK) Limited, with a sister company involved in waste, trialled the production of macadam with crushed glass to replace 30 % of the aggregate in conventional mixtures, case study A1 - Appendix A. The resulting macadam, under the trade name *Glasphalt*, is intended for use in the structural layers of a pavement because glass will not have the skid-resistance required for the surface course due to its propensity to polish quickly. Initial trials with the material were monitored and demonstrated that the presence of glass does not significantly affect the physical properties of the asphalt, which is durable for at least 2 years (Nicholls and Lay, 2002).

Research at Leeds University investigated the properties of asphalt mixtures containing recycled plastic aggregate. Recycled waste plastics, predominately composed of low density polyethylene (LDPE) in pellet form, were used in dense graded bituminous mixtures to replace (by volume) a proportion of the mineral aggregate of an equal size, i.e., 5.00-2.36 mm. The incorporation of LPDE recycled plastics and manufacture of *Plastiphalt* mixtures required no modification to existing asphalt production plant facilities and techniques. The *Plastiphalt* mixtures had lower densities than conventional/control mixtures containing mineral aggregate only. About 30% aggregate replacement by volume with LDPE resulted in a 16% reduction in the weight of the mixture. This result could be advantageous in terms of haulage costs or when surfacing multi-storey car parks and bridge decks. The *Plastiphalt* mixtures had much higher stability, approximately 2.5 times that of the control mixtures. Overall, the mechanical properties of aged, recycled *Plastiphalt* mixtures containing plastic aggregate replacement are superior to those of the control mixtures entirely composed of mineral aggregates (Zoorob and Suparma, 2000).

The only regular use of tyre rubber in the UK in trafficked asphalt is in a proprietary thin surfacing system marketed by Colas Limited under the trade name *Colsoft* where the rubber is used as aggregate. However, it does not use a large proportion of the material. More rubber is used in playground and sports surfacings in order to provide some elasticity when people fall. Another use of scrap rubber in the UK is as relatively large pieces bound by bitumen to form a topping to French drains alongside roads (Carswell and Jenkins, 1996). The idea, as well as to use scrap tyres, is to minimise the damage caused by flying particles dislodged by vehicles over-running unbound drains.

It can be seen from the above review that the use of recycled glass, plastic and rubber in surface and binder courses is relatively limited in the UK. Whilst recycled glass and rubber have been used in full-scale field trials, there is still a need for further research to overcome the technical problems highlighted and improve end-product performance. The use of recycled plastics is a relatively new development and further work is required to support the wider use of this material.

3.2.2 Pavement quality concrete

Concrete is the construction material with most potential to incorporate a wide range of secondary and recycled materials. There are, however, some technical issues to be considered with some materials when bound with cement. For example, the use of glass and recycled concrete aggregate (RCA) could increase the risk of concrete deterioration due to alkali–silica reaction. This risk could be much reduced with the use of cement replacement materials and decreasing the amount of cement (alkali) in concrete.

Reclaimed asphalt pavement aggregates are commonly used in asphalt mixtures, hot or cold, but there is little information about their uses in cement-bound and pavement quality concrete mixtures. The material comprises primary aggregates coated with bitumen. The material has the potential to reduce the rigidity of concrete and enhance its flexibility. By optimising the mix design, Hassan *et al*. (2000) replaced 100% of the natural coarse aggregate with reclaimed asphalt pavement in concrete. The reclaimed asphalt pavement-concrete gave lower strength and modulus properties than the control concrete (without reclaimed asphalt pavement) but exhibited enhanced ductility and high strain capacity. These advantages of improved elastic deformation suggested the use of the material in crash barriers and other applications requiring shock absorbency.

3.2.3 Base and sub-base

Base and sub-base layers have a large potential to incorporate many alternative materials such as blast furnace slag, coal bottom ash and boiler slag, glass, mineral processing waste, municipal solid waste incinerator ash, reclaimed asphalt pavement, reclaimed concrete pavement, and steel slag.

Case study A2 demonstrates the successful use of granular material treated with fly ash (GFA), using 82% incinerator bottom ash as the granular material in the sub-base and base courses. In fact the increased level of Loss on Ignition (LOI) in the current production of fly ash, limits its use in structural concrete and there is a great potential for using the material as a binder in hydraulic bound material with a variety of recycled aggregates.

Work at Dundee University has indicated that the use of incinerator bottom ash (IBA) in ready mix concrete resulted in engineering properties that complied with those of C20 concrete. Pre-cast concrete units manufactured using IBA achieved compressive strengths equal to or above that of control specimens. Although the chloride and sulphate contents of IBA limits its use in structural concrete, other applications are viable (Halliday and Dhir, 2002).

The use of non-ferrous wastes in road construction is mainly governed by location and arisings. Recent research at BRE (BRE Report 423, 2001) highlighted the potential use of non-ferrous metal wastes such as aluminium, lead and zinc slags as aggregate replacement in cement and bituminous composites.

TRL has carried out laboratory testing of mixtures including a number of secondary aggregates and binders, and a full-scale trial of six sub-bases constructed with these mixtures, carried out in TRL’s Pavement Test Facility (PTF) (Atkinson *et al.*, 1999). The secondary materials investigated were china clay sand, blastfurnace slag, steel slag, fly ash, gypsum and cement kiln dust. At the same thickness, all the trial foundations incorporating secondary and recycled materials performed better than the control foundation made of unbound, granular Type 1 sub-base, with two sub-bases performing even better than the CBM1 control. They concluded that this improved performance results in the opportunity to thin the upper pavement layers and/or increase the life of the pavement with associated environmental and cost benefits.

3.2.4 Other applications

In addition to the high value applications listed above, a wide range of materials can be used in other applications, such as capping, embankment and fill. In these applications the material specifications are less restrictive than in the higher value applications.

There is a conflicting argument about the use of high-quality materials, such as crushed concrete, in unbound foundations. Even if the materials are locally available, there are concerns about whether these materials should be used in foundations or conserved for higher-value applications within the top layers of pavement construction.

3.3 Existing and potential markets

Information on existing and potential markets, for the identified materials, has been obtained from different sources including the examination of UK and international experiences, informal consultations with aggregates producers and contractors, and expertise at TRL and other organisations. This section also discusses material properties, processing and the barriers to achieving the potential markets.

3.3.1 Construction and demolition waste

Construction and demolition waste (CDW) covers a wide range of material and includes concrete, masonry and asphalt road materials that arise from the demolition of buildings, airfield runways and roads. CDW that is re-used as substitutes for natural aggregates falls into the category of recycled aggregate. Excluding asphalt road planings there are four main categories of construction and demolition waste:

- *Clean crushed concrete:* crushed and graded concrete containing less than 5% of brick or other stony material.
- *Clean crushed brick:* crushed and graded brick containing less than 5% of other material such as concrete or natural stone.
- *Clean demolition debris:* crushed and graded concrete and brick.
- *Crushed demolition debris:* mixed crushed concrete and brick that has been screened and sorted to remove excessive contamination, but still containing a proportion of wood, glass or other impurities.

CDW makes up the most significant component of total alternative material arising, Table 3.1, but could be variable in composition, properties and impurities. The reliability and quality control of the material is therefore an essential requirement. CDW is mainly available in urban areas, and could be used locally to replace natural aggregates with economic and environmental benefits. Recycled aggregate producers strongly support the development of the quality control protocol by the Quarry Products Association (Construction Research Communications, 2000) and the permitted use of recycled aggregates within the SHW and British Standards. These have greatly widened the material acceptance amongst clients and contractors.

In spite of the implementation of quality control systems and the improved consistency of the material, in road construction most CDW is still currently used in general bulk fill, capping and sub-base applications. It usually takes some time to gain more practical experience on the use of new materials and also in identifying the best applications. Good quality processing of CDW increases the aggregate prices and this should be met with high demand in the markets for high value applications to compete with primary aggregates. Whilst coarse recycled aggregate could be used in bound applications, the amount currently utilised in these high value markets is rather limited. Also, separation of coarse and fine CDW adds costs, with no high value use for the fine materials.

Reclaimed asphalt aggregate has been considered in this report as part of CDW. The material is being produced in the range of 4-5 Mt/a with a high-value application in the manufacture of new asphalt. Most of the reclaimed asphalt is obtained from hot rolled asphalt (HRA), which is of high quality with high bitumen content, making it suitable for recycling. Reclaimed asphalt is currently recycled in hot asphalt mixtures, up to 50% is permitted by the SHW, in base and binder course applications. The material is also used as unbound granular material with the additional benefit of some binding properties. However, there is a trend to reduce the use of HRA, replacing it with new asphalt mixtures incorporating modified binders. Modified asphalt contains less bitumen content and there is a lack of knowledge on recycling.

Whilst the material is produced in large quantities and has a potential for use in many applications, the efficient utilisation of CDW has not been carried out to the highest possible level. Recycled concrete aggregate (RCA) has a potential for use, at high replacement levels, in concrete applications, including those of structural concrete such as bridges. There is however a lack of information on the performance characteristics of the material and long term durability, including alkali-silica reaction. Blended CDW aggregates (crushed concrete and bricks) are of lower strength than RCA and therefore could be used in low strength concrete and in cement, hydraulic and bituminous bound materials.

The use of reclaimed asphalt in concrete and cementitious bound applications is limited in the UK. The material has been used successfully in other countries in road construction with improved performance.

Probably the most urgent need for efficient use of CDW is to identify high value applications for CDW fines. The production of RCA from concrete results in a significant amount of fines, with relatively low value applications. In fact most of recycled aggregate producers prefer not to separate the coarse and fine fractions due to the limited use of CDW fines within the construction industry. CDW fines mainly contain higher levels of cement and possible contamination of chloride and sulphate salts, depending on the material source, but could possess some hardening properties.

3.3.2 Incinerator bottom ash

Municipal solid waste incinerator (MSWI) ash is the by-product produced during the combustion of municipal solid waste in incinerator plant facilities. Several individual ash streams are produced including grate ash, siftings, boiler ash, scrubber ash and precipitator ash. Incinerator bottom ash (IBA) commonly refers to grate ash, siftings and, in some cases, the boiler ash stream, and forms about 80 to 90% of total ash production. Fly ash (which is different to coal fly ash) is also collected from the incineration process but with potential high concentrations of toxic materials impeding its use in the construction industry.

The incineration residues mainly contain clinker, glass, ceramics, metal, and unburnt organic matters. 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 (CIRIA C513, 1999). Current production of processed IBA accounts for about 1.35Mt/a, Table 3.1, with a potential increased rate in the coming years. More than half of IBA production is recycled and the remainder is sent to landfill. Current markets include aggregate replacement in cement and bitumen bound materials, granular sub-base, masonry blocks and bulk fill applications.

In road construction, IBA has been mainly used as aggregate replacement in cement bound material and asphalt and other fill applications. There is a potential for increased use as aggregate in concrete and asphalt composite. The material also has some pozzolanic properties making it more suitable for use in hydraulic bound materials. The pozzolanic properties would reduce the use of portland cement and contribute to the long-term strength development and improved interface characteristics at the binder/aggregate interface in cementitious mixtures. The material also has a potential for use in the production of lightweight aggregates.

3.3.3 Glass

Glass is another alternative material with a potential use in high value applications. The amount recycled is currently low, about 33%, out of about 2.2Mt/a produced from glass cullet. Potential sources of glass include cullet, bottle bank glass, kerbside collection glass, pubs and clubs, and other waste flat glass from demolition and replacement window industries. Recycled glass is currently used in various applications including; recycled back to glass, aggregate in asphalt and concrete, sand for bedding paving blocks, general replacements of sand in fill applications, water filtration and treatment, and as abrasives and fluxing agent for bricks.

With the exception of the water filtration market, the existing market has low demand for recycled glass due to the low-value application of the material and the relatively high processing costs, compared to primary aggregate. It has been indicated that aggregate producers are reluctant to send packaging glass to the aggregates industry with the current low values of packaging waste recovery note (PRN) (www.letsrecycle.com).

Due to the low demand for recycled glass within the construction industry there is a need to widen existing markets and develop new high-value applications of the material. Potential markets include cement replacement and fine aggregate replacement in concrete and cement bound materials. There is, however, some concern about the durability of glass within the alkali environment in concrete, which will be discussed in the following section in more detail.

3.3.4 Rubber

Post-consumer tyre rubber is a relatively new material, with relatively limited applications, in the construction industry. The extent of use of tyres is dependent on the end-product requirement and the degree of processing needed, with associated costs. With minor processing whole tyres and tyre bales have been used as embankments, basal drainage layers for new landfill sites and to control erosion in fluvial and coastal protection. Shredded tyre has been generally used in fill and drainage applications. Crumb rubber requires a high degree of expensive processing but provides additional markets in the field of road surfacing dressing, and sport and safety surfacing.

The majority of waste tyres are either worn out tyres from road vehicles or tyres removed prior to the disposal of 'end of life' vehicles. In the UK some 435,000 tonnes of used tyres are produced each year and require some form of treatment or disposal. EU Council Directive 1999/31/EC prevented the disposal of whole tyres to landfill after July 2003, and disposal of shredded tyres will be prevented by July 2006. Uses for waste tyres other than disposal to landfill must be found.

Steel-belted radial tyres are the predominant source of tyre scrap. Tyres can be recycled as tyre bales, whole tyres, slit tyres, shredded or chipped tyres, ground tyres, or processed to a crumb rubber or powdered rubber. Slit tyres are produced in tyre cutting machines that either slit the tyre into two halves or separate the sidewalls from the tread of the tyre. Tyre shreds are flat, irregularly shaped tyre chunks with jagged edges that may or may not contain protruding, sharp pieces of metal, which are parts of steel belts or beads. The size of tyre shreds may range from as large as 460 mm down to 25 mm with most particles within the range of 100 mm to 200 mm. Tyre chips are more finely and uniformly sized than tyre shreds, ranging from 76 mm down to approximately 13 mm in size. Ground rubber particles are intermediate in size between tyre chips and crumb rubber. The particle sizing of ground rubber ranges from 9.5 mm to 0.85 mm. Crumb rubber is normally particles finer than 4.75 mm. Powdered rubbers have particle sizes finer than 1 mm.

Tyre waste has a range of potential and existing uses in highway construction:

- *Embankment construction*. Shredded or chipped tyres have been used as a lightweight fill material for construction of embankments.
- *Aggregate substitute*. Ground rubber has been used as a fine aggregate substitute in asphalt mixtures. In this process, ground rubber particles are added into the hot mix as a fine aggregate in a gap-graded surface course.
- *Asphalt modifier*. Crumb rubber can be used to modify asphalt binder (e.g., increase its viscosity) in a process in which the rubber is blended with asphalt binder (usually in the range of 18 to 25% rubber).
- *Retaining walls*. Whole and slit tyres have been used to construct low height retaining walls for stabilising highway embankments.
- *Drainage*. Shredded tyres have been used to provide the top 200 to 300 mm of granular drains alongside highways. This reduces problems caused by stone scatter resulting from vehicle over run.
- *Backfill*. Chipped tyres have been used to provide free draining backfill to retaining structures such as bridge abutments. Their light-weight also reduces the settlement of the overlying road pavement.
- *Thermal insulation*. Tyre waste can be used as an insulating aggregate to prevent frost penetration in road sub-base.

3.3.5 Plastic

The amount of plastic waste currently generated in the UK is about 2.5 million tonnes per annum. The British Plastics Federation figures indicate that the current recycling rate of post-use plastic waste generated by the domestic, commercial and industrial sectors is approximately only 5%. The two main types of plastic are thermoplastics, which soften when heated and harden again when cooled, and thermosetting plastics, which harden by curing and cannot be re-moulded. Thermoplastics are by far the most common types, forming approximately 80% of the plastic waste stream, and are also the most easily recyclable. The most common types of thermoplastics include high density polyethylene (HDPE), polyvinyl chloride (PVC), and polyethylene terephthalate (PET).

Recycling of plastics is limited in practice to plastic containers, since much of the remaining plastic is in the form of film, which is difficult to separate. Processing of the plastic waste results in municipal shredded waste plastic. This material is then further processed by being granulated or pelletised. It is then used by being melted or partially melted and extruded to form the end product. The recycled plastic may be added to virgin plastic during the process. Potential uses for recycled plastic waste in highway infrastructure include:

- *Geogrids or separation membranes*. Geogrids, manufactured from HDPE, are commonly used to strengthen unstable slopes or prevent cracking in asphalt. Separation membranes can take the form of impervious sheets to restrict water or gas movement in the ground, or permeable heat bonded plastic felts as surround to drains alongside roads or to separate fine-grained soils from course soils.
- *Soil stabilisation and paving systems*. Soil filled honeycomb grids, manufactured from polyethylene, can be used to provide environmentally friendly and durable soil stabilisation and paving solutions. Other uses include erosion protection in surface drains.
- *Road aggregate*. There is potential for the use of pelletised or shredded plastic waste in concrete and cold mix asphalt pavements.
- *Lightweight aggregate*. This can be used in the manufacture of low density concrete. It also has potential for use as backfill to structures or drains.

- *Polymer concrete*. This uses inorganic aggregates bonded together with plastic glue. It can be used in pre-cast components and has the potential for use as overlays to pavements and bridge decks.
- *Sheet piling*. Recycled PVC has been used to manufacture sheet piling and has the potential for use in the provision of low height retaining walls.
- *Asphalt binder*. In the USA the addition of polyethylene into the binder has been shown to improve the mixture's ability to withstand permanent deformation and provides enhanced resistance to temperature and load-induced cracks.
- *Plastic pipes*. Recycled PVC can be used to produce drainage pipe.

The use of recycled plastic as aggregate in concrete and asphalt is, however, limited in the UK. The low density of plastic, compared to primary aggregate, makes it more suitable for lightweight applications. Waste plastic also has a potential for use in cold asphalt mixtures, sheet piles and ground barriers and as binder in hot asphalt mixtures.

3.3.6 Power station fly ash

The current production of furnace bottom ash is about 0.75Mt/a, all of which is used in block manufacture. Power station fly ash is however produced in higher quantities of about 5.5Mt/a, with about 55% used in various applications as general fill, grout, concrete additive, blocks and hydraulic binder, whereas the remaining 45% is sent to landfill. There is, however, concern about the changing material composition, due to the use of lower NO_x emission levels and the increased use of co-combustion materials, leading to a lower level of fly ash utilisation in high-value applications. The material may be of increased variability, with higher content of loss-on-ignition (LOI). Carbon reduction technology is being installed in a number of power stations to reduce the level of LOI in order to produce ash with high-value application in the concrete industry.

Fly ash producers would like to widen the utilisation of the material in new applications, such as hydraulic bound material in road construction. Bricks are another potential application for fly ash, but this is currently limited due to transport costs. Similarly to other secondary and recycled aggregates, the greatest barrier is the interpretation of the definition of waste, and the excessive costs and time needed to deal with waste legislation. When fly ash is used in fill applications, there are some concerns about leaching and pollution of surface and ground waters. There is also a problem of perception that fly ash is a toxic waste material, which can prevent its use in some situations.

