Guide to Pavement Technology Part 4E: Recycled Materials
Guide to Pavement Technology Part 4E: Recycled Materials

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Abstract

Part 4E of the Guide to Pavement Technology presents the latest information on recycled materials as they pertain to products manufactured from recycling various wastes accepted through registered recycling and reprocessing facilities. In particular, the guide deals with the specification, manufacture and application of various products derived from the resource recovery of: construction and demolition waste (C&D waste) from the building industry; reclaimed asphalt pavement (RAP) from maintenance and rehabilitation activities; and reclaimed glass from the glass disposal industry.

In addition, the guide presents a process by which other sources of wastes may be assessed for their suitability to be used in pavements, e.g. industrial slags from the ore extraction industry and ash from coal burning power stations.

Keywords

recycled, reclaimed asphalt pavement, milling, cold mix, cold in situ recycling, hotmix recycling, specification, construction and demolition waste management, glass, slag, fly ash, resource recovery

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1. Introduction

1.1 Scope

Part 4E of the Guide to Pavement Technology presents the latest information on recycled materials as they pertain to products manufactured from recycling various wastes accepted through registered recycling and reprocessing facilities. In particular, this guide deals with the specification, manufacture and application of incorporating recycled materials into products commonly used in pavement construction viz:

- construction and demolition waste (C&D waste) from the building industry
- reclaimed asphalt pavement (RAP) from maintenance and rehabilitation activities
- industrial slags
- ash and flyash
- reclaimed glass from the glass disposal industry.

These recycled materials may be processed into products of their own accord or incorporated in part into traditional products such as granular materials and asphalt.

An environmental process which may be followed to evaluate the suitability of a new source of waste with the potential to be recycled into pavement material products is introduced in this guide.

In situ recycling of existing pavements is not specifically addressed in this guide; this issue is included in the following parts of the Guide to Pavement Technology:

- Part 4A: Granular Base and Subbase Materials
- Part 4B: Asphalt
- Part 4C: Materials for Concrete Road Pavements
- Part 4D: Stabilised Materials
- Part 4L: Stabilising Binders
- Part 8: Pavement Construction

Typical products manufactured through the resource recovery and recycling industry pertinent to this guide are:

- unbound granular pavement materials sourced from C&D waste
- aggregates sourced from C&D waste, reclaimed pavement materials and glass for use in the manufacture of new concrete and asphalt
- fine aggregates sourced from C&D waste and glass reprocessing
- engineered and general fill sourced from C&D waste.

This guide does not include products derived from other recycling operations such as plastics, tyres, metals and oils.

An overview of the application of recycled materials as road pavement materials (i.e. granular, cementitious and asphalt) is presented in Andrews (2005).
1.2 Guide to Pavement Technology

The Guide to Pavement Technology consists of the following parts:

- Part 1: Introduction to Pavement Technology
- Part 2: Pavement Structural Design
- Part 3: Pavement Surfacing
- Part 4: Pavement Materials
  - Part 4A: Granular Base and Subbase Materials
  - Part 4B: Asphalt
  - Part 4C: Materials for Concrete Road Pavements
  - Part 4D: Stabilised Materials
  - Part 4E: Recycled Materials
  - Part 4F: Bituminous Binders
  - Part 4G: Geotextiles and Geogrids
  - Part 4H: Test Methods
  - Part 4I: Earthworks Materials
  - Part 4J: Aggregates/Source Rock
  - Part 4K: Seals
  - Part 4L: Stabilising Binders
- Part 5: Pavement Evaluation and Treatment Design
- Part 6: Unsealed Pavements
- Part 7: Pavement Maintenance
- Part 8: Pavement Construction and Construction Assurance
- Part 9: Pavement Work Practices
- Part 10: Subsurface Drainage.
2. Environmental Aspects of Recycling

2.1 Composition of Waste

Of the 32.4 million tonnes of solid waste generated in Australia in 2002–03, the Productivity Commission estimated that approximately 27% (or about 8.7 Mt) was municipal waste, 29% (or 9.4 Mt) was commercial and industrial (C&I) waste, and 42% (or 13.6 Mt) was construction and demolition (C&D) waste (Figure 2.1). These estimates do not include waste generated and dealt with on-site by the waste generator (Senate Standing Committee on Environment, Communications and the Arts 2008).

In Figure 2.1:
- municipal waste comprises those materials from kerbside collections, including recycled paper, plastic, glass, metal cans and garden waste, of which 64% is disposed to landfill
- commercial and industrial waste comprises metals, food and garden timber (9%) and plastics, of which 50% is disposed to landfill
- construction and demolition waste principally comprises timber, bricks, plaster off-cuts, concrete, rubble, steel and excavated earth, of which 35% is disposed to landfill.

In New Zealand, C & D waste may represent up to 50% of all waste generated, with 20% of all waste going to landfill and 80% to clean fill (Ministry for the Environment NZ 2002).

2.2 Waste Hierarchy for Pavement Materials

Waste reduction, reuse and recycling strategies have been developed in both Australia and New Zealand, e.g. Towards Zero Waste (Department of Sustainability, Victoria 2005). The typical objectives of such waste management strategies and Acts are to:
- encourage the most efficient use of resources and to reduce environmental harm in accordance with the principles of ecologically sustainable development
- ensure that resource management options are considered against a hierarchy of the following order:
  - avoidance of unnecessary natural resource consumption
  - resource recovery (including reuse, reprocessing, recycling and energy recovery)
Provide for the continual reduction in waste generation:

- to minimise the consumption of natural resources and the final disposal of waste by encouraging the avoidance of waste and the reuse and recycling of waste.