3.3.7 Slag

Slags are non-metallic by-products from metal manufacturing. The slag occurs as a molten liquid melt and is a complex solution of silicates and oxides that solidifies upon cooling. Ferrous metallurgy produces blast furnace slag from iron making and steel furnace slag from steel making. There are many non-ferrous types including those derived from the manufacture of copper, nickel, phosphorus, lead, lead-zinc and zinc.

The current production of blastfurnace slag (BFS) is about 4Mt/a with reduced amounts of air cooled blastfurnace slag (ACBFS) and increased production of ground granulated blastfurnace slag (GGBS), representing about 75% of total BFS production. ACBFS is fully utilised as aggregate, principally in asphalt, with well-established experience and specifications. Basic oxygen steel (BOS) slag has in the last few years begun to substitute ACBFS as aggregate in asphalt. The current production of BOS slag is about 1Mt/a, with about 25% being used in asphalt surfacing courses. The material contains a large amount of fine dust, about 40-50% of which is not utilised.

With the increased production of GGBS, there is a need for wide high value applications of the material as cement replacement in concrete and as a binder in hydraulic bound material. There is also a potential to increase the utilisation of BOS slag in asphalt to 60%, instead of 25% currently, with potential markets for the coarse fraction in concrete and the fine fraction in soil stabilisation. The high density of the material causes increased transport costs and limits its economic transport distance. BOS also has a potential to expand in concrete applications but needs to be weathered evenly before use. The biggest barrier to the greater use of the material is however the definition of waste.

Table 3.2 provides a summary of the existing and potential high-value markets for the materials identified in this report.

4 Review of international experiences

4.1 Introduction

There is extensive international experience in the use of alternative and secondary aggregate materials in highway infrastructure. This section presents information obtained from Europe, USA, and other countries. Each section describes some of the experiences within the region based on available data on arisings, utilisation and case studies. Most secondary and recycled aggregate materials have found a range of uses from low value applications through to higher value ones. However, the review focuses more on materials and applications identified in Section 2 to highlight the potential for increased high-value utilisation of alternative materials in the UK.

4.2 Europe

Information on European experiences of using alternative aggregate materials in highway infrastructure was obtained from different sources including informal consultations and published data. The majority of information was, however, obtained from research work and other publications such as:

- ALT-MAT (ALTernative MATerials in road construction), part funded by the European Commission and carried out by a consortium of nine organisations in seven countries (Reid *et al.*, 2001).
- Sustainable Concrete Construction (Conference Proceedings 2002).

Table 3.2 Existing and potential markets for the identified materials

Material	*Existing market*	*Potential market*
CDW:Asphalt planings.	Hot asphalt mixtures (up to 50% replacement). Unbound granular material.	Increased recycling in hot asphalt. Aggregate in concrete.
CDW:Blended aggregate.	General fill and sub-base applications.	Cement bound material and ready mix concrete. Low-strength concrete.
CDW: Recycled concrete.	Bulk fill and capping. Sub-base	Increased level in pavement quality concrete (PQC) pavement. Structural concrete. Fine RCA as sand replacement in trench backfill.
IBA.	Cement and bitumen bound mixtures. Bulk fillMasonry blocks.	Aggregate in asphalt and concrete. Wider utilisation in bound materials and in masonry blocks.
Glass.	Aggregate replacement in asphalt and concrete. Sand for bedding paving blocks. Replacement of sand in general fill applications. Water filtration and treatment.	Increased recycling level in existing markets. Partial replacement of cement in concrete.
Tyre rubber.	Embankment. Fill and drainage applications. Surfacing material.	Noise barrier construction. Thermal insulation. Aggregate in asphalt and concrete.
Plastic.	Limited applications.	Aggregate in asphalt and concrete. Lightweight aggregate. Binder in asphalt.
Fly ash.	Fill and grout applications. Concrete additive. Blocks. Hydraulic binder for earth works.	Hydraulic binder in sub-base, base and PQC. Bricks.
BOS slag.	Coarse aggregate in asphalt (25%).	Increased coarse aggregate in asphalt (60%). Coarse aggregate in concrete. Fines: soil stabilisation.
GGBS.	Cement replacement in concrete.	Increased use in concrete applications. Hydraulic bound material.

- Waste Materials in Construction (WASCON 2000).
- Recycled Materials in European Highway Environments (FHWA-PL-00-025, 2000).

Whilst numerous publications are available on the use of secondary and recycled material in Europe, language was the main restriction in reviewing the data. Generally, it was found that published information and data was more readily available from the USA than from Europe.

The Federal Highway Administration (FHWA) conducted various international review programmes to provide information on state-of-the art technology and the best practices used worldwide. One of these programmes is the Recycled Materials in European Highway Environments with the objectives of reviewing and documenting innovative policies, programmes, and techniques in Europe (FHWA-PL-00-025, 2000). The U.S. delegation met with more than 100 representatives from transportation and environmental ministries, research organisations, contractors, and producers involved with recycled materials in five countries: Sweden, Denmark, Germany, the Netherlands, and France.

The report shows that marketplace factors are dominant, but are generally supported by government policies and regulations such as bans on landfill, landfill taxes and natural aggregate taxes. In the European countries visited it was observed that recycling occurs when it is economical to do so. It is shown that to reduce uncertainty and allow recycled materials to compete with natural materials clear and unambiguous engineering and environmental test methods and performance standards are required. The report highlights the Netherlands as developing and integrating the most successful recycling practices.

4.2.1 The Netherlands

The Netherlands is probably the most advanced country on the use of secondary and recycled materials in road construction. A study visit was conducted during the project to the Road and Hydraulic Engineering Division of the Directorate General of Public Works and Water Management (DWW). It was clearly indicated that the government has developed and integrated the policies, economic tools and regulations needed to increase recycling in highway infrastructure. Table 4.1 shows the production and utilisation levels of alternative materials in various applications, with the exception of dredged soil (DWW-023, 2002). Within the recycled aggregates, construction and demolition waste is highly utilised within the structural layers of road pavements and structural

Table 4.1 Materials production and recycling in the Netherlands, million tonnes per annum (Mt/a) (DWW-023, 2002)

Material	*Production (Mt/a)*	*Recycled (Mt/a)*	*Recycling (%)*	*Applications*
Building waste	16,2	15,3	94%	Road bases; aggregate for concrete.
Soil	10	9,8	98%	Embankments.
Asphalt granulate	4,5	3,15	70%	New asphalt; road bases.
Blastfurnace slag	1,2	1,2	100%	Cement; road bases; hydraulic engineering.
Soil tarra (washed from sugar beets, potatoes etc)	1	1	100%	Embankments; sometimes dikes.
Incinerator bottom ashes	1	0,8	80%	Embankments.
Coal fly ash	0,96	0,96	100%	Cement, concrete, asphalt.
Phosphoric slag	0,55	0,55	100%	Hydraulic engineering; aggregate for asphalt.
Steel slag	0,5	0,5	100%	Road bases; hydraulic engineering.
Smoke gas desulphuring gypsum	0,38	0,38	100%	Building blocks / panels.
Drilling soil (from tunneling)	2,15	0,65	30%	Embankments.
Mine stone (import)	0	0,2	100%	Hydraulic engineering.
Others	3,1	1,9	61%	
Total	41,5	36,3	87%	

concrete. The relatively low recycling level of reclaimed asphalt (asphalt granulate) is due to the presence of tar, which contains the harmful substances phenols and polycyclic aromatic hydrocarbons (PAH) that might leach into the ground water. Recently, the use of tar in road construction was banned in the Netherlands and a number of plants have been built for thermal treatment of contaminated asphalt and soil. It is important to highlight that the cost of treating one tonne of tar asphalt is about one third of the disposal cost.

The Netherlands is a relatively small country with a high population density and shortage of space. These in turn limit the extraction of natural aggregate and landfills. The government policy is to ban landfill of most wastes, through high taxes, and to use financial incentives to promote recycling. For example construction and demolition wastes, which are produced in large quantities, are currently banned to landfill and are considered in high value applications, as shown in Table 4.1.

Informal consultation with DWW indicated that the Dutch practice is not only concerned with the amount of recycling but also the high-value applications of recycled materials. As part of the DUBO (Duurzaam Bouwen/ Sustainable Construction) policy, the government outlined the best use of alternative materials in various reports, directives and guidelines (Structuurschema Oppervlaktedelfstoffen), meaning ‘Structure Scheme Surface Extracted Materials’ as published in www.duborws.nl/kennissysteem/index.

The Dutch government also has a very active role in supporting research and development of specifications and guidelines for using alternative materials. DWW research is mainly focused on the fundamental properties of materials and performance characteristics, based on full-scale testing, to verify laboratory testing and to determine the risks of using alternative materials. The Dutch sustainability policy also emphasises the future recycling of alternative materials and uses life-cycle analysis to give credit and added value to products made with alternative materials.

4.3 USA

Experiences on the use of secondary and recycled materials as aggregates in infrastructure and utility construction and maintenance were obtained from a number of sources including:

- The Recycled Materials Resource Center, University of New Hampshire which provides access to:
  - User Guidelines for Waste and Byproduct Materials in Pavement Construction, Federal Highway Administration, USA. (http://www.rmrc.unh.edu/ Partners/UserGuide/begin.htm)
  - The international conference - Beneficial use of Recycled Materials in Transportation Applications, Washington DC 2001. (http://www.rmrc.unh.edu/ Post2001Conf/overview.asp)
  - The National Cooperative Highway Research Program (NCHRP) Waste and Recycled Materials (WRM) database. (http://www.rmrc.unh.edu/ Resources/PandD/NCHRP/nchrp.asp)
- Texas Department of Transport. 1999: The Year of Recycled Roadway Materials. (www.dot.state.tx.us)

All information was easy to access and well presented. The NCHRP database is very user-friendly providing information on 21 waste and recycled materials for use in transportation related construction applications. The database is divided into nine major categories that are intended to provide the user with both general and detailed engineering and environmental tests to assess the suitability of each WRM for use in transportation related applications as well as recommendations for monitoring WRM field trials.

Table 4.2 indicates the provision in State Department of Transport specifications for the use of alternative highway construction materials. This information has been gained from the NCHRP database. Unlike the UK, there are specifications for the use of PFA, FBA, glass cullet, and scrap tyre in asphalt bound layers. There is even a specification for the use of roofing shingles (scrap bituminous roofing material) in asphalt bound layers.

Table 4.2 USA provision for use of alternative materials in highway works

Application	*Embankment & fill*	*Capping*	*Unbound sub-base*	*Bitumen-bound layers*	*Cement-bound layers*	*Cement-bound base*	*PQ concrete*
Crushed concrete	✓	✓	✓		✓	✓	✓
Reclaimed bituminous materials	✓	✓	✓	✓			
Blast-furnace slag	✓	✓	✓	✓	✓	✓	✓
Steel slag			✓	✓			
PFA	✓	✓		✓	✓	✓	✓
FBA		✓	✓	✓			
Glass cullet	✓		✓	✓			
Scrap tyre	✓			✓			
Roofing shingles				✓			

✓ *Indicates provision in State Department of Transport specifications in one or more States*

4.4 Applications in highway infrastructure

4.4.1 Surfacing and binder courses

Construction and demolition waste (CDW): CDW material is highly utilised in some countries, more than 90% in the Netherlands, in various high-value applications.

An estimated 45 million tons of reclaimed asphalt pavement are produced each year in the USA, with approximately 33% used in hot-mix asphalt production. Texas DOT has extensive experience with the use of reclaimed asphalt pavement and suggested methods to improve the success of its use including minimising the handling and hauling of reclaimed asphalt pavement to maximise its value. Separation by source is recommended where possible and producing a homogenous material from any ‘composite’ piles. Crushing and screening ensure that the asphalt bond is broken as much as possible and eliminates oversized stones.

Glass: Studies in the USA have shown that using mixed colour glass cullet in roadway construction avoids the expense of a sorting process and offers an attractive alternative to aggregate in locations where aggregate sources are scarce and glass cullet is economically priced. Glass cullet has been used in highway construction in the USA as an aggregate substitute in asphalt paving. However, less than 5% of the waste glass produced in the USA has been used in highway construction.

In Switzerland an investigation was carried out to compare recycled glass (crushed glass bottles) to natural aggregate for use in asphalt pavements (Reid *et al.*, 2001). Swiss Standards define the requirements for natural aggregates used in bituminous pavements. Alternative materials have to meet the same quality demands and therefore the same test methods are applied. Mixtures containing 30% of broken recycling glass showed some problems with adhesion between binder and the smooth glass surface. Nonetheless, test results for stability, water sensitivity and rutting lie within the limits for asphalt mixtures. If adhesion could be improved, for example by roughening of the surface, recycled glass could be improved further as an alternative material for asphalt mixtures.

Municipal solid waste incinerator (MSWI) ash: US experience on the use of MSWI ash to substitute primary aggregate in asphalt pavements has indicated satisfactory performance, particularly in base or binder course application. In this application, the ash is used to replace the sand-size or fine aggregate portion of the mixture (NCHRP). Processed ash, if screened to less than 19 mm with the removal of ferrous and non-ferrous metal, can be introduced to replace primary aggregates. From 10 to 25% are normally used in surfacing course applications.

Sludge ash, resulting from the incineration of sewage sludge, has been used in asphalt paving mixtures to replace both fine aggregate and mineral filler size fractions. Sludge ash can also be vitrified to produce a frit (fused material) for use as an aggregate substitute. A number of test pavements have been successfully placed in Minnesota using sludge ash in asphalt mixtures. A plant producing a vitrified frit-like product that was approved by the New York State Department of Transportation for use as a fine aggregate substitute in paving mixtures operated in New York State for approximately 3 years, but it closed in 1995.

Roofing shingles: Roofing shingles are a logical ingredient for hot asphalt mixtures because they are both made of aggregate and bitumen. Roofing shingles incorporated into asphalt paving mixtures not only modify the binder but also, depending on the size of the shredded material, function like aggregate or mineral filler. Organic felt and glass felt particles in particular tend to function like a mineral filler substitute.

In the USA, the Texas DOT ‘Year of the Recycled Roadway Materials’ reports that performance of a one and half mile section of Route 15 near Sparta, New Jersey, constructed with 5% by weight of post-industrial shingles, was ‘very good, comparable to control sections’. Minnesota DOT found a test section containing 9% shingles by weight of aggregate performed satisfactorily. Texas DOT tested two 1000-foot sections, one with 5% post-industrial shingles and one with 5% post-consumer shingles, plus one control section. Pavement sections with roofing shingles did not deviate from the control section in terms of structural integrity. However, roofing shingle appeared to require more bitumen than anticipated, with post-consumer shingles seeming harder to handle than post-industrial shingles. Higher mixing temperatures are recommended to properly coat the material. All these examples demonstrate the potential for the use of this material in asphalt bound layers.

Rubber: Scrap tyres are a major waste for which potential uses are sought. Extensive research has been undertaken on incorporating tyre rubber into asphalt, particularly in North America (including Anderson, 1995; Ayres and Witczak, 1995; Carrick *et al*., 1997; Dutta and Ibadat, 1996; Freeman, 1994; Hanson *et al*., 1994; Maupin, 1995; Rust *et al*., 1994).

Waste tyre has a range of potential and existing uses in highway construction. Ground rubber has been used as a fine aggregate substitute in asphalt pavements. In this process, ground rubber particles are added into the hot mixture as a fine aggregate in a gap-graded surfacing course mixture. Crumb rubber can be used to modify the asphalt binder (e.g. increase its viscosity) in a process in which the rubber is blended with bitumen (usually in the range of 18 to 25% rubber).

Arizona Department of Transportation has over 14 years success using ground tyre rubber in pavements. Their work has shown the following benefits of asphalt rubber (Way, 2001):

- Less reflective cracking.
- Less maintenance.
- More durable.
- Resist truck tyre damage.
- Good in hot and cold climates.
- Less noise.
- Engineering use for old tyres.

Work carried out at Chung-Hua University, Taiwan (Chiu, 2001) using ground tyre rubber in asphalt pavements has indicated promising results. Ground tyre rubber in Taiwan can meet the ASTM D-6114 requirements and could be successfully used in the wet process to produce asphalt mixtures. The initial field data show that asphalt-rubber mixtures performed better than the control mixtures (without rubber), with relatively higher temperatures for mixing and paving. Asphalt-rubber layers in general produced lower noise levels and improved skid resistance.

4.4.2 Pavement quality concrete

Construction and demolition waste (CDW): Texas DOT, USA, has experience with concrete pavement sections utilising 100% recycled concrete aggregates, both coarse and fine. Test results of field trials were very encouraging showing no adverse effects on pavement performance. The risk of alkali-silica reaction was minimised with the use of fly ash as a cement replacement material.

In Australia a series of trials have been carried out to assess the suitability of using reclaimed asphalt pavement in concrete, Dumitru *et al*. (1999, 2000). The results indicated that reclaimed asphalt pavement slightly increased the water demand and reduced bleeding with no effect on air content. The compressive strength and modulus were lower than the control, however, the ratio of flexural to compressive strength was improved with less cracks at early ages. They concluded that the material has a great potential for use in road construction, where both flexural and modulus properties are of importance.

Municipal solid waste incinerator ash (MSWI): Environmental issues are a major concern for the wider utilisation of MSWI in various applications. Work at the University of Fukuoka, Japan (Soeda, 2001) showed ageing and washing of fly ash are important treatments for reducing the leaching of lead and chloride. The compressive strength of concrete containing fly ash was comparable to that of concrete without fly ash, though the values varied slightly depending on the fly ash treatment methods. Both the carbonation depth and chloride content of concrete containing aged incineration fly ash tend to increase as the ash content increases. Corrosion of reinforcing steel was accelerated when the chloride ion content in the fly ash was high. Lead elution from concrete containing aged fly ash satisfied the environmental requirement.

Plastic: In the USA the potential use of recycled plastics as an aggregate is being recognised. As reviewed by Aggregates Information Service (AIS) which is now available from Aggregain (www.aggregain.com), in Massachusetts, the Department of Environmental Protection has issued a Statewide Beneficial Use Determination (BUD) for the use of processed plastic as a substitute for virgin aggregate in cold mix asphalt pavement. It is important to notice that BUD does not consider plastic chips to be solid waste when stored and used in accordance with the permitted specifications.

Conigliaro Industries (www.conigliaro.com) is a US example of one company that is producing lightweight aggregate from recycled plastics. The material is made from various sources including shred and ground plastic computer and electronic housings, mixed flowerpots, and mixed consumer plastics. This plastic aggregate is not used in highway applications at present but is used to produce 'Plas-Crete' wall blocks that use the ground plastics (50% by volume) in place of coarse aggregate in the concrete mixture. The blocks produced are approximately 20% lighter than comparable concrete blocks. It is conceivable that these products could have potential in many lightweight concrete infrastructure applications.

Experiments have been conducted in Italy using plastic material (consisting of 45% PVC, 45% PET and 10% other plastic types) as aggregate replacement in asphalt mixes. A number of tests were carried out in accordance with the Italian specifications (CNR) and gave the following results (Bocci *et al.*, 2000):

- Plastic materials, as replacement for natural stone aggregate, have proved thermally stable at the manufacturing temperatures of hot-asphalt mixes.
- The mixture performs better when plastics are a fine sand (1 mm) replacement and added in the last phase of the asphalt mixing.
- The best form of replacing aggregate with plastics is using the weight of equivalent granulmetric fractions. In this case the volume of plastics introduced is higher than the corresponding aggregate fraction, as the density of plastics is approximately one half that of the aggregate used.

- The maximum value of plastic to be used in asphalt layers is 10% in weight compared to the aggregate mixture.
- Mixtures made in the optimum conditions demonstrated no significant problems in performance and adhesion.

Work in Japan investigating the recycling of waste plastics, mainly bottles of PET, in replacing natural aggregate in lightweight and low-strength concrete applications (Koide *et al.,* 2002). The plastic aggregate was produced by crushing lumps of cooled molten waste plastic (85% PET). The results indicated that, at 100% replacement of aggregates with plastics, the concrete has many advantages in lightweight applications with adequate compressive strength. At lower replacement levels of 35 to 40%, high strength properties could be obtained with a density of approximately 1.8 g/cm^3. In general concrete incorporating waste plastics exhibited high resistance to high temperature (up to 60^{o}C) and freeze thaw.

4.4.3 Base and sub-base

Construction and demolition waste (CDW): The Transportation Research Center, City University of New York, carried out an evaluation of reclaimed asphalt pavement as a graded aggregate in base course applications. The work confirmed that 100% reclaimed asphalt pavement could be used in place of graded aggregate, for low to medium traffic. Reclaimed asphalt pavement was found to have similar stiffness modulus and California Bearing Ratio to graded aggregate. However, permanent deformation properties indicated rutting potential (Baker, 2001).

Municipal solid waste incinerator (MSWI) ash: In the USA it has been found that processed ash can be used as a primary aggregate replacement in base applications. Ash can also be stabilised with portland cement or lime to produce a stabilised base material. MSWI ash has relatively high salt content and trace metal concentrations. If the metals leach or particles become mobile, trace metals or ash particles could be transported in the ambient air, water and soils. This presents some concern over the use of MSWI ash. If fly ash is separated from the bottom ash it will reduce the presence of volatile metals and organics in the ash stream.

Work conducted in Austria for the ALT-MAT project investigated and compared the properties of MSWI, from two sources in Vienna, the Spittelau plant and the Floetzersteig plant, with dolomite aggregate. Several tests were performed according to the Austrian Standard for base and sub-base materials on the MSWI bottom ashes. The MSWI bottom ashes investigated did not fulfil the Austrian requirements for base and sub-base material. An improvement in the mechanical properties of the Austrian MSWI bottom ashes would be necessary to fulfil the present national requirements for sub-base and base applications. This could be acheived, for example, by lowering the amount of the fine fraction (<0.063 mm) to improve the particle size distribution and hence reduce permeability and frost susceptibility (Reid *et al*., 2001).

In Eastern Denmark a road section was constructed in 1993 with MSWI ash as the unbound sub-base layer. The road is heavily trafficked and constructed as follows:

Asphalt wearing course	30 mm
Asphalt concrete	90 mm
Unbound gravel	200 mm
MSWI bottom ash (test section) / natural sand (control section)	300 mm
Boulder clay	Subgrade

Inspection of the road indicated good performance with low values of rutting. The structural condition of the road was relatively good in spite of the fact that the road is heavily trafficked. The bearing capacity, as measured with a Falling Weight Deflectometer (FWD), was however not as good for MSWI bottom ash as for similar natural aggregates (Reid *et al*., 2001).

The leaching tests performed on MSWI bottom ash and the sub-grade material collected at various depths indicated that some salts had leached from the sub-base and migrated into the underlying sub-grade. Only a very limited amount of salts can be leached from the natural sand excavated from the reference site. All the bottom ash samples investigated comply with the current Danish quality criteria for utilisation. The future guidelines are likely to accept the use of bottom ash in pavement sub-base but not under the road shoulder sections.

Two similar sites in France have utilised MSWI ash in road construction at La Teste and Le Mans (ALT-MAT). The city of La Teste is located in the south-west of France. The road investigated is the access lane to the incineration plant of the urban district. The road was constructed in 1976 and was designed as a loop 320 m long and 7 m wide, with traffic of 30 to 40 heavy lorries a day. The MSWI bottom ash produced by the incineration plant has been used in the sub-base layer as an unbound graded aggregate. The thickness of the sub-base layer is estimated to be 400 mm. The base course was limestone unbound graded aggregate 100 mm thick. During the construction, no geotextile was laid between the MSWI bottom ash layer and the underlying natural soil. The road was covered with asphalt surfacing only in 1995.

The city of Le Mans is located in the west of France. The test road is an urban road located on the outskirts of the city and managed by the metropolitan district. The section was constructed in 1978, and was made with a MSWI bottom ash section 430 m long and 10 m wide. It supports traffic of 12,000 vehicles a day, plus a bus route. Heavy lorry traffic is not allowed in this residential area.

The MSWI bottom ash produced by the Le Mans incineration plant has been used in the sub-base layer and as an unbound graded aggregate. The thickness of the sub-base layer is estimated to be 300 mm. The base course was a natural crushed, unbound, graded aggregate 100 mm thick. During the construction, no geotextile was laid between the MSWI bottom ash layer and the underlying natural soil. The road was covered with asphalt mixture 150 mm thick.

The MSWI ash section obtained positive results in several tests (good deflection for a flexible structure, no pollution of the underlying soil, very low leaching, very good bearing capacity, good particle size distribution). These results are even more interesting when it is considered that the material did not undergo any particular preparation before use. Neither the structure designs, nor the technical implementation, were particularly altered for this non-standard material. Moreover, before 1991, MSWI fly ash, which is far more polluting than bottom ash, was not separated from it (Reid *et al*., 2001).

Japanese experience on the use of MSWI ash has indicated that the use of treated bottom ash in pavement base applications produces sufficient strength as compared to primary aggregates. The material satisfies the Japanese environmental standards with phosphate and ageing processes (Shimaoka, 2001). Field trials have shown that the incorporation of MSWI ash in road bases provides sufficient road bearing capacity. Heavy metals have been immobilised and the bottom ashes met the soil environmental standards. Also the fineness of the scrubber residue from MSWI with its pozzolanic properties, contributes to high value application of the material as an admixture for concrete.

4.4.4 Other applications

Construction and demolition waste (CDW): Findings from Swinburne University of Technology in Australia indicated that, in regard to strength, recycled concrete aggregate has engineering properties that make it a suitable substitute for coarse aggregate in the production of concrete. No significant levels of chemical impurities were present in the samples examined and therefore, no abnormal microstructure developed in the concrete. It was evident that the inherent porosity of the recycled concrete aggregate, if utilised and enhanced in a certain manner, could lead to the development of concrete that is sound absorbent. The sound absorption coefficient was, on average, 3.7 times higher than that of the control normal-density concrete. This indicated that there was a link between the porosity of recycled concrete aggregate and the enhancement of concrete's sound absorbent characteristics (Krezel and McManus, 2000).

Rubber: In the USA whole tyres have been used to construct retaining walls. Texas DOT constructed an experimental embankment using tyre shreds as a fill material in El Passo. The embankment consists of 100% shredded tyres covered with compacted soil and appears to be functioning without problem. Shredded or chipped tyres have also been used as a lightweight fill material for construction of embankments.

Plastic and fly ash: Research at the University of Massachusetts and Tufts University (Kashi, 2001), has produced a Synthetic Lightweight Aggregate (SLA); 80% high carbon fly ash and 20% mixed plastic. The SLA is appropriate for a wide variety of geotechnical and concrete applications. Initial evaluations have shown that SLAs pose no significant environmental risk. The production of synthetic aggregates may be a useful application for both plastic and PFA because the resulting aggregate has a wide range of high value applications.

4.5 Comparison between UK and international experiences

This section summaries the main findings from a review of the current Specification for Highway Works (SHW), international and UK experiences, consultations with aggregate producers and other research organisations. It also highlights the potential new materials and high-value applications of recycled and secondary aggregates in highway infrastructure in the UK.

The SHW does not cause an obstacle for the wider use of alternative aggregate materials. There is, however, a potential for additional materials and applications to be considered. Also, recipe specifications and prescribed materials limit the use of alternative materials. The use of end-product performance specifications should enable a wider range of recycled materials to be utilised in highway infrastructure. The requirements of recycled aggregates would not be limited to grading and mechanical strength properties, but extended to cover the overall performance of composites in service.

Construction and demolition waste is produced in large quantities in the UK (approximately 94 Mt/a). UK experience on the use of this material is restricted to the coarse fraction with limited application for the fine fraction. The review indicates the potential wider use of fine aggregate in high value applications. Also the use of recycled asphalt pavement is restricted to asphalt bound materials. This material has a great potential for use in cement-bound and pavement quality concrete by improving flexural and modulus properties.

The UK SHW currently has no specific provision for the use of some alternative materials, which have been permitted in other international specifications. For example, glass and tyre rubber are included in USA specifications for highway works (Table 4.2). Only draft specifications are available in the UK for glass and MSWI bottom ash. The review also indicated the potential use of waste plastics in both asphalt and concrete pavements.

There is also a lack of specification on the use of hydraulic bound materials for base layers. Current research at TRL is looking at introducing slag bound material and fly ash bound material, which could also incorporate coarse secondary and recycled aggregates.

As indicated from the international survey reviewed in Section 3.5, the use of steel and blastfurnace slags, coal fly ash, ground granulated blastfurnace slag and mining waste is well established in the UK market. However, there is limited use of scrap tyres, building and demolition by-products and waste glass. There is great potential for further materials to be utilised in the UK market, such as waste plastic and MSWI bottom ash.

5 Barriers

There are many barriers that could inhibit the wider use of secondary and recycled aggregates. Those considered here are classified into technical, environmental and regulatory barriers. Cost is another important factor influencing the use of alternative aggregates when compared to primary aggregates. Primary aggregate is relatively cheap compared to other construction materials and it is not easy for alternative aggregates to be produced to similar good quality with low costs. The government strategy for sustainable construction has led to the introduction of landfill tax and the aggregate levy, which influence the cost balance. In this section, the main technical, environmental and regulatory barriers are highlighted, with possible methods to overcome them.

The main barriers to the use of alternative aggregates, as reviewed by Reid and Chandler (2001), are:

- Lack of suitable specifications for new methods and materials.
- The difficulty of balancing supply and demand for alternative materials.
- Concerns over the reliability and quality control of new methods and alternative materials.
- Perceived problems with new methods and materials, either personally or relayed via the press or colleagues.
- A lack of awareness of the possibilities and of successful applications of new methods and materials.
- Concerns about pollution of the environment through leachate or dust generation.
- Conditions of contract which do not encourage innovation or flexibility.
- The complexity of the waste management licensing system and the potentially long timescale required to obtain licences and exemptions.
- The perception that new methods and materials will be more expensive than traditional ones.

However, the relative importance of these barriers to potential users of the materials varies substantially between the particular materials under consideration. A generic distinction may be drawn here between recycled and secondary aggregates, in that there tend to be fewer barriers associated with using recycled aggregates than for secondary aggregates, because the recycled materials' characteristics tend to be more familiar to users in the construction industry. For this reason, the barriers for recycled aggregates also tend to be easier to overcome because the associated risks are generally easier to characterise, which in turn instils more confidence in the users that the material will be fit for purpose. For example, in respect to pollution of the environment through leachate production or dust generation in use, it is unlikely that there would be a concern associated with using clean crushed recycled concrete in unbound road applications over and above those associated with conventional aggregates. However, this would be a cause for concern if incinerator bottom ash was used for the same application (see Section 5.2 for further discussion).

Most of the barriers are related to the development of new materials and methods, which indicates the long timescale required for them to be accepted by the different stakeholders of highway infrastructure. The problem becomes more complicated with the lack of end-performance specifications, and therefore the comparison between alternative and conventional materials is based on long-term performance monitoring, which is sometimes not available for new materials and applications.

The following sections discuss the main technical, environmental and regulatory barriers. The technical aspects restricting the use of new materials have been discussed for each material to highlight specific barriers to potential high value applications. The environmental and regulatory barriers are however discussed in a more general way because many of the issues are common for different secondary and recycled aggregates.

5.1 Technical barriers

By discussing the availability of materials, locations, existing and potential markets, this section provides information on the high-value utilisation of the identified alternative materials and the main technical issues restricting their uses.

5.1.1 Construction and demolition waste

The properties of CDW are mainly related to its composition, which in turn is based on the source. Crushed concrete, bricks and reclaimed asphalt from clean sources, i.e. of uniform composition such as concrete slabs from road and airfield pavements, can easily be used to replace natural aggregate in various applications. However, the presence of contamination in the forms of wood, plaster, anhydrite, aerated concrete, soil, aluminium, tar, glass, plastic and chloride can adversely affect the quality of CDW, providing constraints on its wider high-value utilisation (RILEM Report 22, 2000).

Segregating and processing could take place either on site (mobile plant) or in crushing plants (fixed plants). Processing and haulage costs mainly influence the utilisation of CDW, and could make it less competitive than primary aggregate unless high-value applications are identified.

BRE Digest 433 (BRE, 1998) summarises the relevant requirements of crushed concrete and brick for different applications and provides a classification in terms of brick content, aggregate density, and the maximum permissible level of impurities and other foreign materials. Recycled concrete aggregate with a relatively low content of brick and impurities was defined as the highest quality material, whereas crushed brick was defined as the lowest quality.

A considerable amount of research has been carried out on the re-use of CDW, particularly that arising from road constructions (Sherwood, 2001), which has led to its inclusion in the SHW for various applications. It is important to highlight that the SHW limits the content of fine material, masonry, asphalt and foreign materials for use in PQC.

The review shows that CDW has a great potential for more efficient use within the construction industry. Coarse RCA can be used as aggregate for concrete including high-grade applications. There is also a potential for a higher market price for CDW fines due to their hardening properties. Separation of CDW fines could contribute to more dust generation, however, this effect could be minimised when carried out in controlled environments. Using CDW fines will reduce the environmental impacts associated with portland cement in terms of emissions, energy consumption and resource depletion.

5.1.1.1 Recycled concrete aggregate

Recycled concrete aggregate (RCA) has a potential to replace up to 100% of natural aggregate in PQC. The properties and amount of the hardened mortar surrounding the aggregate along with the nature of the source aggregate mainly influence the quality of RCA. The surrounding mortar in RCA possesses different properties to that of natural aggregate, being more porous with high alkali content. For RCA replacements up to 20% by weight of natural aggregate, there are almost no variations in compressive strength of concrete made with the same water/binder ratio. Strength reductions of between 20 to 30% occur at 100% replacement level.

RCA could offer improved properties when compared to primary aggregate in the construction of concrete pavements. The surface texture and particle shape of RCA result in a higher ratio of flexural to compressive strength making it more suitable for concrete pavement than other smooth rounded aggregates. However, the porous nature of RCA increases the water demand to achieve similar workability to primary aggregate and, to some extent, adversely affects the density, modulus of elasticity, porosity, shrinkage and thermal deformation of concrete.

Prakash and Krishnaswami (1998) conducted an experimental investigation to assess the suitability of coarse RCA for pavement quality concrete. The strength and workability of conventional aggregate concrete were found to be better than that for recycled concrete aggregate. However, the shortcomings of RCA in workability and strength were overcome with the use of a chemical superplasticiser, resulting in higher compressive, tensile and flexural strengths compared to natural aggregate concrete.

A full recycling regime has been developed in Vienna in the reconstruction of 120 km of carriageway on the concrete motorway to Salzburg (Sommer, 1998). The old concrete pavement was crushed and processed into two fractions; coarse (4-32 mm) and fine (0-4 mm). The coarse RCA was used to replace 64% of the natural aggregate for the production of the new concrete pavement. The surface texture of the RCA enhanced the bond with the cement matrix and resulted in higher flexural strength than that of quartz gravel concrete with similar water/cement ratio. The risk of higher shrinkage of the RCA concrete was reduced with good curing and the use of longitudinal joints at an early stage of construction. Case study A3-Appendix A, provides an example of the Austrian experience with the use of recycled aggregate.

Whilst RCA has a great potential for use in concrete pavement, there are some concerns about the long-term durability of RCA in structural concrete. These are mainly due to the porous surrounding mortar of RCA that affects the ability of concrete to resist the ingress of deleterious materials such as chloride, sulphate and carbon dioxide. Another durability issue is the additional alkalinity of RCA making it more susceptible to alkali-silica reaction (ASR). With a lack of data on the long-term performance of RCA, the material has been classified from a precautionary viewpoint, as highly reactive (BRE Digest 330, 1999; Concrete Society TR30, 1999), which limits its uses.

TRL is currently undertaking a research project for the Highways Agency to investigate the use of RCA in structural concrete, such as for bridges. By reviewing the susceptibility of RCA to ASR, Hassan (2003) highlighted that this conservative approach of classifying RCA as highly reactive acts as a disincentive to developing further use of the material in high-value applications. Some natural aggregates, or minerals within natural aggregates, have an initial low alkali contribution, but may supply over time significant amount of alkalis to the concrete pore solution. Also the porosity of RCA should contribute to the reduction of ASR expansion and hence reduce its susceptibility to ASR in a similar manner to that of porous aggregate, and air entrained concrete.

Under suitable conditions with available moisture, high alkalinity and reactive silica, there is a risk of ASR reoccurrence if ASR had previously damaged the concrete. Cuttell *et al*. (1997) reported signs of localised areas of ASR with widespread distress in concrete pavements constructed with RCA from old concrete suffering from ASR. According to Stark (1996), this risk could be much reduced by the use of low-alkali cements and cement replacement materials such as fly ash. It is also believed that roller compacted concrete could be made with low cement content, thus providing new applications for materials susceptible to ASR with reduced risk.

5.1.1.2 CDW fines

Whilst coarse CDW is permitted by many specifications for various applications in highway infrastructure, there is still a need to develop a high-value market for the CDW fines. The fine CDW fraction, passing 5 mm sieve, is mainly considered to affect adversely concrete properties by increasing the water demand and levels of contamination. In many instances, separation of coarse and fine CDW is not considered due to cost implications and the material is used in low-value applications. Therefore, there is a need for a better understanding of the material behaviour and potential high-value applications.