Internationally, Environmental Protection Acts enshrine waste hierarchy as a core principle for the management of waste streams generated from all sources. This has been modified for pavement materials (PIARC 2008) as shown in Figure 2.2. In this figure, the ascending order of preference is towards the apex of the triangle.

**Figure 2.2: Waste hierarchy for pavement materials**

![Waste hierarchy for pavement materials](source: PIARC (2008))

The following examples of each level in the revised hierarchy shown in Figure 2.2 illustrate their application to pavements.

- **Waste reduction**: this is not only about the economic use of materials during construction but also pavement design, maximising pavement life and minimising pavement maintenance.

- **Reuse**: a common way of reusing an existing pavement is to overlay or resurface it. This takes advantage of the residual strength of the existing material without incurring the cost of its removal.

- **Recycling**: the highest quality, and most expensive, materials are generally located in the upper layers of pavements. Usually, recycling the uppermost layer makes best use of a recycled pavement material’s residual properties and results in the greatest savings. Using this approach, recycling surface asphalt into a new surfacing is seen as a more optimal use than recycling it into an unbound basecourse. In-place recycling, and the use of cold recycling processes, are examples of techniques that have energy conservation advantages. An examination of the life cycle costs, and the total energy used in recycling, is recommended to assist in choosing the optimum process.

- **Landfill**: dumping of pavement materials into landfill is the least preferred option as it takes least advantage of the residual properties of the pavement materials; replacement with new materials is also generally necessary.
2.3 Presence of Contaminants

2.3.1 General

Environmental authorities place tight restrictions on the spread of harmful heavy metals, pesticides and carcinogens through the environment. Unless appropriate controls are in place, recycling waste materials and industrial by-products provides a potential path for the spread of undesirable chemicals.

In addition, the presence of asbestos – either in fragment (non-friable) or fibre (friable) form – is strictly controlled under the Environmental Health Commission (EHC 2005).

2.3.2 Leachable Contaminants

Specified limits are available through the National Environment Protection Council (NEPC 1999) which provides investigative levels for soil and groundwater for both Australia and New Zealand. The NEPC guide presents a number of levels of contamination in relation to land use ranging from Level A to Level F. As a guide:

- Level A represents standard residential usage with garden/accessible soil (i.e. cultivation), including day-care centres, kindergartens, preschools and primary schools.
- Level F represents commercial/industrial applications.

Typical environmental contamination intervention levels are presented in Table 2.1.

Table 2.1: Environmental contamination intervention levels

<table>
<thead>
<tr>
<th>Substance</th>
<th>Health investigation Level A (mg/kg)</th>
<th>Health investigation Level F (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Metals</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arsenic</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>Cadmium</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>Chromium (VI)</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>Copper</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>Lead</td>
<td>300</td>
<td>5000</td>
</tr>
<tr>
<td>Mercury (inorganic)</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>Nickel</td>
<td>600</td>
<td>3000</td>
</tr>
<tr>
<td>Zinc</td>
<td>7000</td>
<td>35 000</td>
</tr>
<tr>
<td><strong>Organics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aldrin/Dieldrin</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Chlordane</td>
<td>50</td>
<td>250</td>
</tr>
<tr>
<td>Polyaromatic hydrocarbons (PAH)</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>Petroleum hydrocarbons C16-C35 aromatics</td>
<td>90</td>
<td>450</td>
</tr>
<tr>
<td>Petroleum hydrocarbons C16-C35 aliphatics</td>
<td>56000</td>
<td>28 000</td>
</tr>
<tr>
<td>Petroleum hydrocarbons &gt; C35 aliphatics</td>
<td>56 0000</td>
<td>280 000</td>
</tr>
</tbody>
</table>

*Source: NEPC (1999)*
At this stage the most conservative (Level A) is widely adopted by authorities specifying recycled materials for use in roadworks, with Level F adopted for non-sensitive sites based upon an environmental assessment of the site being considered. However, authorities should develop their own policy documents for the use of recycled materials. Key considerations should include the source and nature of the material (e.g. demolition concrete, industrial by-product), and the in-service operating environment (e.g. sealed roads, unsealed shoulders, likely human exposure, risk and consequences of leaching into watercourses). Such policy documents should be developed in consultation with state EPAs.

### 2.3.3 Asbestos

The detection of asbestos in C&D materials received at recycling facilities is controlled by a formal risk management procedure as outlined in the draft national procedure (Waste Management Association of Australia (WMAA) 2008).

In terms of tolerable limits, the Victorian Government has set a limit of 10 mg/kg (0.001%) by weight for construction materials that contain asbestos. In 1998, The Netherlands applied the same threshold to aggregates produced from recycled C&D wastes.

Although the State of Victoria has set a limit, no specific requirements, or limits, for asbestos contamination in recycled aggregate products have been set for adoption in Australasia.

However, Australia has set a limit of 0.1% by weight of asbestos for the purpose of classification of products, whether they are asbestos fibers or asbestos fragments (EHC 2005). In other words, any product that contains 0.1% by weight of asbestos, or more, would be classified as carcinogenic and would need to be handled and labeled according to EHC requirements.

The testing of recycled aggregate products for estimating the exposure risk to purchasers of the product is difficult to determine because of the presence of minute samples of asbestos in a large volume of material. However, in the unlikely event that a sample of asbestos is visually located within a large sample, further investigation of the likelihood of more asbestos being present should be undertaken in accordance with EHC requirements.

In New Zealand management of asbestos associated with demolition is controlled by the Department of Labour Guidelines (1999).

### 2.4 Framework for Determining Suitability of Recycled Materials

The framework for the use of recycled and alternative materials in roadworks is shown in Figure 2.3. It is based on the Australian/NZ Standard Risk management (AS/NZS 4360–2004).