In Germany, Winkler and Mueller (1998) carried out an experimental study to examine the effect of brick, masonry and concrete fines on the hydration and strength development of mortars. The materials were ground to a fineness similar to that of portland cement and used to replace up to 60% by weight of cement. Brick powder replacement of up to 20% was found to improve workability with a slight reduction in strength, less than 10%. X-ray diffraction results indicated reduced amounts of portlandite in mortars due to additional pozzolanic reaction between metakaolin in the bricks and portlandite from the hydration of the cement. No signs of pozzolanic reactions were detected for the masonry powders, which therefore gave lower strength values. The hardening properties of the concrete powder were related to its fineness; when ground to a high fineness, it improved the workability and strength of mortars. The pozzolanic activity of crushed waste-clay bricks has also been reported by Toledo-Filho *et al*., (2001). By replacing 20 to 42% of the cement by powered brick waste, the brick concrete gave higher compressive strength than for portland cement at all replacement levels.

RCA fines were also used as the main binder to produce low-strength cementitious composites in Sweden (Karlsson, 1998). RCA from a residential building in Gotebory had been separated into fine and coarse fractions. The fine RCA fraction was ground and mixed with a surface activator additive and then mixed with coarse RCA and sand. With a ground RCA fines content of 350 kg/m^3, the resultant composite gave a 28-day compressive strength of 2.8 MPa.

Dutch experience on the use of CDW fines indicated potential use as fine aggregate in concrete. At the same effective water content, replacement of river sand with recycled sands did not affect the workability of the fresh concrete in an adverse way, but improved the bleeding characteristics. Full replacement of river sand with 100% washed CDW fines, or 25% unwashed material showed only a slight reduction in strength (Van der Wegen and Haverkort, 1998).

The fine RCA fraction was successfully used with cement to stabilise granular sub-base; case study A3 - Appendix A. Sommer (1998) highlighted that old sub-base often does not contain enough fines to produce a strong cement-bound material. The stabilised sub-base was covered with a thin layer, 50 mm, of asphalt before placing the concrete pavement and no problem with reflected cracking has been reported.

5.1.1.3 Reclaimed asphalt pavement

Reclaimed asphalt aggregates have been traditionally used in low-grade fill applications. SHW permits the use of up to 50% of the material in base and binder courses, and up to 10% in the surfacing course. There is, however, a limited use of the material in cement-bound material and pavement quality concrete. Developing a wider range of high-value applications will contribute to a more efficient use of the material with economic benefits.

Austrian experience on the use of 10% reclaimed asphalt pavement as aggregate in concrete indicated excellent strength and durability. However, for the Salzburg project (Sommer, 1998) a higher replacement level of 35% was used for the hard shoulder, with economic benefit compared to imported natural gravel. Reclaimed asphalt pavement was found to adversely affect the strength properties of concrete. However, the use of a chemical admixture and cement replacement material reduced the water requirement to achieve similar strength levels to that of concrete without asphalt aggregate.

Stabilisation of tar bearing material was conducted in the Salzburg-Vienna motorway project (Sommer, 1998). In some sections the old construction used tar-bound sub-base below the concrete pavement. Tar contains harmful substances, phenols and polycyclic aromatic hydrocarbons (PAH), that might leach into the ground water. The new construction involved mixing tar-bearing material with granular material and stabilising with cement that prevented leaching. The binding efficiency of naphthalene contaminant was found to be more efficient with the use of special cements than portland cement. The special cements contained adsorptive constituents, which are not identified.

5.1.1.4 Crushed bricks

Brick can be reclaimed from demolition and reused in conservation work and for new build in conservation areas (CIRIA, 1999). This is, however, not an easy task due to the bonded mortar which is difficult and time-consuming to remove and which may damage the brick. In such situations, the bricks can be crushed and reused as demolition waste. Crushed bricks are weaker than crushed concrete with higher porosity values, but they still have a potential for high value applications in the concrete industry. Zakaria and Cabrera (1996) studied the performance and durability of concrete made with crushed bricks and artificial fly ash-clay aggregates. Both aggregates were found to produce concrete with moderately high strength and to contribute more to the strength development at later ages. This was attributed to the pozzolanic effect of the burnt brick, in agreement with other researchers (Schulz and Hendricks, 1992; Winkler and Mueller, 1998).

5.1.2 Incinerator bottom ash

Technically, processed IBA has a potential for various applications in highway infrastructure. However, there are some considerations of chloride and sulphate contents when used in concrete. The main barrier to use is related to environmental issues of potential pollution. As reviewed by CIRIA (CIRIA C513, 1999), BS 6543 (1985) provides little guidance on the use of MSW residues, except identifying them as a possible source of contamination. IBA was classified as a material that would require measures to protect against leaching (CIRIA Report 167, 1997). The material therefore has more potential for use in cementitious and bituminous bound applications, with reduced leaching potential.

Laboratory and field studies were carried out to investigate the use of grate IBA to substitute aggregate in asphalt binder course (Karpinski *et al.*, 2000). The relatively higher porosity of IBA aggregate required additional bitumen content, however, both asphalt mixtures with and without IBA showed identical performance. The tensile strength, resilient modulus and thermal stress properties were similar for both aggregates at different temperatures.

Paine *et al*. (2000) carried out a laboratory investigation on the use of unprocessed (raw) and processed IBA as cement-bound material (CBM) sub-bases in pavements. For the same cement content, processed IBA gave higher strength than raw IBA, however, both ashes required more cement than primary aggregate to achieve the 7MPa strength requirement of CBM2. The tank-leaching test indicated higher levels of cadmium, copper and potassium in IBA mixtures, but below the limits of UK environmental and drinking water quality standards.

Research in Germany (Westiner *et al.*, 2000) indicated the importance of the dimensional stability of hydraulic bound material containing IBA, in addition to strength and durability. This is mainly because of the possible additional expansion due to ASR, sulphate attack, and the presence of aluminium and free calcium. A steam cycles test was developed to accelerate these processes and examine the expansion of different qualities of IBA and binders.

Dutch experience (Mulder, 1996) indicated the possibility of using MSWI fly ash, after treatment, in high-value applications, such as road bases. The treatment involved a combination of washing and stabilisation with cement and other additives. Washing resulted in removing >90% of the cadmium and chloride, and >50% of zinc and sulphate. The leaching characteristics of the stabilised material satisfied the requirements of the Netherlands specifications. In contrast, unwashed fly ash did not meet the specifications. It is important to highlight that in the Netherlands, the processing costs of washing and stabilisation were equal to the costs for disposal of the material.

An example of the use if IBA in cement bound material is given in case study A4 - Appendix A.

5.1.3 Glass

Crushing of waste glass produces particles that are generally angular in shape with some flat and elongated particles. Proper crushing can virtually eliminate sharp edges and the corresponding safety hazards associated with manual handling of the product. Consistency of supply is one of the key issues regarding the technical applications for recycled glass. Glass can be crushed to large sizes (more than 5 mm) and small sand sizes (less than 5 mm) and can contain a proportion of contaminants. Larger-sized recycled glass has a high 'flakiness index', which may limit its applications, whereas the smaller sand sized particles have the greatest prospect as an aggregate replacement in asphalt and concrete pavements (WRAP, 2003). There are currently no accepted standards for glass in terms of its physical and chemical properties.

The main technical problem with the use of glass in asphalt courses is the adhesion between the bituminous binder and the smooth glass surface. Flat and elongated particles can contribute to pavement ravelling and stripping. Poor skid resistance, high tire wear, and excessive glare limit its use in the surfacing course of roads. Asphalt anti-stripping agents can be used to improve the bond characteristics with glass particles (Texas Department of Transport, 1999). The material has wider utilisation in base and binder courses. Based on laboratory investigation and full-scale road trails, Nicholls and Lay (2002) reported that macadam could be successfully manufactured with 30% of the coarse aggregate replaced by crushed glass. The bond between glass and the bitumen binder slightly reduced the indirect tensile stiffness modulus but without any detrimental effect on the performance of the mixture.

The use of crushed glass in concrete has another durability concern, similar to that of RCA, due to alkali-silica reaction (ASR). The amorphous silica in glass reacts with the alkalis of cement forming expansive products of silica gel, leading to concrete cracking and premature deterioration. This problem can be reduced or even overcome with the use of low alkalis binders, such as low alkali cement and cement replacement materials but greater technical understanding of glass behaviour in the concrete environment is still needed.

Polley *et al*. (1998) investigated the effect of partial replacement of fine aggregate by glass on the strength and performance characteristics of concrete. Results indicated that up to 20% replacement of fine glass, 75 mm to 1.5 mm, had no adverse effects on the strength properties of concrete, when compared to a control concrete mixture made with natural aggregate at the same water content. Coarser glass particles, >1.5 mm, however, result in poor compressive strength due to unfavourable shape and surface characteristics. The strength development of the glass concrete was initially slow but proceeded at a faster rate at later ages to give higher strength than the control concrete at 1 year. This feature indicates the possibility of additional pozzolanic reaction in glass concrete, similar to that of fly ash. Durability aspects as assessed by freeze-thaw testing and ASR showed promising performance, with the potential for fly ash to mitigate ASR. Glass was also used in the manufacture of lightweight aggregate by mixing powdered glass with an expansive agent and heating at 880°C (Ducman *et al.*, 2001). A porous aggregate was produced with a relatively high water absorption value of about 11%. The aggregate was highly reactive in the mortar alkalinity but did not cause either expansion or cracks due to the accommodation of the gel within the porous structure of the aggregate.

Research on glass concrete has indicated that the expansion due to ASR is dependent on the glass particle sizes, content, type and colour (Jin *et al*., 2000). For clear soda-lime glass with 10% replacement of fine aggregate maximum expansion occurred for sizes between 1.18 to 2.36 mm. Mortars containing finer glass sizes, ≤ 100 μm, exhibited similar expansion to the control mortar without glass. Also, the maximum expansion was found to shift towards smaller sizes with increasing reactivity from clear soda lime to Pyrex and fused silica, with the highest for amorphous silica. The expansion of the mortar bars, made with clear glass, was found to be directly proportional to the glass content, with no pessimum content. Interestingly, the expansion due to ASR was found to be strongly dependent on the glass colour. The colour of glass is normally obtained by adding certain oxides to the glass melt, such as Fe_2O_3 for amber and Cr_2O_3 for green colour. Clear glass was the most reactive followed by amber. Green glass however caused no expansion, with a potential use, when finely ground, as an inexpensive ASR suppressing admixture.

Waste glass has also been used in a more added-value application as a partial replacement of cement in concrete. Shao *et al.* (2000) found that ground soda lime glass finer than 38 mm exhibited pozzolanic behaviour when mixed with lime and cement. Concrete mixtures were made by replacing 30% of the cement with ground glass and then compared to portland cement, fly ash, and silica fume concrete mixtures. The glass concrete gave relatively higher strength than the portland cement concrete at 90 days, with a 50% reduction in expansion due to ASR. When compared to fly ash concrete, the glass concrete gave higher compressive strength at both early and late ages, indicating improved pozzolanic reaction.

5.1.4 Rubber

Rubber has been successfully used in the USA in asphalt mixtures. As reviewed in Section 3.3.4, the use of rubber in asphalt has many advantages of increased elasticity with greater resistance to cracking and deformation under traffic loads and lower noise. However, there is limited use of rubber in the UK due to the relatively small quantities of material available, lack of specification and knowledge on material performance, and variability within the rubber constituents and properties.

Rubber also has a potential use in concrete as aggregate replacement. The elastic nature of rubber particles acts to allow the concrete to withstand large deformations, delay crack widening, and prevent sudden failure compared to plain concrete (Toutanji, 1996). Topcu and Avular (1997) used a three phase composite material model to determine the elastic modulus of concrete made with fine and coarse rubber aggregate. Rubber aggregate tends to decrease the strength properties of concrete, with more reduction in compressive strength than flexural strength. The reduction of strength makes the material less attractive in the construction industry, and therefore more research is needed on optimising the mixture design and the use of admixtures to improve strength. The improved elasticity and deformation properties of rubber concrete may make it suitable for use in crash barriers on roads.

5.1.5 Plastics

CIRIA Report C513 (1999) summarises the constraints on the use of plastics as limited experience, lack of specifications, inconsistent properties, lack of warranties for recycled products, lack of government/industry investment, high costs of collection, processing and transport, and potential hazardous leaching. Nevertheless, the material has been used in various applications including geogrids or separation membranes, soil stabilisation, sheet piling, pipes, noise barriers, asphalt binder and aggregate replacement in concrete and asphalt pavements, as well as lightweight concrete.

Successful applications were reported on the use of both shredded and pelletised waste plastics to replace some of the natural aggregate in asphalt mixtures (Zoorob and Suparma, 2000; Bocci, 2000). The results indicated improved performance of asphalt due to increased strength and resistance to deformation.

Replacement of natural aggregate in concrete is, however, associated with reduction in strength, (Hooper, 2002; Rung, 1996; Sowerby, 2002). The use of chemical admixtures is therefore recommended to reduce the water demand and compensate for the strength loss. The low density of the plastic makes concrete more suitable for lightweight applications. One of the main issues about using plastic in composite is the poor bond with the cementitious matrix due to its surface characteristics. Hooper (2002) and Koide (2001) found that the plastic particle shape and size could vary widely and significantly influence the properties of concrete. It has been reported that the bond characteristics can be improved by chemically treating the plastic prior to its use (Naik *et al*., 1996, Shehata 1996 and Schroeder 1994).

Plastic packaging waste was mixed with fly ash to produce engineering composites with various applications within the construction industry (Todd, 1996). The engineering properties indicated that the composite is viscoelastic, with behaviour similar to that of bituminous mortars which can support substantial load without failure but large deformation. The composite exhibited very low porosity and permeability with suitable non-structural applications in paving blocks, footpaths, kerb units, fence posts, and crash barriers.

5.1.6 Fly ash

A good example of the efficient and competitive use of alternative materials is coal fly ash. This material was formerly regarded as a waste with no high-value applications. The recognition of pozzolanic properties, however, added more value to the material as a partial cement replacement in concrete, with improvements in workability, heat of hydration, and long-term performance. Fly ash has been widely used in innovative industrial products, with its main high-value application in the concrete industry. Cabrera and Woolley (1985) reported that the twenty-five year strength properties for fly ash concrete were much better than that of portland cement concrete with excellent durability performance.

The current production of fly ash is about 5Mt/a with large stockpiles of about 55Mt. Fly ash has varying physical and chemical properties and the governing factor for the use of fly ash in concrete is national and international standards, which can sometimes cause obstacles to the wider use of the material. Other by-products include furnace bottom ash and the desulphurisation residues, which are fully utilised in the UK in the manufacture of mainly blocks and plasterboards, respectively.

The properties of fly ash have been changed within the last decade to reduce the emission of nitrous oxides (NO_x) using low combustion systems. Incomplete combustion of fly ashes results in higher carbon content. The use of co-combustion materials, such as wood chips, bone meal, municipal sewage sludge, paper sludge and petroleum coke, results in different forms of carbon with varying properties. Limits on carbon content in fly ash are considered as a mandatory requirement in specifications, measured as loss-on-ignition. Some co-combustion materials such as petroleum coke contain higher levels of contaminants than coal, such as nickel and vanadium, and this can lead to the perception that fly ash is a toxic waste material.

Hassan and Page (2001) reviewed the effect of high carbon fly ash on the properties of concrete. Carbon occurs in several distinct forms with varied pore structures and pore sizes that are not distinguished by the standard LOI test. These carbon forms affect the concrete properties to different degrees and consequently it is technically inadequate to state the adverse effect of carbon without identifying the carbon type and properties. This is the main technical barrier facing the wider utilisation of fly ash currently produced in the UK and there is a need for more research to overcome this problem.

There is no doubt that the continuing use of fly ash in high-value applications, such as cement replacement material, contributes to the efficient use of the material, enhances the use of other secondary and recycled materials and the development of new applications, case study A4. Fly ash reduces significantly the susceptibility of RCA and glass to ASR in concrete, as discussed earlier. The material also has a great potential for use with the relatively recent developments and applications in road construction in the UK, such as hydraulic bound materials and roller-compacted concrete. Successful case studies with good performance have been reported on the use of fly ash bound material, also know as GFA (granular fly ash) in sub-base and base layers in the A52-Staffordshire (Sear, 2001) and the A259-Ramsgate (Walsh and Williams, 2002) and as a slow hardening trench reinstatement material (Kennedy, 2002).

5.1.7 Slags

From a technical point of view, the use of granulated blastfurnace slag (GBS) as aggregate in bound applications has many advantages. The relatively porous nature of the material with the rough surface texture improves the bond characteristics at the aggregate/binder interface, resulting in higher flexural strength and improved performance characteristics. Grinding blastfurnace slag into ground-granulated blastfurnace slag (GGBS) increases the processing costs but with more value for use as cementitious binder. The use of GGBS in concrete also has many advantages of enhanced durability, increasing frost resistance and reducing the risk of alkali-silica reaction.

With the increased production of GGBS, there is a need to widen the application in the UK market. Blastfurnace slag has been successfully used in other countries in hydraulic bound material. This application is relatively new in the UK and the main barriers are lack of specifications and knowledge on material application and behaviour. Slag bound material (SBM) makes use of the cementitious properties of GBS when activated with lime and gypsum and is used in base applications. The material is know as grave-laitier in France, and has been used since the 1960s with several successful applications. SBM has many advantages of reduced costs, early trafficking, and reduced susceptibility to deflection cracking, when compared to cement bound material. An example on the use of SBM in road construction is given in Appendix A, case study A5. TRL is currently reviewing national and international experiences to develop a design guide on the use of the material within the structural layers of pavements.

Basic oxygen steel slag (BOS), produced from steel making, is mainly used as aggregate replacement in asphalt mixtures. The reduced production of air-cooled blastfurnace slag has provided more opportunities for wider utilisation of the material. The material is relatively non-porous and has a higher density and crushing value than blastfurnace slag. This might increase the transport costs, but the material provides improved resistance to abrasion and skidding resistance for surfacing course applications (Roe, 2003). The material is permitted by the SHW for all granular and bitumen bound applications, but not in cement bound and PQC.

BOS contains a considerable amount of fine dust, about 40-50%, and the producers are looking for wider applications for the coarse material, and new applications for the fine BOS. The main technical barrier on the use of BOS in concrete is the tendency of the material to expand due to the presence of free magnesium and calcium in moist environments. In most applications, the slag needs to be weathered before use to minimise the dimensional instability of the material. However, the nature of expansion is not fully understood and there is a need for more research to investigate the possibility to compensate for the shrinkage of concrete.

There is also a small quantity of non-ferrous slag produced at localised areas in the UK with potential use in road construction (BRE Report 423, 2001). These include by-products derived from the manufacture of copper, aluminium, nickel, phosphorus, lead, and zinc. Preliminary research at BRE indicated the potential use of zinc slag as partial replacement of sand in PQC. There is, however, some concern about the long term durability and environmental issues associated with the use of non-ferrous slag.

5.1.8 Summary of technical barriers

Table 5.1 provides a summary of the main technical barriers reviewed above with methods to overcome these barriers for all identified materials.

5.2 Environmental barriers

5.2.1 Risks associated with leaching

One of the most problematic aspects of using alternative materials relates to characterising and controlling their leaching properties. In this report, the leaching properties of a material describes the complex physico-chemical process by which pollutants may potentially enter watercourses from the construction where they are used. Whether the pollutants that enter watercourses by this method cause harm depends largely on the proximity of sensitive receptors (e.g. humans, habitats) and whether the pollutants are able to reach the receptors via a viable pathway. In evaluating the risks posed by materials used in highway construction applications, three dimensions are important:

- The intrinsic hazard associated with a given material (e.g. high metal content, high pH, etc.). These characteristics of the material may cause difficulties if they are dispersed into the environment by leaching. For example, high concentrations of metals such as copper or zinc may cause damage to vegetation or agriculture on the land surrounding the road, or a high pH might adversely affect fish in adjoining water courses if the leaching hazard is realised.
- The potential for the hazard to be realised (e.g. use in unbound applications is more likely to result in leaching because of the greater opportunity for water ingress, and the chemical speciation of any contaminant may affect its mobility, etc.).
- The characteristics of the receiving environment where the material is used.

Table 5.1 Summary of technical barriers and methods to overcome them

Material	*Technical barrier*	*How to overcome*
Coarse RCA.	Increased water demand and lower strength in concrete. Susceptibility to alkali-silica reaction.	Use of chemical admixtures. Use of cement replacement materials and low cement content (RCC).
Fine CDW.	Increased water demand and levels of contamination.	Chemical admixtures in bound applications. Pozzolanic properties-binder replacement.
MSWI bottom ash.	Contamination. High contaminant levels.	Use in bound applications. Wash and use in stabilised applications.
Glass.	Adhesion with bitumen in asphalt. Alkali silica-reaction in concrete.	Use modified binders, or avoid surfacing layers. Use of cement replacement materials and low cement content (RCC). Pozzolanic properties-binder replacement.
Rubber and plastic.	Lack of specification and knowledge on material performance.	More research aiming at high value applications.
Fly ash.	Varying properties with high LOI. Lack of specification on hydraulic bound material.	More research on the effect of carbon type on concrete properties. Development of new applications of hydraulic bound materials and RCC.
Blastfurnace slag.	Lack of specification on hydraulic bound material.	Increased understanding of material properties and performance.
Steel slag.	High density-increased transport costs. Expansion in concrete.	High value application in surfacing course to offset the high transport cost. More research on the nature of expansion.

It is the variability in the characteristics of the receiving environment and differences in the potential for the hazard to be realised that make it very difficult for environmental regulators to give general agreement for the use of such materials. Each usage of materials may need to be evaluated on a case by case basis to evaluate whether the risk posed by leaching is tolerable. In sensitive locations, the regulators may need to request site-specific and material-specific tests to ensure that excessive concentrations of pollutants do not accumulate, causing environmental damage.

However, it is also important to consider that the same principles apply to natural materials as to alternative aggregates. Natural materials may also cause leaching effects. For example, some mudstones can generate an iron-rich, acidic leachate, characterised by deposits of hydrated iron oxides as an orange precipitate. For this reason, it is important to be aware of the composition and hence the leaching properties of all materials used in highways, not just those of alternative aggregates.

A number of methods have been used to assess the risk to controlled waters associated with using such materials in construction applications. These are reviewed in:

- CIRIA Report 167 (1997).
- Environment Agency R & D Publication 20 (Environment Agency R & D 20 1999).
- ALT-MAT (Reid *et al.*, 2001).

In the CIRIA method cited, leaching tests were carried out and then the products were classified into three groups in terms of the risk they represented. This was an evaluation of whether the material's leaching of a restricted set of contaminants was likely to breach EU water quality standards. The results for the alternative materials were compared with limestone with DoT Type 1 grading, which was used as a control in the leaching tests. On this basis, the results were classified into three categories for use, depending on the leaching risk posed by the unbound material:

- Gp.1 = unrestricted use of the by-product.
- Gp.2 = some restrictions may apply for unbound materials.
- Gp3 = some restrictions will apply to unbound material.

The report focussed on unbound applications of the materials, rather than when used in the manufacture of bound materials such as asphalt. It was largely concluded that the by-products in the report posed no hazard to controlled waters if used in bound applications. The leaching tests only included a limited range of pollutants, and did not include a range of potential organic contaminants (the study only included monohydric phenols).

The Environment Agency has produced an alternative to simple laboratory testing to evaluate the risk of leaching associated with alternative materials in construction uses (Environment Agency R & D 20 1999). This uses a modelling methodology for setting targets for remediation of contaminated land, which can be applied to the use of alternative materials (Reid and Chandler, 2001). It is a risk assessment methodology based on a tiered source-pathway-receptor analysis. The method is entirely site-specific, and cannot provide generic limiting values for the permitted concentration of contaminants in groundwater and surface water.

In the ALT-MAT project, a model to evaluate the risk posed by using alternative materials in transport infrastructure has been developed. The model is also site-specific and is based on evaluating an 'allowable increase' in the concentration of contaminants in groundwater where the materials are used (Reid *et al.*, 2001). The 'allowable increase' relates to legislative water quality objectives. To generate the most robust results, leaching tests should be carried out (e.g. pH-static tests) and the results used to model the effects of leaching, in order to evaluate the risk posed by the use of the materials.

It has been observed that leaching is largely influenced by the pH developed in the material where it is used. For this reason, Reid and Chandler (2001) have recommended that if the pH is likely to change over time, that leachate quality predictions should be made on the basis of pH-static tests at an appropriate pH, to account for such variations.

Where adverse leaching properties are likely to be an issue in using alternative materials in a project, it is possible to minimise the risks by using two strategies (Reid and Chandler, 2001):

- Source-based methods seek to remove contaminants that might cause leaching at source, to prevent future leachate formation. For example, metals can be removed from incinerator bottom ash using magnets.
- Pathway-based methods seek to prevent the contaminants from finding a pathway to a receptor, thus preventing a risk being realised. For example, ensuring that the road uses a low permeability pavement material such as asphalt, to prevent water ingress.

However, many such measures can increase the financial costs associated with using alternative materials. This leads to a need to consider the feasibility of using the materials on a strictly case by case basis.

5.2.1.1 Additional considerations for specific materials

Tyre rubber has been the cause of some concern in respect of leaching, mainly because of the intrinsically high concentration of metals and organic materials. Tyre rubber (rubber crumb) fell into category 1 (CIRIA Report 167, 1997). Another recent review found that rubber crumb gave rise to no serious leaching despite utilising leaching tests designed to maximise the release of species i.e. more aggressive conditions than would be expected in use (CIRIA Report C513 1999).

Incinerator bottom ash has a very high pH when it has just been produced and with time this is reduced with hydration to less alkaline values, which reduces the mobility of contaminants (Reid and Chandler, 2002). The material should be aged before it is used in earthworks to address the need to reduce the material's pH, as well as for other technical reasons discussed earlier. Incinerator bottom ash was classified into category 3, according to the CIRIA method (CIRIA Report 167, 1997). The material has also been known to cause fish avoidance from streams (CIRIA Report 167, 1997). When the material is used as fill, reactions including oxidation, hydration and carbonation of minerals may occur over time, which will affect the pH of the material. Where this is likely, it has been recommended that predictions of leachate quality be made on the basis of pH-static tests at the appropriate pH, since the pH of the material largely influences the mobility of contaminants (Reid and Chandler, 2001)

Fly ash has been considered unlikely to cause problems with water pollution in previous evaluations (British Standards Institution, 1985). It tends to have a naturally high pH, which reduces with weathering (CIRIA Report C513 1999). There are some concerns under investigation in respect of the dioxin and polycyclic aromatic hydrocarbon content and its potential to leach into watercourses, particularly where co-combustion materials have been used such as wood or sewage sludge pellets (Sear, 2001).

Slags have been classified in Group 1 using the CIRIA report leaching test (CIRIA Report 167, 1997). Environmental impacts associated with use of these materials are rare and can usually be attributed to bad practice and inappropriate use. The most common form in use is ground granulated blast furnace slag (GGBS); a cementitious binder. The report showed that no serious leaching effects occurred using steel slag, although some restrictions should be made when using electric arc furnace slag as an unbound material in road construction (CIRIA Report C513 1999). Slags tend to have a very high pH when they have just been produced and with time this is reduced with hydration to less alkaline values, which reduces the mobility of contaminants (Reid and Chandler, 2001). The material should be aged before it is used in earthworks to address the need to reduce the material's pH, as well as for other technical reasons associated with dimensional stability. However, slag materials should also not be used if they have been left for a long time, since they may be of an unknown history and possibly contaminated with other materials. In particular, the problems of disintegration following internal sulphate attack are well known (CIRIA Report C513 1999). However, slag generally contains less than 1% total sulphur, most of which is unavailable for leaching as it is bound up within the aggregate. Therefore the potential leaching is minimal, although the material should not be used in areas with poor drainage (BRE IP/18/01, 2001).

Glass is comprised largely of silica, a major constituent of sand. Any leaching problems are caused as a result of failure to remove materials at source. For example, in sources from the municipal waste stream, lightweight materials such as paper must be removed to minimise such risks. A good washing and screening process is required to affect this. Similar arguments will apply for *plastics.*

Leaching potential from *construction and demolition waste* would need to be determined on a case by case basis, depending on its constituents. Broadly, a distinction is often made between a coarse fraction and fines (<5 mm). The fines fraction is thought to be a cause of leaching problems, including high values for chloride and sulphate content. It is possible that this may be addressed by separating the fines from the coarse fraction, thus allowing the wider use of the coarse fraction by reducing the risk of leaching from the fines. However, this material stream is most likely to be affected adversely by the presence of putrescible materials such as timber, which should be separated at source, ideally controlled by rigorous quality control procedures.

5.2.2 Potential to generate dust

Dust is defined as small solid particles in the range 1-75 µm (microns) in diameter. Above this size, particles would be classified as grit (ODPM, 2000). Particles up to 100 µm enter the body during breathing but it is only the very small particles below about 10 µm (known as PM10) that can reach deep into the lungs. Although airborne dust can cause physical discomfort (e.g. eye and throat irritation) this is normally associated with levels of exposure in the occupational environment (i.e. on-site). Dust rarely reaches levels necessary to give physical discomfort off site.

Stationary sources of dust include material crushing, screening and segregation plant and conveyor transfer of material. If dust is not collected or controlled it is easily dispersed. In terms of mobile sources, dust arising from open areas of a site or uncontrolled sources such as stockpiles and material spillages is difficult to measure and control. The sources of dust from various operations are summarised in Table 5.2.

A key consideration for construction sites to be classed as a 'good neighbour' by residents and other businesses is the ability to control dust, and it is therefore also a central concern of local planning authorities. There are two key concerns to investigate for alternative materials:

- Whether the material is physically likely to cause a dust nuisance (related to its density and how finely divided the material is).
- Whether the dust is likely to be more harmful than the corresponding primary materials it replaces, thus increasing the potential to cause more harm to the environment and human health if it is inhaled or otherwise widely dispersed.

Table 5.3 describes the potential effects of dust on receptors (people) and environmental resources.

The most effective way of mitigating dust problems is to minimise the dust becoming airborne at source. This is best done at the design stage by enclosing plant and/or by the addition of moisture. Although other fugitive dust is less easily controlled, good housekeeping and effective management can make significant contributions.

For example, measures to prevent PFA from becoming airborne at Musselburgh Ash Lagoon have included:

- If necessary stopping all operations until the likelihood of a 'dust blow' passes.
- Nominating a 'dust suppression operative' responsible at all times for ensuring the monitoring of exposed surfaces and to activate dust suppression measures as necessary (ODPM, 2000).

Enclosures can help eliminate wind entrainment of dust and therefore provide an effective method of minimising propagation from source. For example, temporary enclosures can be constructed using sheet material such as plywood on scaffolding or masonry (ODPM, 2000).

Dust may also be suppressed by using fine water spray directed into dust clouds. The effectiveness can be further improved by adding a chemical wetting agent to the water. In prolonged dry weather the frequency of watering will need to be increased (ODPM, 2000).

In the case of alternative materials, good site practices should control the generation of dust, in exactly the same way as they do for primary materials. There is no *a priori* reason why dust generation should be an insurmountable problem for any material.

5.2.2.1 Additional considerations for specific materials

Having made these general statements, only one of the materials is anticipated to need extra care in handling to avoid dust generation. *Fly ash* may cause increased pollution of the atmosphere from dust in comparison with natural pozzalanic materials like clays, because of its lower density. However, this should be easily controlled using standard good practice to reduce dust generation on construction sites. In addition, its lightweight characteristics are often an advantage in certain construction projects and in the manufacture of certain aggregate-derived materials, such as bricks (CIRIA Report C513 1999).

5.2.3 Health and safety

Health and safety issues are related to either physical or chemical properties of materials. They are linked to the probability of certain hazards posed to human health associated with the processing and use of alternative materials being realised. Broadly, since health and safety

Table 5.2 Some causes of dust generation on handling alternative materials

Operation	*Potential scale of impact*
Segregation and storage of material at source.	Generally low because material is fairly large sized.
Collection of material and loading for transport .	Generally low if material is handled carefully.
Transport of material.	Low if material is sheeted or wet.
Segregation of material at point of processing.	Variable impact (increases with degree of handling).
Deposition of segregated material for storage .	Variable impact (increases with size of stockpile).
Processing of material (screening and crushing).	High impact.
Grading of processed material into different product sizes.	High impact (depends on moisture content).
Deposition of processed material for storage.	High impact (depends on method of deposition).
Collection of alternative aggregates and loading for transport.	Fairly high impact/vulnerable to wind blow.
Transport of alternative aggregates to supply.	Low if well contained and sheeted or wet.
Transport of unwanted material.	Low if well contained and sheeted.

Table 5.3 Potential effects of dust on receptors and resources (ODPM, 2000)

Receptors/resources	*Potential effects*
People at home.	Health effects if very small particles. Nuisance through surface soiling.
Industry requiring clean conditions.	Nuisance through surface sealing. Effects in clean processes.
Landscape.	Loss of visual amenity through deposition.
Nature conservation.	Covering of the leaf surface, resulting in shading and consequently reduction in net photosynthesis, altered pigment levels and/or reduced productivity. Blocking of stomatal pores to prevent them from fully functioning. Alteration of leaf surface chemistry which may affect disease resistance. Addition of nutrients from the dust which may lead to increased growth and/or deficiencies. Changes in pH levels over time if the dust has different pH conditions to surrounding soils.
Water environment.	Creation of a surface film on still water bodies. Increase in suspended material in water courses. Knock-on effects on aquatic ecology.
Air quality.	Increased atmospheric particulate concentrations.
Cultural heritage.	Surface soiling.

legislation applies equally to alternative and primary materials, there is no reason to suppose that alternative materials are intrinsically more dangerous to human health than primary materials. However, there is likely to be more experience of characterisation and mitigation of such hazards in the case of primary materials, simply because there is more experience of using the materials generally. This implies that alternative technologies and methods of working are required to reduce the risk associated with using alternative materials to an acceptable level. These techniques may be entirely new in themselves, creating a knowledge gap in the industry and a requirement for research and development. This may discourage operators from using the material, simply because of the time required to learn about or conduct some research to create such methods, which will inevitably require some investment.

5.2.3.1 Additional considerations for specific materials

There are some difficulties to overcome in this respect with using *glass* materials in highway construction activities. Currently there are no standards for crushing glass for aggregates, and the manufacture of aggregates from this material stream poses a number of safety issues, relating to sharp hazards. The main difficulties faced in processing are:

- Ensuring that broken bottles do not get into processed product.
- Ensuring that the sharp edges are removed so that the product does not pose a hazard in use either to operatives laying the material or to the public.

In use, glass can also become de-bonded from the surface, causing cuts and tyre damage. Increased glare from road surfaces can be a visual hazard. However, glass is unlikely to be used as coarse aggregate in surface layers in the UK.

5.3 Regulatory barriers

Informal contacts with aggregate producers highlighted the Environment Agency interpretation of the definition of waste as one key barrier to the use of alternative and secondary materials. The associated costs with additional paper work and management to acquire waste licences or exemptions increases the cost of the material thus making it less competitive.

The main area of legislation affecting the use of these materials is the waste management licensing regime. The main objective of the waste management licensing system is to ensure that waste management facilities:

- Do not cause pollution of the environment.
- Do not cause harm to human health.
- Do not cause serious detriment to the amenities of the locality.

The complexities of the legislation and the constantly changing interpretation of waste definitions mean that it is always worth contacting the regulator early in the preparation of a project. Waste Management is carefully controlled and regulated. Those handling alternative materials which have been classified as waste need to know their legislative obligations. Broadly, the main considerations are:

- There are legal definitions of the circumstances in which materials are treated as waste for the purposes of legislation and interpretation can be difficult.
- Licences may be needed even for the storage of waste.
- Planning permission may be needed for temporary storage of waste, operation or recycling plant and final disposal.
- Carriers of waste must be registered with the Environment Agency.
- A Duty of Care under criminal law obliges producers of waste to ensure its safe disposal or treatment.

The Environment Agency provides advice and guidance on any uncertainties with obligations for England and Wales.

The legislative basis for waste management licensing is provided in Part II of the Environmental Protection Act 1990 and associated regulations. The legislation defines the circumstances where waste management licences are required, the time period for the determination of the different types of application, the criteria for the rejection of applications and the appeal provision. The other key legislative sources affecting the system are:

- The Waste Management Licensing Regulations 1994 (as amended).
- The Environmental Protection (Duty of Care) Regulations 1991.
- The Controlled Waste Regulations 1992 (as amended).
- The Special Waste Regulations 1996 (as amended).
- The Pollution Prevention and Control Act 1999.
- The Pollution Prevention and Control (England and Wales) Regulations 2000.

Pollution Prevention and Control provisions are unlikely to apply to alternative materials unless they are classified as 'hazardous waste'.

Some activities are exempt from waste management licensing, and are listed in Schedule 3 to the Waste Management Licensing Regulations. None of these exemptions apply to wastes controlled under the Special Waste Regulations. Exemptions include (ICE, 1997):

- Keeping (storing) waste where it is produced pending its collection.
- Gathering together and temporarily storing small quantities of waste in connection with its collection for disposal elsewhere, not necessarily at the place of production.
- Concrete, brick and tile crushing, where this is regulated by local authority air pollution control.
- The deposit of wastes including soil and rock in connection with land reclamation.
- The manufacture of certain building materials (including roadstone and aggregate), soil or soil substitutes from certain wastes, including construction and demolition waste.
- Storing waste in connection with these activities.
- The secure storage of moderate quantities of certain waste articles, for example architectural salvage, if they are destined for recovery.
- Storing construction, demolition or excavation waste where it is to be used for construction, either after work has begun or for three months before it starts (repeating the effect of the existing exemptions under the 1988 regulations).
- Storing road planings at any site provided they are to be used for construction.