The framework provides an overall approach generally undertaken in conjunction with the appropriate legislative organisations and regional councils in which decisions concerning material needs, material sources, material characterisation, risk assessment and treatment, project use and operational phase issues can be considered.

#### 2.4.1 Framework Description

**Step 1: Project description and context**

Include a discussion of all relevant factors for the proposed project, including:

- wider project context including relevant catchment or regional management plans
- environmental impact assessment, EPA development approvals, permits, etc.
- description of location and environmental values (proximity, sensitivity, etc.); a potential risk associated with coastal areas is acid sulphate soils
- baseline site, soil and water characteristics: desk-top study of available information relating to underlying geochemical profile
- existing/prior land uses
- constraining factors such as hydrology (groundwater, surface drainage), topography, climate and geology (soils)
- project design including materials requirements.

**Step 2: Identify potential sources of materials**

Key factors to consider are engineering considerations, economic feasibility and environmental factors; for example:
- quantity of materials required
- potential sources of alternative materials from existing industry
- availability of potential materials
- location and transport distances involved
- potential project uses, including structural fill, subbase and base materials, drainage layers, embankment and backfill materials, substitutes for aggregates in asphalt and granular bases, fill blending with waste quarry materials, fence posts, road safety bars, roadside furniture, etc.

**Figure 2.3: Framework for suitability of recycled materials**

Step 3: Materials characterisation

Description of materials:

- chemical composition, including pH, conductivity, concentration of trace metals, sulphates, total carbon, total dissolved solids, total suspended solids (physical characteristics are covered in other guidelines/specifications)
- potential contaminants
- likely treatments required.

Material classification (e.g. based on environment legislative classifications):

- clean fill
- intermediate landfill cover
- low level contaminated.

If classified as clean fill, proceed to Step 6, otherwise proceed to Step 4.

In terms of sampling and testing guidelines, readers are referred to relevant EPA guidelines and Australian and New Zealand standards.

Step 4: Risk assessment

- Identify potential hazards:
  - based on the materials classification in Step 3 identify project activities and phases that may create environmental hazards (e.g. construction phase, operation phase).
- Identify exposure mechanisms:
  - environmental exposure mechanisms, including:
    - water quality impacts via leachate
    - air quality impacts (e.g. dust)
    - land contamination resulting from construction activities (e.g. exposure of acid sulphate soils)
    - vegetation impacts associated with clearance
    - fauna impact (i.e. habitat disturbance)
  - identify interactions and secondary stressors.
- Identify environmental receptors:
  - describe environmental sensitivities associated with the receiving environment, including water, land, soil, air quality, vegetation, fauna values and human amenity (e.g. noise). For example, does the site contain any of the following site conditions shown in Table 2.2.
Table 2.2: Environmental sensitivities associated with the receiving environment

<table>
<thead>
<tr>
<th>Groundwater factors</th>
<th>Surface drainage factors</th>
<th>Soils factors</th>
<th>Proximity to high value or sensitive areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>High watertable</td>
<td>Is site susceptible to flooding?</td>
<td>Presence of acid sulphate soils</td>
<td>Within 50 m of a stream or wetland</td>
</tr>
<tr>
<td>Background pollutant levels</td>
<td>Tidal/estuarine influence</td>
<td>Soils prone to subsidence</td>
<td>Nearby important remnant vegetation</td>
</tr>
<tr>
<td>Acidic or saline groundwater</td>
<td></td>
<td>High permeability soils</td>
<td>Nearby habitat for vulnerable, rare or threatened flora or fauna species</td>
</tr>
</tbody>
</table>


- Evaluate environmental risk:
  - Estimate likelihood and consequences/severity of environmental exposures associated with identified mechanisms.
  - Is the risk exposure acceptable?
  - Are the acceptability criteria OK? If so, proceed to Step 6.
  - Is a risk management plan required to reduce likelihood, control consequences or avoid risks? If so, proceed to Step 5.

**Step 5: Risk treatment**

- Identify appropriate environmental safeguards.
- Describe the range of risk treatment options to be considered, including:
  - materials pre-processing
  - encapsulation
  - leachate barriers, collection and containment system
  - neutralisation.

**Step 6: Operational phase**

- Describe implementation requirements included in the environmental management plan (operations), including:
  - post-construction monitoring requirements (e.g. ground water, frequency of testing)
  - sampling
  - auditing.

2.4.2 Environmental Considerations of Materials other than C&D Waste in Roadworks

An example of the selection of recycled materials (on an environmental basis) from any source intended for use in roadworks is described in Operational Instruction 21.6 (DTEI 2008b). In this document, the process considers the situation where the material is to be used, viz:

- plant growth (areas where plants will be grown, vegetated areas)
- unsealed applications – sensitive
- unsealed application – non-sensitive
- sealed applications.
Examples of unsealed applications are road shoulders, unsealed roadways (dirt roads), embankment batters, unsealed car parks, roadside vehicle stopping areas, rest areas, noise mounds and buffers.
3. Granular Products

3.1 Unbound Granular Basecourse and Subbase

The products most commonly recycled in the manufacture of unbound granular basecourse and subbases are predominantly sourced from either recovery and/or reuse of in situ pavement material, or construction and demolition waste.

In terms of construction and demolition waste, there are a number of commercial operations throughout Australia and New Zealand which produce granular material. They primarily comprise:

- **Primary materials**: the principal source stone, making up more than 80% of the product. Examples include concrete, often containing steel reinforcement.

- **Supplementary materials**: basically stone-based materials which supplement the primary material. When limited in quantity they have little detrimental effect on product performance. Examples include brick, crushed stone, tiles, masonry and glass.