It is likely to be more difficult to determine the regulatory requirements for materials that have physical or chemical characteristics that are difficult to characterise because of natural variations in the material. This requires that the regulator is supplied with reliable information on which to base such risk assessment. This is likely to be a significant issue for all of the materials discussed in this report. This is a potential difficulty with all the materials discussed, if quality assurance systems cannot reliably characterise the materials.

Reid and Chandler (2001) have proposed a flow chart to enable the industry to determine whether a waste management licence is required for the use of alternative materials in a specified application, Figure 5.1.

A key criticism of the current regulatory system for waste management has been that the same criteria are not used to judge the suitability of materials for use in construction projects across the country. This has led to the observation that there are inconsistencies in the application of the waste management licensing regime in respect of alternative materials (Barritt, 2003). The main source of such confusion surrounds whether materials are treated as wastes or raw materials, and thus whether they are subject to control under the legislation. A second consideration is whether the materials, if they are treated as wastes, will qualify for one of the exemptions.

The interpretation by the Environment Agency of when a recycled material ceases to be waste has changed recently in response to cases in the European court. Previously, when a secondary or recycled material had been subject to a recovery process such that it could be used in construction in the same way as a natural aggregate, it would generally no longer be considered as waste. Thus, for example, construction and demolition waste that had been processed to conform to the Specification for Highway Works requirements as recycled aggregate would no longer have been considered waste. However, the new interpretation is that the material remains a waste until it has been placed in an engineering structure, e.g. as sub-base or aggregate in concrete. This has major implications, especially for materials whose processing is not covered by existing exemptions, such as tyres. The Environment Agency has recently issued a statement that a waste management licence will be required for all storage and processing of tyres, a condition that did not apply before. This will have a serious effect on attempts to use tyres as recycled materials in construction, by imposing additional costs and burdens in comparison to natural aggregates. The issue of the definition of waste and the application of the waste management licensing regulations to secondary and recycled aggregates is probably the most important barrier to their greater use in construction, and needs to be addressed as a matter of urgency.

A further consideration is the uncertainty as to whether an alternative material will be considered suitable for use. This may also be a factor inhibiting engineers from considering using such materials. While there is the advantage of administrative certainty by using blanket statements about the suitability of alternative materials in certain construction uses, the actual characteristics of the receiving environment will vary from site to site. It is difficult to imagine that the same environmental protection standards will be able to be applied across a geographical area, since the regulator's prime responsibility is to safeguard the environment, human health and amenity. If

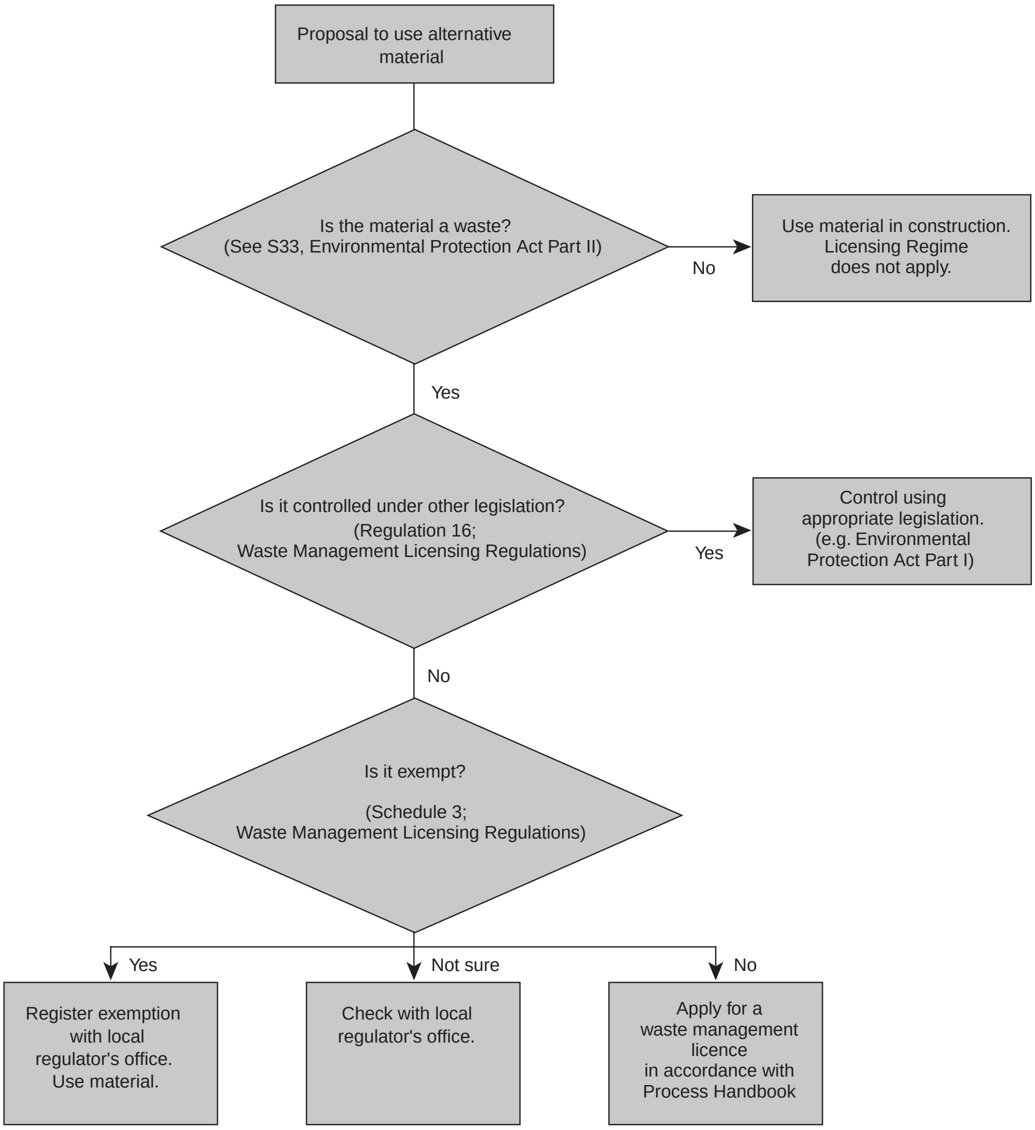

Figure 5.1 Flow chart for the application of waste management licensing regime to transport infrastructure in England and Wales

material decisions were not made on a case by case basis, the regulator could be expected to err on the side of caution in providing generic guidance, to ensure the protection of the most sensitive environments. This could lead to a lower use of alternative materials than might be the case otherwise. However, the 'case by case' argument applies equally to existing primary materials as it does to alternative materials. There is certainly a case for providing a 'level playing field' for alternative materials, so that there are no additional barriers to their use in comparison with primary materials.

Thus a tension exists between the need for certainty that alternative materials will be acceptable for certain engineering uses and the need to consider the specific characteristics of the environment where the materials are used. This requires consideration and resolution, if the use of these materials is to be encouraged.

6 Material lifetime and future recycling

When considering environmental aspects and costs in use associated with material lifetimes there are two distinct methods of analysis, Life cycle assessment (LCA) and Whole life costing (WLC). LCA considers cradle to grave issues associated with a material from initial source to final disposal, whereas WLC only considers the service-life.

LCA differs from a process-specific or site-specific assessment, as it includes a number of processes that may be carried out in different geographical areas or at different times. The objective is to document energy and materials use across the whole life cycle of a product or service. It involves procedures to evaluate the environmental burdens associated with products, processes, or activities by identifying and quantifying energy and raw materials used and wastes released to the environment. The process takes account of the entire life cycle of the product, process, or activity, encompassing extraction and processing raw materials, manufacturing, transportation and distribution, use, re-use, maintenance, recycling and final disposal.

Whole life costing is a process that aims to look at 'every cost incurred in respect of a facility or product from inception to disposal', i.e. the total costs associated with the procurement, use during service-life and disposal at the end of life. The objective is to make investment decisions with an understanding of the consequences of different initial decisions. Ideally, costs should include not just the direct costs of constructing and maintaining a facility but also the costs imposed on the environment (e.g. users, society in general, etc.) by its use and operation. For example, whole life costs of road pavements comprise the costs of constructing and maintaining the pavement, the costs to road users (e.g. cost of time, accidents, fuel consumption, etc.) and costs to the society (e.g. cost of the impacts of noise, and other emissions). For most facilities, it is difficult to identify 'end of life' and evaluations are based on a fixed period that takes account of major cost consequences of the initial choice (e.g. 40 years for road pavements). The Discount Rate (the current rate of 3.5% for infrastructure projects is being reviewed by the Treasury) also influences the choice of a realistic analysis period. Additionally, to enable a fair comparison of alternative products or options with different patterns of spend, the Residual Value at the end of the analysis period is a key element of the process. For example, the value at the end of the analysis period will be influenced by the recyclability of the materials.

LCA and WLC are evaluated with the use of often sophisticated modelling techniques, utilising computer programmes that combine and evaluate set parameters and conditions. Hinet and Netstrat are two network level deterministic whole life cost models, used to evaluate pavement maintenance requirements and present optimised maintenance strategies for the Highways Agency trunk and motorway network in England. COMPARE is a whole life cost model used to produce optimal pavement designs based on whole life costs. Current research is looking to develop probabilistic approaches to network modelling based upon Monte Carlo simulation and Markov Tree analysis to analyse condition and deterioration based upon probability distribution curves, and to produce an integrated model to combine the whole life costs of individual components. Similar models exist for the evaluation of tunnels, earthworks, bridges and drainage.

The demonstrated 'value' of secondary and recycled materials can varying depending on which criteria are used in its assessment, and this uncertainty is a key barrier to the use of secondary and recycled aggregates. Individually, WLC and LCA techniques cannot comprehensively cover all financial, environmental, and social costs and benefits associated with the use of alternative aggregate or material choices. Multi-criteria assessment (MCA), however, provides a methodology that combines both approaches. A comprehensive MCA framework incorporating WLC and LCA tools taking account of the economic, environmental and social issues could enable prioritisation of the alternative options available and is an important step in lowering this barrier. This assessment would be further aided by a greater understanding of the long term performance of secondary and recycled aggregates.

6.1 Cost of material

The initial cost of a material is a major factor in any decision on its use. There are various factors that affect a material's cost, mainly availability, processing costs, transport costs and incentives.

Material availability significantly effects the price of an aggregate. The large amount of primary natural aggregate available results in a low price. In comparison, the relative scarcity of some secondary and recycled materials results in a higher price due to economies of scale. Variability in the material quality and consistency has a direct impact on the performance of the material and therefore its cost. The whole life costs associated with products that use secondary and recycled aggregates will depend upon the characteristics of the products, the use being made of them and the required performance. For example, some secondary and recycled aggregate sources yield material that is 'sub-standard' compared to primary aggregates, and these may require greater processing and handling than primary aggregates or the use of additives etc., to make them acceptable for use. The location and subsequent transport costs are one of the most significant factors in using any material. Natural primary aggregate is available in many locations and in large quantities thus reducing the transport costs. Many secondary and recycled aggregates are produced in either a few locations or in many locations but in relatively small quantities. This would result in either long journey distances or multiple journeys to provide the same quantity as a primary aggregate. Governments in a number of European countries have acted to encourage increased use of recycling. This may be in the form of defined maintenance policy (e.g. mandatory requirement to recycle a minimum percentage of existing materials) or more direct economic instruments. For example, the UK Government has acted to adjust the economic balance in favour of recycling by means of economic instruments such as the aggregates levy that make the price of aggregates better reflect the true social and environmental costs of quarrying and encourages use of alternative and recycled aggregates.

6.2 Performance of materials

This project focuses on the high value utilisation of alternative materials in cementitious and bituminous applications and the performance and service life when included in these composites is considered in this section. Generally, the performance of composite construction materials can vary widely depending on the quality of its constituents, the mixture proportions and the way in which it is handled, placed, compacted and cured. When the composite is in service, loading and exposure environment play important roles in controlling the long-term performance and service life. Figure 6.1 shows an illustration of the performance of a pavement, i.e. the resistance of a particular pavement to deterioration when subjected to traffic loading and the environment. This performance function is a logical way in which to assess service life because it considers the intrinsic properties of the material, traffic loading, and surrounding environment.

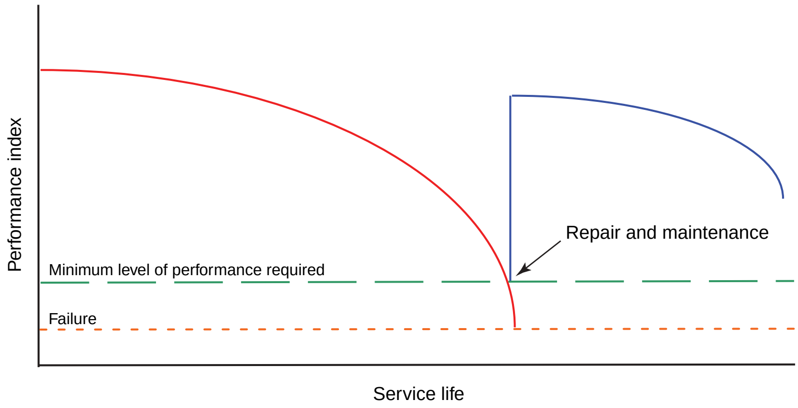

Figure 6.1 Performance-life function of pavements

The performance of pavement materials tends to decline with time due to many factors. Fatigue and structural deformation under traffic loading are the main cause of deterioration. Deterioration can also occur due to failure within the materials themselves, such as hardening and bleeding of the binder in asphalt and differential movements, penetration of harmful salts, and reactive aggregate in concrete. Most of these deterioration mechanisms appear in the forms of distresses and cracks followed by pavement disintegration. At a minimum performance level, before failure, the pavement reaches its service life, where repair and major maintenance are necessary.

The current Department of the Environment, Transport and the Regions pavement design standards are described in Volume 7 of the Design Manual for Roads and Bridges (DRBM). For whole life cost considerations, it has been stated that:

> *'A minimum whole life cost for a new pavement is generally achieved when a design life of approximately 40 years is assumed. For this reason, the standard design life for all types of pavement, with appropriate maintenance, is 40 years. An important factor is the degree to which future maintenance is likely to cause disruption.'*

The design life was established by considering the performance and long term monitoring of a wide range of asphalt and concrete pavements and practical experience on the use of, mainly, conventional construction materials.

The use of alternative materials is relatively new in construction with lack of information on the material behaviour and long term performance. This explains the difficulty of assessing the material lifetime of secondary and recycled aggregate when used in pavements. In order to support the wider and efficient use of alternative materials and to provide a fair comparison with conventional materials there is a need for:

- Developing accelerated testing to assess the long-term performance of alternative materials.
- The use of end-performance specifications, where links between material properties and performance could be established.

6.3 Design for recycling

It is often difficult to deal effectively, in environmental terms, with construction components that were originally designed without any consideration of their ability to be recycled in the future. As a consequence of this lack of forethought, materials can be difficult to reuse and may be hard to separate. A relevant example is the difficulty in characterising the CDW material stream and reusing components or materials from the stream in high specification applications. For this reason, an element of design that requires consideration but which is often neglected in highway infrastructure is the design of pavements to maximise the opportunity to recycle materials in the future. This is known as 'Design for Recycling', and has two main components:

- Making strategic decisions about the type of material recycling systems to be encouraged in highway infrastructure.
- Choosing materials wisely in new product design, since they become part of the material recycling system later.

The material recycling system could be characterised in two ways; closed-loop and open-loop. Closed-loop recycling involves the reuse of materials to make the same product over and over again. An example in road infrastructure would be the recycling of road planings into new road asphalt. The alternative is open-loop recycling, which reuses materials to produce different products. An example here would be reusing glass bottles after processing as an aggregate in asphalt or in concrete. The preferred mode of recycling will depend on the particular material stream, but in general, closed-loop recycling is preferable. This is mainly due to having better control of issues such as quality control, because the material characteristics are more easily defined and controlled.

Graedel and Allenby (1998) have proposed a number of simple rules to follow, in order that the potential for recycling in future can be maximised in industrial systems. Using these principles, it is possible to make some recommendations for maximising the potential to recycle materials used in road infrastructure:

- **Minimise the use of materials**. Advanced materials with better structural characteristics and better design guidance may allow less material to be used to achieve the required stiffness and load bearing characteristics.

- **Minimise the materials diversity** (i.e. the number and type of materials used). Material selection should be optimised across road infrastructure to limit the variety of materials incorporated, in order to maximise the opportunity to reuse materials in the future.
- **Choose desirable materials**, which have recycling potential as well as good manufacturing and use characteristics. A key recommendation here is to use recycled or low environmental impact materials as far as possible.
- **Eliminate unnecessary product complexity**. If too many different types of material with different properties are used in road infrastructure, it becomes more difficult to characterise the material to be recycled.
- **Make products efficient to disassemble and make the materials easy to recover**. If necessary, it should be possible to separate materials for recycling in future. Trace impurities and hazardous components may prevent future recycling.

In addition to this list, they have formulated some specific guidance for minimising environmental impacts from industrial products by choosing materials more effectively. Traditionally, these choices have been made with regard to cost, aesthetic appearance, structural performance, compatibility with other materials used and durability. However, since environmental criteria are also important in material choices, the following principles should be followed:

- Choose abundant, non-toxic, non-regulated materials if possible. If toxic materials are required in manufacturing, try to generate them on-site instead of having them formulated elsewhere and transported. Transporting toxic materials should be minimised to reduce the risk of accidental releases.
- Choose materials that either are natural or mimic natural materials as far as possible.
- Choose materials for which recycling at the end of life is feasible and for which a recycling infrastructure exists.
- Design for minimum use of materials in products, processes and product use.
- Use materials from recycling streams rather than from primary material extraction.

7 Conclusions and recommendations for future work

This report provides a review of the high-value applications of secondary and recycled aggregates in highway infrastructure. Information was obtained from various sources including specifications, current UK and international experiences, and consultations with aggregate producers and other research organisations. Based on this review, the following conclusions and recommendations for future work can be offered.