- **Friable materials**: they may be tolerated but, if present in sufficient quantities, can be detrimental to product quality and performance. Examples include plaster and clay lumps.

- **Foreign materials**: they are detrimental to performance and undesirable if present in the product. However, they cannot be completely eliminated. Examples include rubber, plastic, paper, cloth, paint, wood and vegetable matter.

- **Bituminous materials**: these may be tolerated in unbound materials (provided they are not stabilised with cementitious binders). They may be stabilised by the addition of bituminous binders (hot or cold). Examples include asphalt (slabs and planings) and sprayed seals.

In conjunction with this section of the guide, the reader is directed to the use of recycled concrete and masonry in the manufacture of pavement material products such as granular materials and concrete described in Australian Standard HB 155–2002. This document incorporates a description of material properties and case study performance of recycled concrete and masonry materials processed into unbound granular materials, aggregates and concrete manufactured from recycled aggregate.

3.1.1 Specifications

Recycled materials may exhibit properties that do not conform to traditional specifications for crushed rock or natural gravels in terms of particle size distribution, plasticity or hardness. However, material specifications for recycled materials (predominantly C&D waste sourced from concrete and masonry) have been developed in New Zealand and most Australian States.

While there is enormous diversity in the potential sources of recycled materials, the traditional engineering properties of strength and durability applicable to natural materials will form the core of any specification for recycled material.

In addition to the traditional classification and strength parameters, some specifications require performance based testing, such as that undertaken using repeat load triaxial equipment. Some industrial by-products may also exhibit self-cementing characteristics whereby crushing strength is required. Additional specification requirements may also be necessary to address contaminant materials.

Of the specifications available, examples cited in this Guide have been taken from those published by Resource NSW (now the Department of Environment and Climate Change – DECC), Main Roads Department WA, the NZTA and DTEI SA.
Specifications for commercially produced granular recycled materials sourced from C&D waste are similar to those for quarry materials, with possibly some slight modification to Atterberg limits – to take account of the higher porosity of the crushed concrete and brick, and strength properties – to take account of the cement mortar surrounding the aggregate stone.

**Particle size distribution (PSD)**

The PSD requirements of recycled materials are identical to those for quarried products.

**Atterberg limits**

As the porosity of the cement mortar is higher, the liquid limit (LL) of most recycled products is higher than that of quarried products. As a guide, the value of the LL is increased from 25% to between 27% (Resource NSW 2003) and 45% (Main Roads WA Specification 501–2007).

**Strength properties**

Stone hardness is measured using the Los Angeles abrasion test, the wet/dry strength test, the wet/dry strength variation test or the unconfined compressive strength (UCS) test. Typical values are shown in Table 3.1.

### Table 3.1: Example strength parameters for recycled materials

<table>
<thead>
<tr>
<th>Organisation</th>
<th>Parameters adopted by organisations for granular products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource NSW¹</td>
<td>Wet strength 70 kN min.</td>
</tr>
<tr>
<td>MR WA²</td>
<td>LA value 45% max.</td>
</tr>
<tr>
<td>NZTA³</td>
<td>Crushing resistance 130 kN min.</td>
</tr>
<tr>
<td>DTEI⁴</td>
<td>Resilient modulus 300 MPa min.</td>
</tr>
</tbody>
</table>

**Sources:**
2. MRWA (2007)
3. TNZ (2006)
4. DTEI (2008a)

*Note: * performance based.

**Supplementary and deleterious materials in C&D products**

Recycled construction and demolition materials that originate from building sites or roadworks may be contaminated with a range of undesirable materials. Current specifications typically place upper limits on supplementary materials and deleterious materials as described in Table 3.1.

A range of limits for supplementary and deleterious materials are shown in Table 3.2. They are determined primarily using RTA, NSW Test Procedure T276 (RTA 2001).
Table 3.2: Supplementary and deleterious material limits in granular products

<table>
<thead>
<tr>
<th></th>
<th>Resource NSW</th>
<th>MR WA</th>
<th>NZTA</th>
<th>DTEI SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplementary materials</td>
<td>3–30% max.</td>
<td>5% max.</td>
<td>3% max.</td>
<td>20% max.</td>
</tr>
<tr>
<td>(brick, crushed stone, tiles,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>masonry, glass)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Friable materials</td>
<td>0.2% max.</td>
<td>2% max.</td>
<td>1% max.</td>
<td>1%</td>
</tr>
<tr>
<td>(plaster, clay lumps)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foreign materials</td>
<td>0.1% max.</td>
<td>0.5% max.</td>
<td>0.5% (includes</td>
<td>0.5%</td>
</tr>
<tr>
<td>(rubber, plastic, paper,</td>
<td></td>
<td></td>
<td>bitumen)</td>
<td></td>
</tr>
<tr>
<td>cloth, paint, wood,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vegetable matter)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bituminous materials</td>
<td>0.1% max.</td>
<td>0%</td>
<td>0%</td>
<td>bitumen content</td>
</tr>
<tr>
<td>(asphalt (slabs and planings),</td>
<td></td>
<td></td>
<td></td>
<td>1% max</td>
</tr>
<tr>
<td>seals)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asbestos</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

3.1.2 Granular Bituminous Materials

Recycled asphalt in the form of crushed slab asphalt or asphalt planings has been used as an unbound granular subbase and basecourse material on minor roads and as a low-dust surfacing in unsealed road applications. Some examples are shown in Figure 3.1.

Figure 3.1: Application of recycled asphalt on (L) country town street and (R) rural access road

Source: ARRB Group

Granular bituminous materials are received either as:

- Granular asphalt planings, stockpiled and used without further processing
- Asphalt planings and/or slab asphalt (excavated bituminous pavement material which may contain some granular basecourse), crushed and screened. In some instances the processing conforms to a specification similar to a standard crushed rock.

Asphalt planings milled and directly reconstituted into an unsealed wearing surface should contain sufficient fine material approximating a grading similar to a Class 2 granular material in order to provide a tight surface.

3.2 Recycled Glass

Approximately 850 000 tonne of glass is consumed in Australia each year, with 350 000 tonne recovered for recycling. That is equivalent to about 1.4 billion bottles being diverted away from landfill. Similarly, in New Zealand approximately 250 000 tonne of glass is consumed each year, with over 90 000 tonne recycled.
Glass cullet is recycled container glass (previously used for bottles, jars and other similar glass vessels) prior to processing. The material is typically collected via bottle banks, kerbside collection schemes and from premises handling large quantities of containers. The term ‘cullet’ also refers to waste glass produced as a result of breakage and rejection on quality control grounds during the manufacturing process.

The primary aim of processing it is to return it to the glass-making process to manufacture glass containers or other products. However, in some commercial operations it is incorporated into granular materials.

### 3.2.1 Contaminants in Glass Cullet (AS HB 155:2002)

By the time the cullet has been recovered for recycling, it is typically broken into smaller fragments and may contain other materials which have been introduced and carried with it during its use and disposal viz:

- ceramics, which may include dishware, porcelain caps, pottery, heat-resistant cookware (e.g. Pyrex), mirror glass, laboratory glass, light bulbs, crystal and window glass; they may require removal either manually or through automated systems.
- metals, which are generally in the form of container lids and seals.
- organics, including paper labels, wood, plants, food residue, etc. which are removed through washing and screening operations.

### 3.2.2 Use of Glass as a Granular Material

Glass cullet is a hard, granular material that can be used as a fine aggregate when crushed. In terms of its physical and mechanical properties, crushed glass cullet behaves in a very similar manner to sand, having a similar particle density. In many circumstances there may be economic benefits associated with the use of glass cullet in place of natural sand.

An example standard specification for glass cullet recovered from waste is given in TNZ M/4 (2006).

A trial example of the use of recycled glass as a pipe embankment material, undertaken by the Department of Environment and Climate Change (NSW), is illustrated in Figure 3.2 and reported in DECC (2007).

**Figure 3.2: Recycled glass as sand pipe bedding**

Source: DECC NSW (2007)

Typically up to 5% reclaimed glass in the form of cullet is permitted in granular products.

Powdered glass cullet is pozzolanic, meaning that it will react with lime to form stabilised materials. As with all pozzolans, the contribution to strength development is less than that of Portland cement, meaning that cement combinations comprising these two materials will produce lower compressive strengths than Portland cement alone. However, there are clear economic benefits associated with the use of cullet as a cement component. The abrasion resistance of concrete containing powdered cullet is also improved.
3.3 Other Recycled Sources

Other main potential sources of recycled materials in base materials include industrial slags and bottom ash and fly ash.

3.3.1 Industrial Slags

Approximately 3 400 000 tonne of iron and steel slag products were produced in Australasia in 2007. Of this, 25%, or 679 000 tonne, was used in cementitious applications and 60%, or 1 630 000 tonne, was used in non-cementitious or road construction applications.

The use of slags in Australasia is shown in Figure 3.3. The different types of slag are:

- GBFS – granulated blast furnace slag
- BFS – blast furnace slag (rock slag)
- BOS – basic oxygen steel slag
- EAF – electric arc steel slag.

**Figure 3.3: Slag use in Australasia in 2000**

![Slag use in Australasia in 2000](source: ASA (2002))

The use of industrial slags is described in the Australasian Slag Association publication *A Guide to the Use of Iron and Steel Slag in Roads* (ASA 2002) as presented in Table 3.3 whilst typical properties of slags are presented in Table 3.4.
### Table 3.3: Use of slags in roads

<table>
<thead>
<tr>
<th>Slag source</th>
<th>Common nomenclature</th>
<th>Manufacturing process</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blast furnace iron slag</td>
<td>Rock slag or air-cooled slag</td>
<td>Crushing and screening slag which has been slowly air-cooled. Also available as uncrushed slag, i.e. spalls or skulls.</td>
<td>• base&lt;br&gt;• subbase&lt;br&gt;• concrete aggregate&lt;br&gt;• filter aggregate&lt;br&gt;• construction fill and select fill&lt;br&gt;• scour protection&lt;br&gt;• rockwool</td>
</tr>
<tr>
<td>Granulated sand or slag sand</td>
<td>Rapidly quenching molten slag with high-pressure, high-volume water sprays.</td>
<td></td>
<td>• subbase&lt;br&gt;• construction fill&lt;br&gt;• construction sand&lt;br&gt;• stabilising binder&lt;br&gt;• cement manufacture&lt;br&gt;• grit blasting&lt;br&gt;• reinforced earth wall infill&lt;br&gt;• glass manufacture</td>
</tr>
<tr>
<td>Ground granulated slag (GGBFS)</td>
<td>Grinding granulated slag to cement fineness.</td>
<td></td>
<td>• cement replacement able to enhance concrete durability and other desirable properties&lt;br&gt;• stabilising binder, either alone or blended</td>
</tr>
<tr>
<td>Pelletised sand (not produced in Australia)</td>
<td>Water-quenching molten sand on a sloped table and rotating drum which throws the pellets into the air for further cooling</td>
<td></td>
<td>• cement manufacture&lt;br&gt;• lightweight aggregate for concrete masonry products</td>
</tr>
<tr>
<td>Expanded slag or lightweight slag (not produced in Australia)</td>
<td>Controlled cooling of slag which has been air-cooled and watered.</td>
<td></td>
<td>• lightweight aggregate for masonry products and structural concrete&lt;br&gt;• skid resistant aggregate</td>
</tr>
<tr>
<td>Basic oxygen steel slag</td>
<td>BOS slag</td>
<td>Crushing and screening slag which has been air-cooled and watered.</td>
<td>• sealing aggregate (skid resistant)&lt;br&gt;• asphalt aggregate&lt;br&gt;• base, subbase&lt;br&gt;• construction fill&lt;br&gt;• subsoil drains&lt;br&gt;• grit blasting</td>
</tr>
<tr>
<td>Electric arc steel slag</td>
<td>EAF slag</td>
<td>Crushing and screening slag which has been air-cooled and watered.</td>
<td>• sealing aggregate (skid resistant)&lt;br&gt;• asphalt aggregate&lt;br&gt;• base, subbase&lt;br&gt;• construction fill&lt;br&gt;• subsoil drains&lt;br&gt;• grit blasting</td>
</tr>
</tbody>
</table>