7.1 Conclusions

1. The use of secondary and recycled aggregates in highway infrastructure is increasing, but predominantly in low-value fill applications. There is a potential for optimising their use in high-value applications, such as cement and asphalt bound layers.
2. The specification for highway works (SHW) permits the use of a wide range of secondary and recycled aggregates in various applications. There is, however, a potential for new materials and applications to be considered.
3. SHW currently has no specific provision for the use of some alternative materials, which have been permitted in other international specifications, such as glass and rubber that have provision in USA specifications. There is also a lack of specification on the use of hydraulic bound materials using fly ash and slag bound materials, for base layers in road construction.
4. The use of recipe specifications and prescribed materials limits the use of alternative materials. Secondary and recycled aggregates may possess different intrinsic properties to those of primary aggregate; however, this may not be reflected in their overall performance in service.
5. Lack of knowledge on material performance characteristics and their behaviour in composites, together with the lack of end-performance specifications constitute the main technical barriers for the use of new materials and applications.
6. Examination of UK and international experiences indicated a number of materials, which have potential for higher-value applications but at present have either limited or no such utilisation in the UK. These include construction and demolition wastes, incinerator bottom ash, glass, plastic, and tyre rubber as alternative aggregates.
7. Recycled aggregates from construction and demolition wastes constitute the largest material arising but their current use is not fully optimised. The susceptibility of recycled concrete aggregate to alkali-silica reaction could be minimised by reducing the cement content in concrete and the use of cement replacement materials.
8. There is a great potential for optimising the use of the fine fraction of construction and demolition waste and glass by exploiting their hardening/pozzolanic properties in cement bound applications.
9. Waste plastic and rubber are produced in relatively small quantities but have the potential to improve the deformation properties of concrete and asphalt mixtures.
10. The main barrier to the wider use of incinerator bottom ash (IBA) is related to environmental issues with potential pollution. However this could be minimised by use in cementitious and bituminous bound applications. A draft specification for the use of IBA has been produced by the Highways Agency.

11 Environmental risks associated with the use of alternative materials are largely restricted to characterising and controlling their leaching properties. Their use in bound applications should reduce their leaching potential.

12 The EA interpretation of the definition of waste and the associated licensing issues is the key regulatory barrier to the use of alternative aggregates. Measures resulting in confident characterisation of the risks posed by materials would aid the regulator in determining whether the materials fall within licensing exemptions.

13 A multi-criteria assessment framework to enable prioritisation of the alternative options available for secondary and recycled materials, considering economic, environmental and social issues, is an important step in increasing the understanding of the relative value of these materials in relation to that provided by primary aggregates.

14 Lack of knowledge on the long-term performance of new materials and applications restricts the prediction of the expected service life. There is a need for more accelerated testing and the use of end-performance specifications.

15 Improved design for future recycling could be achieved with enhanced material selection and optimising the quantities and diversity of materials used.

7.2 Recommendations for future work

A number of recommendations can be made where further research and development is required to support the wider and more efficient use of secondary and recycled aggregates and help overcome the technical, environmental and regulatory barriers to the use of new materials. These recommendations can be listed as follows:

7.2.1 Specifications

1 Development of *end-product performance* specifications to enable a wider range of recycled materials to be utilised in highway infrastructure.

2 Development of design guidelines and specifications for *new applications* such as hydraulic bound materials and roller-compacted concrete.

3 Development of guidelines on *the most appropriate use of alternative materials* to support the use of high quality materials, such as recycled concrete aggregate and granulated blastfurnace slag, in high-value applications.

7.2.2 Technical

4 *Innovative research* investigating the fundamental properties of aggregate that influence its performance in composites, such as optimised mix design and the aggregate/binder interface.

5 Establish a comprehensive bank of data on the *long term performance* of alternative materials used in service that would enable a reasonable comparison with primary materials and the prediction of material lifetime.

6 To develop *accelerated testing* methods and validate them to full scale field-testing for the prediction of material lifetime.

7.2.3 Environmental and regulatory

7 The exemptions for *waste management licensing* and the *definition of waste* generally, should be reviewed with a view to providing simpler guidance to the industry and encouraging the use of new materials in infrastructure.

8 Encouraging the use of secondary and recycled materials in *bound applications* would not only provide added value but also minimises the environmental impacts due to leaching.

9 The environmental regulator (the Environment Agency) and material producers should agree *codes of practice* for the use of the secondary and recycled aggregates. This will remove some uncertainty about when projects using new materials are likely to be given approval, which will remove some of the financial risk incurred by developers due to abortive discussions with the regulator and/or potential remediation work required later.

10 Investigate and determine acceptable limits for the *environmental impact* of primary materials as a standard, to provide a reasonable comparison for alternative materials. There is no *a priori* reason why alternative materials should be considered more likely to cause environmental harm than conventional materials if the relevant quality, health and safety and environmental standards are enforced consistently for all materials used.

11 Development of *quality assurance* systems to provide confidence in material characterisation enabling appropriate environmental risk assessment.

7.2.4 Material lifetime

12 The financial costs or benefits associated with using new materials are poorly characterised over the life cycle of projects. A *multi-criteria assessment* framework methodology may enable these risks and opportunities to be evaluated more comprehensively.

13 Better understanding is required of the application of *'design for recycling'* principles and related life cycle approaches for materials used in highway infrastructure. This will require a critical review of current practice using these principles, to ascertain how the industry can make better use of existing resources to minimise life cycle environmental impacts.

7.2.5 Others

14 All of this advice will need to be *disseminated* widely to the industry and updated regularly to reflect best practice. This will require adequate funding to be set aside for this purpose.

8 Acknowledgements

The work described in this report was carried out in the Sustainable Construction Group of the Infrastructure Division of TRL Limited. Tony Parry was the Quality Audit and Review Officer. The authors are grateful for the financial support of DTI/WRAP and the research management of Mervyn Jones at Davis Langdon Consultancy. The help of aggregate producers in providing information during consultations, and the valuable comments and input of Douglas Boden, Richard Grey, Murray Reid, John Chandler, Cliff Nicholls and Victoria McColl of the TRL/Viridis team are gratefully acknowledged.

9 References

Anderson C (1995). *Asphalt resurfacing structural research, construction report*. Iowa, USA: Department of Transportation..

Atkinson V M, Chaddock B C and Dawson A R (1999). *Enabling the use of secondary aggregates and binders in pavement foundations*. TRL Report TRL408. Crowthorne: TRL Limited.

Ayres M J R and Witczak M W (1995). *Resilient modulus properties of asphalt rubber mixes from field demonstration projects in Maryland.* Transportation Research Record No. 1492, USA.

Baker R F (2001). *Evaluation of reclaimed asphalt pavement and recycled concrete aggregate as a dense graded aggregate base course*. Beneficial use of Recycled Materials in Transportation Applications, Washington DC 2001. (Retrieved: 2003 from http://www.rmrc.unh.edu/Post2001Conf/overview.asp)

Barritt J C (2000). *The future of recycled aggregates in sustainable construction*. Presentation at CIRIA Seminar on Sustainable Waste Management – costs and benefits for construction. London.

Barritt J C (2003). *Overcoming barriers to recycling*. Paper presented at the 2nd International Conference on 'Addressing government sustainability and recycling targets for construction and related industries'. Liverpool: John Moore University.

British Board of Agrément. *Technical approvals for construction.* (Retrieved: 2003 from www.bbacerts.co.uk)

Bocci M, Colagrande S and Montepara A (2000). *PVC and PET plastics taken from solid urban waste in bituminous concrete*. Proceedings of WASCON Conference 'Waste Materials in Construction', Harrogate-UK. Elsevier Science Ltd, pp. 186-195.

BRE Digest 330 (1999). *Alkali-silica reaction in concrete: Parts 1-4*. Watford: Building Research Establishment.

BRE Digest 433 (1998). *Recycled aggregates*. Watford: Building Research Establishment.

BRE Information Paper IP/18/01 (2001). *Blast furnace slag and steel slag: their use as aggregates*. Watford: Building Research Establishment.

BRE Report 423 (2001). *Use of non-ferrous metals industry wastes in construction*. Watford: Building Research Establishment.

British Geological Survey (2001). *United Kingdom minerals yearbook 2000*. (Retrieved: 2001 from www.bgs.ac.uk).

British Standards Institution, London.

BS EN 14227-2: 2001. Unbound and hydraulically bound mixtures. Specifications. Part 2: Slag bound mixtures. Definitions, composition, classification. Draft for public comment.

BS 882: 1992. *Specification for aggregates from natural sources for concrete.*

BS 1047: 1983. *Specification for air-cooled blast furnace slag aggregate for use in construction.*

BS1377: Part 4: 1990. *Methods of test for soils for civil engineering purposes.* Compaction related tests.

BS1377: Part 9: 1990. *Methods of test for soils for civil engineering purposes. In situ* tests.

BS 3892: Part 2: 1996. *Pulverized fuel ash.* Specification for pulverized fuel ash to be used as a Type 1 addition.

BS 4987: Part 1: 2001. *Coated macadam (asphalt concrete) for roads and other paved areas.* Specification for constituent materials and for mixtures.

BS 6543 (1985). *Guide to use of industrial by-products and waste materials in building and civil engineering.*

BS 7533: Part 1: 2001. *Pavements constructed with clay, natural stone or concrete pavers*. Guide for the structural design of heavy duty pavements constructed of clay pavers or precast concrete paving blocks.

BS 7533: Part 2: 2001. *Pavements constructed with clay, natural stone or concrete pavers*. Guide for the structural design of lightly trafficked pavements constructed of clay pavers or precast concrete paving blocks.

BS 7533: Part 3: 1997. *Pavements constructed with clay, natural stone or concrete pavers*. Code of practice for laying precast concrete paving blocks and clay pavers for flexible pavements.

BS 7533: Part 4: 1998. *Pavements constructed with clay, natural stone or concrete pavers*. Code of practice for the construction of pavements of precast concrete flags or natural stone slabs.

BS 7533: Part 6: 1999. *Pavements constructed with clay, natural stone or concrete pavers*. Code of practice for laying natural stone, precast concrete and clay kerb units.

BS 7533: Part 7: 2002. *Pavements constructed with clay, natural stone or concrete pavers*. Code of practice for the construction of pavements of natural stone setts and cobbles.

Cabrera J G and Woolley G R (1985). *A study of twenty-five years old pulverised fuel ash concrete used in foundation structures*. Proceedings of the Institution of Civil Engineering, Part 2:79: pp. 149-165.

Carrick J A, Davidson J K, Aurilio V and Emery J (1997). *Use of asphalt rubber*. Proceedings of the XIIIth world meeting of the International Road Federation, Toronto.

Carswell J and Jenkins E J (1996). *Re-use of scrap tyres in highway drainage*. TRL Report TRL200. Crowthorne: TRL Limited.

Chui-Te Chiu (2001). *The efforts of using ground tire rubber on pavements in Taiwan*. Beneficial use of Recycled Materials in Transportation Applications, Washington DC. (Retrieved: 2003 from http://www.rmrc.unh.edu/Post2001Conf/overview.asp)

CIRIA C513 (1999). *The reclaimed and recycled construction materials handbook*. Construction Industry Research and Information Association Report. London: CIRIA.

CIRIA Report 167 (1997). *Use of industrial by-products in road construction – water quality effects*. Construction Industry Research and Information Association Report. London: CIRIA.

The Concrete Society (1999). *Alkali-silica reaction: minimising the risk of damage to concrete*. Report of a Concrete Society Working Party. 3rd Edition. Concrete Society Technical Report No. 30. Slough: The Concrete Society.

Construction Research Communications (2000). *Quality control: the production of recycled aggregates*. BR 392. London: CRC Ltd.

Cornelius P D M and Edwards A C (1991). *Assessment of the performance of off-site recycled bituminous material*. Research Report RR305. Crowthorne: TRL Limited.

Coventry S, Woolveridge, C and Hillier S (1999). *The reclaimed and recycled construction materials handbook*. CIRIA C513. London: CIRIA.

Cuttell G D, Snyder M B, Vandenbossche J M and Wade M J (1997). *Performance of rigid pavements containing recycled concrete aggregates*. Transportation Research Record, No. 1574, pp. 89-98.

Department for Transport (2002). *Specification for the reinstatement of openings in highways (Second Edition)*. London: Department for Transport.

Design Manual for Roads and Bridges. London: The Stationery Office:

HA 44. *Design and preparation of contract documents*. DMRB 4.1.1.

HA 74. *Treatments of fill and capping materials using either lime or cement or both*. DMRB 4.1.6.

HD25. *Foundations*. DMRB 7.2.2.

Department of Transport (2000). *Recycled materials in European highway environments; uses, technologies and policies*. FHWA-PL-00-025. Washington DC: Federal Highway Administration.

Department of Transport. *User guidelines for waste and byproduct materials in pavement construction*. Washington DC: Federal Highway Administration. (Retrieved: 2003 from http://www.rmrc.unh.edu/Resources/PandD/useful.asp)

Ducman V, Mladenovic A and Suput J S (2001). *Lightweight aggregate based on waste glass and its alkali-silica reactivity*. Cement and Concrete Research; vol. 30, pp. 1489-1492.

Dumitru I, Munn R and Smorchevsky G (2000). *Progress towards achieving ecologically sustainable concrete and road pavements in Australia*. Proceedings of WASCON Conference ‘Waste Materials in Construction’. Harrogate: Elsevier Science Ltd, pp.107-127.

Dumitru I, Smorchevsky G and Caprar G (1999). *Trends in the utilisation of recycled materials and by-product in the concrete industry in Australia*. ‘Concrete 99’. Concrete Institute of Australia, 19th Biennial Conference, Sydney.

Dutta U and Ibadat I (1996). *ASR (Automotive Shredder Residue) modified asphalt for better quality roads*. Proceedings of PTRC European Transport Forum. England: Brunel University.

DWW 2002-023 (2002). *Building materials in the Netherlands 2001. Facts and figures*. Ministry of Transport, Public Works and Water Management, Road and Hydraulic Engineering Division, The Netherlands (in Dutch). ISBN 90-369-3789-2.

Earland M (1996). *Hot mix recycling: Assessment of the performance of remix and off-site trials*. Project Report PR/CE/61/95. Crowthorne: TRL Limited. *(Unpublished report available on direct personal application only)*

Edwards A C and Mayhew H C (1989). *Recycled asphalt wearing courses*. Research Report RR225. Crowthorne: TRL Limited.

Ellis S J (2003). *P3: Construction materials. Sustainable construction in practise (SCiP)*. TRL Limted.

Environment Agency R & D 20 (1999). *Methodology for the derivation of remedial targets for soil and groundwater to protect water resources*. Environment Agency.

Freeman T J (1994). *Results of the six- and twelve-month evaluations of the Texas supplemental maintenance effectiveness research program (SMERP) sites, final report*. USA: Texas Transportation Institute.

Graedel T E and Allenby B R (1998). *Industrial ecology and the automobile*. Prentice-Hall Inc: New Jersey.

Halliday J E and Dhir R K (2002). *Full scale trials using incinerator bottom ash in cement based products.* Sustainable Concrete Construction September 2002. London: Thomas Telford, pp. 429-438.

Hanson D I, Foo K Y, Brown E R and Denson R (1994). *Evaluation and characterization of a rubber-modified hot mix asphalt pavement*. Transportation Research Record No. 1436.

Hassan K E (2003). *Susceptibility of recycled concrete aggregate to alkali-silica reaction*. Project Report PR/CSS/11/03. Crowthorne: TRL Limited. *(Unpublished report available on direct personal application only).*

Hassan K E and Page C L (2001). *The use of high loss-on-ignition fly ash to produce engineering composite materials*. England: University of Leeds. *(Unpublished).*

Hassan K E, Brooks J J and Erdman M (2000). *The use of reclaimed asphalt pavement (RAP) aggregates in concrete.* Proceedings of WASCON Conference 'Waste Materials in Construction'. Harrogate: Elsevier Science Ltd., pp. 121-128.

Hassan K E, Cabrera J G and Head M K (1998). *The effect of aggregate type on the properties of high performance, high strength concrete*. Proceedings of the International Conference 'High performance high strength concrete'. Perth, Australia.

Highways Agency, Scottish Executive Development Department, Welsh Office (Y Swyddfa Gymreig) and the Department of the Environment for Northern Ireland). *Manual of Contract Documents for Highway Works.* London: The Stationery Office

Volume 1. Specifications for Highway Works (MCHW1)

Highways Agency, Scottish Executive Development Department, National Assembly for Wales (Cynulliad Cenedlaethol Cymru) and the Department for Regional Development, Northern Ireland. *Design Manual for Roads and Bridges*. London: The Stationery Office.

Volume 7. Pavement Design and Maintenance HD 26 *Pavement Design*

Hooper F (2002). *Plas-Crete: A lightweight, portland cement concrete product manufactured from discarded mixed No. 3–7 plastics*. GeoTesting Express, Inc., Materials Technology Center 6 City Depot Road Charlton, Massachusetts 01507.

Institution of Civil Engineers (1997). *Briefing note: managing and minimising construction waste*. (Retrieved: March 2003 from http://www.ice.org.uk/rtfpdf/BS-Managing%20&%20Minimising%20Construction%20Waste.rtf)

Jin W, Meyer C and Baxter S (2000). Glascrete – concrete with glass aggregate. *ACI Materials Journal*. vol. 97: no. 2, pp. 208-213.

Karlsson K (1998). *Reactivity in mortar phase in recycled concrete aggregate*. In: Proceedings of the International Symposium on 'Sustainable construction: Use of recycled concrete aggregate'. London. pp. 197-204.

Karpinski S, Zhang X, Janoo V, Gress D and Eighmy T (2000). *A physical evaluation of municipal solid waste grate as an aggregate substitute in asphaltic concrete*. Proceedings of the International Symposium on 'Use of incinerator ash'. Scotland: University of Dundee, pp. 216-226.

Kashi MG (2001). *Synthetic lightweight aggregate from fly ash and waste plastics*. Beneficial use of Recycled Materials in Transportation Applications, Washington DC 2001. (Retrieved: 2003 from http://www.rmrc.unh.edu/Post2001Conf/overview.asp)

Kennedy J (2002). *Trenchmix: evaluation of a slow setting slow hardening trench reinstatement material*. Proceedings of the 4th European Symposium on 'Performance of bituminous and hydraulic materials in pavements'. Nottingham, pp. 155-160.

Koide H, Tomon M and Sasaki T (2002). Investigation of the use of waste plastic as an aggregate for light weight concrete. *Sustainable Concrete Construction*. London: Thomas Telford, pp. 177-185.

Krezel Z A and McManus K (2000). *Recycled aggregate concrete sound barriers for urban freeways, waste materials in construction*. Elsevier Science Ltd.

Manual of Contract Documents for Highway Works. The Stationery Office, London.

Volume 0: *Model contract document for major works and implementation requirements* (MCHW 0).

Volume 1: *Specification for Highway Works* (MCHW 1).

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

Volume 3: *Highway Construction Details* (MCHW 3).

Volume 4: *Bills of Quantities for Highway Works* (MCHW 4).

Maupin G W Jr (1995). *Field trials of asphalt rubber hot mix in Virginia, final report*. Virginia, USA: Department of Transportation.

Megan M A and Potter J F (2000). *In-service performance of recycled asphalt roadbase*. TRL Report TRL473. Crowthorne: TRL Limited.

Mulder E (1996). *Pre-treatment of MSWI fly ash for useful application*. In Proceedings of the International Symposium on 'Bulk inert waste: An opportunity for use'. Leeds, pp.181-184.

Naik T R, Singh S S, Huber C O, Brodersen B S (1996). *Use of post-consumer waste plastics in cement-based composites*. Cement and Concrete Research, vol. 26, no. 10, pp 1489-1492. Elsevier Science Ltd.

Nicholls J C (1997). *Design guide for road surface dressing (fourth edition)*. Road Note RN39. Crowthorne: TRL Limited.

Nicholls J C and Lay J (2002). *Crushed glass in macadam for binder course and roadbase layers*. Proceedings of the 4th European Symposium on 'Performance of bituminous and hydraulic materials in pavements. Nottingham, pp. 197-211.

Office of the Deputy Prime Minister (2000). *Controlling the environmental effects of recycled and alternative aggregates production: Good practice guidance*. (Retrieved: 2003 from http://www.planning.odpm.gov.uk/recycled/practice.htm)

Office of the Deputy Prime Minister (OPDM) (2001). *Survey of arisings and use of secondary materials as aggregates in England and Wales*. (Retrieved: 2003 from http://www.planning.odpm.gov.uk/material/index.htm)

Paine K A, Dhir P K and Doran V P A (2000). *Unprocessed and processed incinerator bottom ash as a cement bound material*. Proceedings of the International Symposium on 'Use of incinerator ash'. Scotland: University of Dundee, pp. 267-278.

Polley C, Cramer S M and Cruz R V (1998). Potential for using waste glass in portland cement concrete. *Journal of Materials in Civil Engineering*, American Society of Civil Engineers, vol. 10, no 4, pp. 210-219.

Prakash K B and Krishnaswami K T (1998). *Suitability of superplasticized recycled aggregate concrete in road construction*. Proceedings of the 8th International Symposium on Concrete Roads. Theme II, Lisbon-Portugal, pp. 25-31.

Reid J M and Chandler J W E (2001). Recycling in transport infrastructure. Crowthorne: TRL Limited.

Reid J M, Evans R D, Holnsteiner R, Wimmer B, Gaggl W, Berg F, Pihl K A, Milvang-Jensen O, Hjelmar O, Rathmeyer H, François D, Raimbault G, Johansson H G, Håkansson K, Nilsson U and Hugener M (2001). Alt-Mat (Alternative Materials in Road Construction): Deliverable D7: Final report. Available on TRL web site www.trl.co.uk/altmat.

RILEM Report 22 (2000). *Sustainable raw materials: construction and demolition waste*. RILEM Publications SARL.

Roe P G (2003). *Basic oxygen steel slag as surface course aggregate: an investigation of skid resistance*. TRL Report TRL566. Crowthorne: TRL Limited.

Rung M M, Whitney D P, Carrasquillo R L, and Fowler D W (1996). *Summary of investigation into organic scrap material substitutions in portland cement concrete*. Preliminary report dated - May 1996. The University of Texas at Austin Center for Transportation Research Report 1349-1F. www.dot.state.tx.us

Rust F C, Harvey J, Verhaeghe B M J A and Nokes W (1994). *Fatigue and rutting performance of conventional asphalt and bitumen-rubber asphalt under accelerated trafficking*. Proceedings of the 6th Conference on Asphalt Pavements for Southern Africa.

Schroeder R L (1994). *Current research on the utilization of recycled materials in highway construction*. *Roads to the 21st century: a key to competitiveness*. Proceedings, international road federation conference and exposition. Canada vol. 6 pp. A81-A104.

Schulz R R and Hendricks C F (1992). *Recycling of masonry rubble*. In RILEM Technical Committee Report No. 6. London: F&FN Spon.

Sear LKA (2001). *The properties and use of coal fly ash*. London: Thomas Telford.

Shao Y, Lefort T, Moras S and Rodriguez D (2000). Studies on concrete containing ground waste glass. *Cement and Concrete Research*, vol. 30, pp. 91-100.

Shehata I, Varzavand S, Elsawy A and Fahmy M (1996). *The use of solid waste materials as fine aggregate substitutes in cementitious concrete composites.* Semisesquicentennial Transportation Conference Proceedings. Department of Industrial Technology. Iowa: University of Northern Iowa.

Sherwood P (2001). *Alternative materials in road construction*. London: Thomas Telford Ltd.

Shimaoka T (2001). *Application of bottom ash from municipal solid waste as road construction materials*. Fukuoka University, Japan. Beneficial use of Recycled Materials in Transportation Applications, Washington DC 2001. (Retrieved: 2003 from http://www.rmrc.unh.edu/Post2001Conf/overview.asp)

Soeda M (2001). *Application of scrubber residue from municipal solid waste to an admixture for concrete*. Fukuoka University, Japan. Beneficial use of Recycled Materials in Transportation Applications, Washington DC. (Retrieved: 2003 from http://www.rmrc.unh.edu/Post2001Conf/overview.asp)

Sommer H (1998). *Recycling with cement on the motorway Salzburg – Vienna*. Proceedings of the 8th International Symposium on Concrete Roads. Theme II, Lisbon-Portugal, pp. 39-42.

Sowerby C R (2002). *The use of shredded waste plastic as coarse aggregate substitutes in cement-based composites*. England: University of Leeds.

Stark D C (1996). *The use of recycled-concrete aggregate from concrete exhibiting alkali-silica reactivity*. Research and Development Bulletin RD114, USA: Portland Cement Association.

Texas Department of Transport (1999). *The year of recycled roadway materials* (Retrieved: 2003 from www.dot.state.tx.us)

The National Cooperative Highway Research Program (NCHRP). *Waste and Recycled Materials (WRM) database*. (Retrieved: 2003 from http://www.rmrc.unh.edu/Resources/PandD/NCHRP/nchrp.asp)

Todd W W (1996). *PFA – A component in building materials produced from the German plastic packaging waste stream*. In: Proceedings of the International Symposium on 'Bulk inert waste: An opportunity for use'. Leeds, pp.203-207.

Toledo-Filho R D, Americano B B, Fairbairn E M R, Rolim J S and Filho J F (2001). *Potential of crushed waste calcined-clay brick as a partial replacement for portland cement.* Proceedings of the 3rd CANMET/ACI International Symposium on 'Sustainable development of cement and concrete'. ACI SP-202, pp.147-160.

Topcu I B and Avcular N (1997). *Analysis of rubberised concrete as a composite material*. Cement and Concrete Research; 27: 8, pp. 1135-1139

Toutanji H A (1996). *The use of rubber tire particles in concrete to replace mineral aggregates*. Cement and Concrete Composites; 18: pp. 135-139.

Trunk Road Maintenance Manual. London: The Stationery Office.

Volume 1: *Highway maintenance code.*

Volume 2: *Routine and winter maintenance code*

Walsh I D and Williams G (2002). *Use of fly ash bound material as road base on A259 Ramsgate harbour approach road.* Proceedings of the 4th European Symposium on 'Performance of bituminous and hydraulic materials in pavements. Nottingham, pp. 175-180.

Way G B (2001). *Where the rubber meets the rubber: 14 years of success using ground tire rubber in pavements*. Washington DC: Arizona Department of Transportation. Beneficial use of Recycled Materials in Transportation Applications. (Retrieved: 2003 from http://www.rmrc.unh.edu/Post2001Conf/overview.asp)

Wegen G van der and Haverkort R (1998). *Recycled construction and demolition waste as a fine aggregate for concrete*. In: Proceedings of the International Symposium on 'Sustainable construction: Use of recycled concrete aggregate'. London, pp. 333-346.

Westiner E M, Locherer L and Worner T H (2000). *Volume stability of hydraulic bound MSWI ash*. Proceedings of the International Symposium on 'Use of incinerator ash'. Scotland: University of Dundee, pp. 247-258.

Winkler A and Mueller A (1998). *Recycling of fine processed building rubble materials*. Proceedings of the International Symposium on 'Sustainable construction: Use of recycled concrete aggregate'. London, pp. 157-168.

WRAP Fact Sheet 8 (2003). *Building on recycled glass as an aggregate*. The Waste and Resources Action Programme, Fact Sheet No. 8. Date issued: October 3, 2003.

York D M (2000). *MSWI plants: sustainable quarries*. Proceedings of the International Symposium on 'Use of incinerator ash'. Scotland: University of Dundee, pp. 259-265.

Zakaria M and Cabrera J G (1996). *Performance and durability of concrete made with demolition waste and artificial fly ash-clay aggregates*. In: Proceedings of the International Symposium on 'Bulk inert waste: An opportunity for use'. Leeds, pp.151-158.

Zoorob S E and Suparma L B (2000). *Laboratory design and investigation of the properties of continuously graded asphaltic concrete containing recycled plastics aggregate replacement (Plastiphalt).* England: University of Leeds.

Appendix A: Case studies

A.1 Case study 1: Glasphalt

RMC has been investigating the possibility of producing asphalt with crushed glass replacing some of the aggregate in conventional mixtures. The product is marketed under the trade name *Glasphalt*. It is intended for use only in the structural layers of a pavement because glass will polish quickly under traffic and will not provide the skid-resistance required for a surface course. As part of the development of *Glasphalt*, RMC has carried out various trials and commissioned TRL Limited to monitor and report on them. The mixtures for the trials were dense binder course and base course macadams. The control mixtures used 100% limestone aggregate whereas, in the *Glasphalt* mixtures, 30% of the limestone was replaced with crushed and screened glass.

Several full-scale road trials have taken place since the successful completion of the pilot trial and a road constructed at Mansfield is shown in Figure A1. The trial has shown that the inclusion of the glass did not adversely affect the properties of the mixture and generally complies with the current set of performance requirements in SHW for materials to be used in the structural layers of pavements.

Figure A1 Utilisation of crushed glass as a aggregate in road construction

RMC Aggregates and TRL Limited believe that a clause permitting the use of crushed glass in asphalt mixtures should include limits on the contaminants within the crushed glass and advice on mixing and compaction temperatures. This study has demonstrated that waste crushed glass can be successfully used in the binder course and base layers of road pavements. Materials:

A.2 Case Study 2: Burntwood by pass, Staffordshire

PFA + IBA + lime = GFA	-	sub-base and road-base courses
Asphalt planings	-	sub-base and road-base courses
Brick hardcore (demolition waste)	-	capping layer

Staffordshire County Council (SCC) funded the construction of the Burntwood By Pass, which was constructed in partnership with Wrekin Construction Ltd. SCC are also responsible for disposing of the ash from Sideway Incinerator Plant. A specification was written for granular IBA material treated with fly ash (GFA). This was used for the construction of a spur, from the Burntwood By Pass, for access to the Rugby Club.

The scheme is approximately 1.5km long and is a wide single carriageway construction. The scheme requires approximately 14.5k tonne of GFA, the construction being 40 mm of stone mastic asphalt on 90 mm of bituminous basecourse, on two layers of GFA with a total thickness of 350 mm constructed on 350 mm of capping material. The bulk of the capping came from demolition waste i.e. brick hardcore supplied by a local recycling contractor involved with utility arisings. The GFA mix was 82% IBA from Ballast Phoenix, 15% PFA from TXU Ironbridge power station and 3% lime. Due to a shortage of suitable IBA and no material being available from Sideway, approximately 3.5k tonne of planings were used to make up the shortfall in granular material.

Figure A2 Placing GFA on the Burntwood By Pass, Staffordshire
(Photographs courtesy of Staffordshire County Council)

Many advantages have been reported on the financial and environmental benefits and ease of material handling, as GFA can be laid using a conventional paver with slow setting allowing remedial work for a longer period of time.

A.3 Case study 3: Construction and demolition waste

In the 1990s parts of the Vienna – Salzburg motorway was reconstructed with the intention of fully recycling the old pavement quality (PQ) concrete into a new PQ layer. Figure A3 shows, schematically, how the system worked.

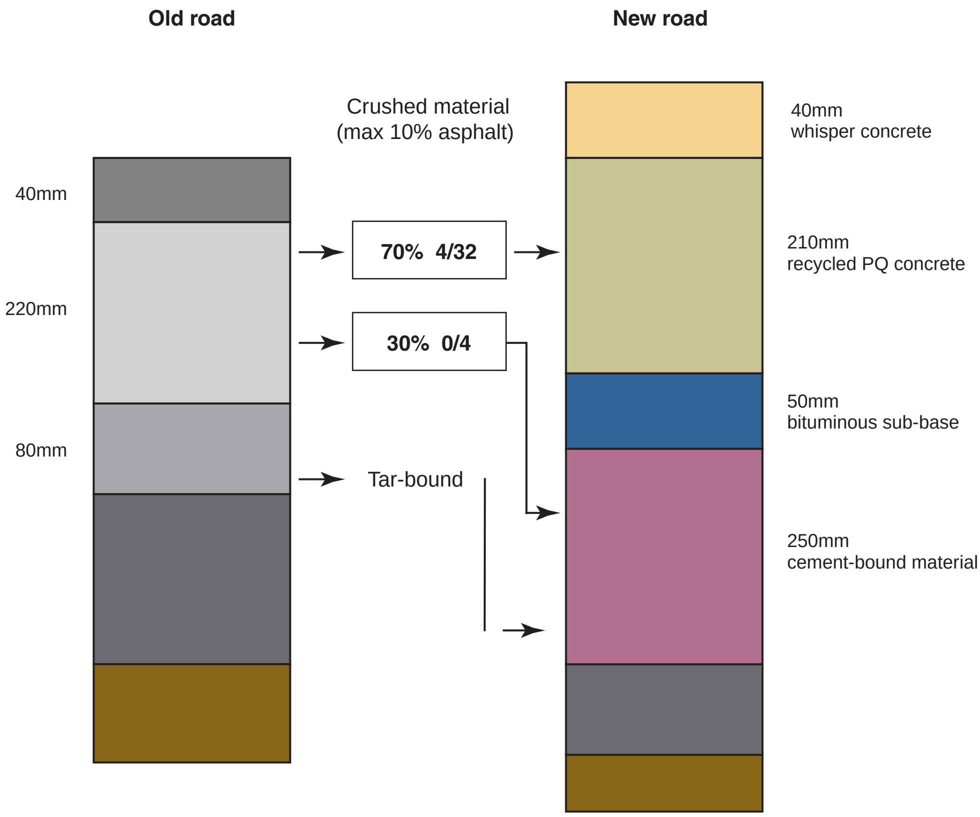

Figure A3 Schematic of the Austrian recycled PQ concrete pavement (Sommer, 1998)

The original PQ concrete was shattered and then crushed and screened. The coarse fraction, particles ranging in size from 32 mm to 4 mm, representing about 70% of the crushed concrete, was reused as aggregate in the new PQ concrete layer. The remaining 30% fine fraction, size 0 to 4 mm, was blended with some of the original granular sub-base and portland cement to form the new cement bound sub-base. The RCA concrete had superior flexural strength because of the better bond to the crushed concrete surface. The PQ concrete layer was then surfaced with 40mm of ‘whisper concrete’. The old PQ concrete was built on a support layer of tar bound material, which was also recycled in the PQ concrete pavement.

A.4 Case study 4: Incinerator bottom ash

Figure A4 Application of IBA in CBM, Waltham Abbey (Ballast Phoenix)

The work comprised a 4km by-pass to Waltham Abbey. The road was originally designed in accordance with Volume 7 of the Design Manual for Roads and Bridges. The design was modified with the approval of by Essex County Council to obtain environmental benefits. In particular, the clay sub-grade was stabilised to construct the sub-base. IBA was processed by Ballast Phoenix at Edmonton to meet the requirements of BS882. This totally replaced primary aggregate in the production of the CBM3. Sitebatch produced a total of 5,800m³ of CBM3 for the project.

A medium strength lower base (using CBM) satisfied the design criteria for CBM 3R (Specification for Highways Works, Series 1000). The CBM aggregate comprised 100% IBA to the given grading, used pith Portland cement. The 7-day compressive strength of the CBM was 12MPa.

A.5 Case study 5: Slag bound material

Figure A5 The use of SBM in the construction of the A485 link road, Carmarthen

The A485 Carmarthen site was constructed in 1999 and comprised two sections of SBM, one with SBM base and the other with SBM base and sub-base. The SBM design consisted of 16% granulated blastfurnace slag, 1.5% lime, 77.5% air-cooled slag aggregate, 5% limestone filler and 7.5% water. The use of SBM allows much more handling time, between batching and laying, than the 2 hours permitted for the control cement bound material – CBM3. The early strength development of the SBM is lower than CBM3, therefore reducing the risk of reflection cracks, whereas the 360-day strength properties, which are used in pavement designs, are comparable to CBM3.

Abstract

This work forms part of the DTI/WRAP sponsored Aggregates Research Programme to support the development of construction markets for secondary and recycled aggregates. The report reviews the use of secondary and recycled aggregates in highway infrastructure, within the context of the Specification for Highway Works (SHW), with the emphasis on high-value applications in road construction. An examination of international experiences has been carried out to highlight the innovative research, techniques and programmes that could be introduced to the UK.

The availability of secondary and recycled materials is discussed in terms of arisings, stockpiles and locations. Informal consultations with materials producers were carried out to identify existing and potential markets and barriers. A number of materials have been identified for which use could be extended to higher-value applications. These include construction and demolition wastes, incinerator bottom ash, glass, plastic, and tyre rubber as alternative aggregates. There is a potential for developing new applications of hydraulic bound materials and roller-compacted concrete using fly ash and slag.

Assessment of the technical, environmental, and regulatory barriers to the use of the new materials/applications is discussed. The report also discusses material lifetime within the context of whole life costing, considering the economic cost of alternative materials, material performance and the potential for future recycling. Finally, the report concludes with a comprehensive set of recommendations highlighting the need for future work to overcome the barriers identified and to support the development of new materials in high-value applications in highway infrastructure.

Related publications

TRL566 *Basic oxygen steel slag as surface course aggregate: an investigation of skid resistance* by P G Roe. 2003 (price £30, code EX)

TRL533 *Guidance on the structural use of plastic sheet piling in highway applications* by D R Carder, K J Barker and M R Easton. 2001 (price £35, code J)

TRL519 *Specification on pulverised-fuel ash for use as general fill* by M G Winter and B G Clarke. 2001 (price £25, code E)

TRL473 *In-service performance of recycled asphalt roadbase* by M A Megan and J F Potter. 2000 (price £25, code E)

TRL408 *Enabling the use of secondary aggregates and binders in pavement foundations* by G M Atkinson, B C Chaddock and A R Dawson. 1999 (price 335, code H)

TRL200 *Re-use of scrap tyres in highway drainage* by J Carswell and E J Jenkins. 1996 (price £25, code E)

RR305 *Assessment of the performance of off-site recycled bituminous material* by P D M Cornelius and A C Edwards. 1991 (price £20, code B)

RR225 *Recycled asphalt wearing courses* by A C Edwards and H C Mayhew. 1989 (price £20, code B)

RN39 *Design guide for road surfacing dressing (5th edition Revised)* by J C Nicholls. 2002 (price £40, code JX)

VR5 *Civil engineering applications of tyres* by K N Hylands and V Shulman. 2003 (price £55, code LX)

Recycling in transport infrastructure by J M Reid and J W E Chandler. Price £35

Prices current at February 2004

For further details of these and all other TRL publications, telephone Publication Sales on 01344 770783, or visit TRL on the Internet at www.trl.co.uk.