*Source: Australasian Slag Association (2002)*
Table 3.4: Physical properties of iron & steel slags

<table>
<thead>
<tr>
<th>Physical property – aggregate</th>
<th>Blast furnace slag</th>
<th>Steel slag</th>
<th>Test method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock slag</td>
<td>2450–2550</td>
<td>3300–3400</td>
<td>AS 1141.5 &amp; 6</td>
</tr>
<tr>
<td>BOS slag</td>
<td>2550–2650</td>
<td>3350–3450</td>
<td></td>
</tr>
<tr>
<td>EAF slag</td>
<td></td>
<td>3300</td>
<td></td>
</tr>
<tr>
<td>Dry strength (kN)</td>
<td>85–100</td>
<td>275</td>
<td>AS 1141.22</td>
</tr>
<tr>
<td>Wet strength (kN)</td>
<td>65–90</td>
<td>230–300</td>
<td></td>
</tr>
<tr>
<td>Wet/dry strength variation (%)</td>
<td>10–20</td>
<td>5–20</td>
<td></td>
</tr>
<tr>
<td>Water absorption (%)</td>
<td>4–7</td>
<td>1–2 (coarse)</td>
<td>AS 1141.5 &amp; 6</td>
</tr>
<tr>
<td>LA abrasion</td>
<td>37–43</td>
<td>12–18</td>
<td></td>
</tr>
<tr>
<td>Polished aggregate friction value (PAFV)</td>
<td>NA</td>
<td>58–63</td>
<td>AS 1141.23</td>
</tr>
<tr>
<td>Sodium sulphate soundness (%)</td>
<td>&lt; 4</td>
<td>58–63</td>
<td>AS 1141.41/42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Physical property – Roadbase</th>
<th>Maximum dry density (kg/m³) (20 mm GMB standard compaction)</th>
<th>Optimum moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blast furnace slag</td>
<td>2050–2150</td>
<td>8–12</td>
</tr>
<tr>
<td>Steel slag</td>
<td>2300–2400</td>
<td>8–12</td>
</tr>
<tr>
<td>Test method</td>
<td>AS 1141.5.1.1</td>
<td>AS 1289.2.1.1</td>
</tr>
</tbody>
</table>

Note: OMC depends on the components of the mix.
Source: Australasian Slag Association (2002)

For evaluation of the satisfactory performance of slag as a granular material and as a stabilisation binder readers are referred to the accelerated load testing of slag road bases at Prospect, NSW, in 1988 (Kadar and Walter 1989), marginal materials stabilised in situ with slag/lime blends at Cooma, NSW, in 1994 (Jameson et al. 1995) and a marginal material stabilised in situ with a slag/lime blend at Dandenong, Victoria, in 1997 (Moffatt et al. 1998).

3.3.2 Ash and Fly Ash

Approximately 13 500 000 tonne of coal combustion products were produced in Australia and New Zealand in 2006/2007. Of this, 1 740 000 tonne (13%) was used in cementitious applications or concrete manufacture, while 744 000 tonne (6%) was used in non-cementitious applications. In all, about 3 680 000 tonne (27%) was used in projects offering some beneficial use (e.g. mine site remediation, local haul roads, etc.).

Readers are directed to the Ash Development Association of Australia (ADAA) website (http://www.adaa.asn.au/welcome.htm). The ADAA has also produced a series of case studies and technical notes, of which the following are directly pertinent to road construction:

- Technical Note 5 – Ultra High Flyash Pavement Construction – was produced following the accelerated loading testing of cement-stabilised fly ash pavements at Eraring Power Station in 1995 (Jameson et al. 1996a).
- Technical Note 6 – Cost Effective Embankment Construction –details the benefits of ash as a lightweight fill, particularly in soft soil environments (Jameson et al. 1996b).
4. Stabilised Materials

Unbound granular products originating from C&D waste can be used in the manufacture of stabilised materials by the application of a range of binders. Further information is provided in Part 4D of the Guide to Pavement Technology (Austroads 2006a). Typical applications include:

- the use of crushed concrete in combination with cement to manufacture modified and bound cement-stabilised basecourse:
  - manufacture of modified materials with a target UCS less than 3 MPa
  - manufacture of cement-treated base (CTB) with a target UCS greater than 3 MPa.

An example of the laying of a recycled cement-stabilised basecourse is shown in Figure 4.1.

**Figure 4.1: Laying recycled cement stabilised basecourse**

Source: ARRB Group.

- The use of RAP in combination with bitumen emulsion to manufacture a bound basecourse and subbase as:
  - part replacement of intermediate layers in deep lift asphalt pavements
  - full depth bituminous residential streets
  - cycle paths
  - industrial surfacings.

An example of the development of a recycled pavement material stabilised with bitumen emulsion is shown in Figure 4.2.

**Figure 4.2: Recycled pavement material stabilised with bitumen emulsion**

Source: Andrews et al. 2006.
5. Recycled Asphalt

5.1 General

It is estimated that about 80% of all reclaimed asphalt, or about 73,000,000 tonne, is recycled as road-making material in the USA each year. In Australia it is estimated that about half of the asphalt removed from road pavements is currently re-used in hotmix asphalt applications. Most of the remainder is used in base or subbase materials, with a small amount in cold recycling or as fill.

The most important use of recycled asphalt pavement (RAP) is as a component in the manufacture of new hotmix asphalt. Other processes for the recycling of asphalt include:

- in situ, using hot processes
- in situ, using cold processes
- cold plant mixing of RAP material.

A range of waste materials may also be recycled as components in the manufacture of asphalt, including:

- coal fly ash and cement kiln dust as fillers in hotmix asphalt
- crumb rubber
- slag aggregate
- foundry sand
- glass cullet.

5.2 Reclaimed Asphalt Pavement Recycling for New Hotmix Asphalt

The use of processed RAP to produce conventional hotmix asphalt is the most common form of asphalt recycling; it is now considered standard practice by most road agencies. There is technical data available that suggests for small quantities of RAP recycled hotmix asphalt is equivalent in quality and structural performance to conventional asphalt in terms of rutting, ravelling, weathering and fatigue cracking. The addition of up to 15% RAP, or even 20% RAP, has little impact on the properties of the asphalt mix. Little change is required to asphalt mix design procedures or production methods other than the preparation of separate mix designs for the required proportion of RAP and establishment of suitable protocols for handling, stockpiling and adding RAP.

Subject to appropriate asphalt mix designs being undertaken, it has been generally found that, where the proportion of RAP exceeds 20% and forms up to around 40% of RAP, the bitumen grade should be adjusted to one grade softer than that otherwise specified to compensate for the stiffness of the aged binder in the RAP.

Modified asphalt plants that provide for improved heat transfer, reduced emissions and effective mixing of recycled materials, are generally desirable for higher proportions of RAP addition (Austroads 2006b). Higher proportions of RAP also require greater control over uniformity of RAP materials; as a result, crushing and screening into separate size fractions is generally recommended.

Notwithstanding the use of modified plants for the production of recycled asphalt, the practical limit for RAP content in hotmix asphalt is widely considered to be about 40% to 50%. This is because the amount is limited by heat capacity, gaseous hydrocarbon emissions and the extent of additional costs in the processing and testing of RAP materials to ensure consistent properties of manufactured asphalt. Special plants based on microwave technology and other indirect heating methods have been developed to limit gaseous emissions from asphalt production with very high proportions of RAP (up to 100%). Such plants have only seen limited use due to higher energy costs and a need for intensive testing of materials.
Details of the specification, design and manufacture of hotmix asphalt containing RAP is addressed in Austroads (2006b and 2007).

5.3 Recycling of Other Materials in Hotmix Asphalt

5.3.1 Crumb Rubber

Crumb rubber is obtained from the recycling of motor vehicle tyres. Mixes with up to 20% of crumb rubber by mass of bitumen binder are regularly used in sprayed sealing work in polymer modified binder applications. Limited use has been made of similar binders in hotmix asphalt to produce flexible mixes with good resistance to reflection cracking. The design and manufacture of such materials is described in the Austroads guides to the selection and use of modified binders (Austroads 2006c and 2006d).

5.3.2 Slag Aggregate

A number of slag types are available in Australia depending on the industry from which they come. Materials with potential use in asphalt are derived from iron and steel manufacture and comprise three basic types.

*Blast furnace (BF) slag*

BF slag is derived from the production of molten iron. When cooled slowly, it produces a light grey vesicular material that can be crushed and screened using normal aggregate processing methods. The material does not generally have sufficient strength and abrasion resistance for use in asphalt except in lightly trafficked situations.

*Basic oxygen steel (BOS) slag and electric arc furnace (EAF) slag*

BOS and EAF slags produced in the manufacture of steel from molten iron or scrap metal are similar in characteristics. When cooled slowly they produce a hard, dense material. The density may be 20% greater than normal aggregates. They have good resistance to abrasion and polishing and have the potential for use in situations where high levels of surface friction are required. Processing costs and the lack of availability of a consistent supply have largely restricted their use in Australia to trial projects only.

*Foundry sand*

Used foundry sand is derived from the metals casting industry. When classified as inert, it has the potential for use in asphalt. It is regularly used in some states in the USA. Some trial projects have been undertaken in Australia with promising outcomes.

5.3.3 Glass

The use of glass cullet as an aggregate in asphalt was developed in the USA in the 1960s. Its use has not grown significantly due to cost and availability, although a number of States in the USA now allow regular use. As discussed in Section 3.2, its use is generally restricted to basecourse applications due to concerns arising from the potential for fretting of small particles of glass from the asphalt surface. Trial use in Australia indicates the potential for production of good quality asphalt materials using up to 20% glass cullet.
5.4 Cold Plant Recycling

Cold plant recycling is similar to cold in situ recycling except that the mixing of RAP, binder and additional materials is performed in a separate mixing plant. Cold plant recycling is more versatile than in situ recycling. It has a number of important advantages:

- The processing of RAP is the same as that required for RAP hotmix asphalt, thus eliminating the need for specialised reclaiming equipment.
- RAP may be combined from different sources.
- Additional processing of RAP can be used to provide greater control over the grading of materials, the use of additives and efficiency of mixing.
- Minor modifications only are required to standard mixing equipment used for other stabilising or asphalt mixing applications.

Cold plant recycled asphalt is suitable for the following applications:

- intermediate or basecourses in deep lift pavements
- shoulder surfacing
- asphalt pavement patching
- pavement shape correction prior to resurfacing.

In environmental and efficiency terms, cold plant recycling provides the following benefits:

- No heating is required.
- High production rates can be achieved.
- Mixes with up to 100% RAP can be produced.
- Materials can be transported and stockpiled for later use without loss of workability.
- Specialised asphalt paving equipment is not necessarily required.
- Materials cure more rapidly than conventional cold mixes manufactured with cutback bitumen binders, thereby providing improved deformation resistance and reduced risk of bleeding through following surfacing treatments.
6. Concrete

6.1 Aggregates from Recycled Concrete

The manufacture of coarse aggregates from demolition concrete (i.e. recycled concrete aggregate – RCA) for incorporation into structural concrete is well established and a national Australian guide is available (AS HB 155–2002).

This Australian guide suggests two classes of aggregate, viz: Class 1A – RCA, having a composition of entirely crushed concrete and little or no brick, and Class 1B – RCA, having a composition that may have up to 30% brick within the crushed concrete. Whilst the particle size distribution and stone hardness are no different to those applying to virgin materials (AS 2758.1), other typical requirements for coarse RCA are shown in Table 6.1.

Table 6.1: Recommended properties of RCA

<table>
<thead>
<tr>
<th>RCA property</th>
<th>Class1A – RCA</th>
<th>Class1B – RCA</th>
<th>Test method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick content (max)</td>
<td>0.5%</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>Stony material (max)</td>
<td>1%</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Friable material (max)</td>
<td>0.1%</td>
<td>0.1%</td>
<td></td>
</tr>
<tr>
<td>Particle shape (2:1 ratio)</td>
<td>35%</td>
<td>35%</td>
<td>AS 1141.14</td>
</tr>
<tr>
<td>Particle density (SSD min)</td>
<td>2.1 t/m³</td>
<td>1.8 t/m³</td>
<td>AS 1141.6</td>
</tr>
<tr>
<td>Bulk density (min)</td>
<td>1.2 t/m³</td>
<td>1.0 t/m³</td>
<td>AS 1141.4</td>
</tr>
<tr>
<td>Water absorption (max)</td>
<td>6%</td>
<td>8%</td>
<td>AS 1141.6</td>
</tr>
<tr>
<td>Aggregate crushing value (max)</td>
<td>30%</td>
<td>30%</td>
<td>AS 1141.21</td>
</tr>
<tr>
<td>Total impurity level (max)</td>
<td>1%</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>Loss on ignition (max)</td>
<td>5%</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Lost substance on washing (max)</td>
<td>1%</td>
<td>1%</td>
<td>AS 1141.24</td>
</tr>
<tr>
<td>Soundness loss (max)</td>
<td>9%</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

Source: AS HB 155 - 2002

The extent to which chemical contaminants are likely to adversely affect concrete properties are generalised in Table 6.2 and determined in accordance with NEPC 1999.

Table 6.2: RCA contaminants affecting concrete properties

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Effect on concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick</td>
<td>Low concentration (0.01%) of Mg (periclase) from refractory bricks. Slaking periclase particles causes internal or localised expansion</td>
</tr>
<tr>
<td>Stony material</td>
<td>Marginal effect at low concentrations below 5%</td>
</tr>
<tr>
<td>Gypsum</td>
<td>May induce ettringite formation in concrete with subsequent expansion</td>
</tr>
<tr>
<td>Wood</td>
<td>May decompose and swell under moist conditions with high potential for ‘pop outs’ in finished concrete</td>
</tr>
<tr>
<td>Clay lumps</td>
<td>Undesirable in concrete contributing to loss of strength through loss of aggregate bonding</td>
</tr>
<tr>
<td>Plate glass</td>
<td>Reactive with cement paste under wet conditions leading to deleterious alkali-silica reactions</td>
</tr>
</tbody>
</table>
Generally trial batches should be prepared to determine the appropriate mix proportions in relation to the characteristics required. Blending coarse RCA with natural aggregates at substitution rates below 30% is typical with no detriment. In addition, due to the high absorption rates, coarse aggregates should be pre-wetted to attain the desired workability. However, the use of RCA fine aggregates should be avoided as they give rise to significant reductions in workability, strength and finish.

### 6.2 Aggregates from Recycled Glass

The use of glass cullet as a replacement for fine aggregate in concrete is still a matter for research and associated trial mixes. In particular, the quality of the cullet in terms of sugar content (unless feedstock or cullet is appropriately washed using high temperature) can have a detrimental effect on cement hydration.

Concrete containing glass cullet as aggregate typically displays higher resistance to abrasion than equivalent materials made using quartz sand or similar materials as fine aggregate. Reduced drying shrinkage is also often observed for mixes containing glass cullet aggregate.

### 6.3 Aggregates from Supplementary Materials

Steel and blast furnace slags have been used in the manufacture of concrete primarily as coarse aggregates (although ground slags and fly ash are blended with commercial cements).

Though not widely used, air-cooled blast furnace slag is generally considered suitable for use as a concrete aggregate. In addition, the compressive strengths of concrete containing slag aggregate are comparable to virgin aggregates. However, steel slag aggregates generally exhibit a propensity to expand because of free calcium oxide (quicklime). To control this reaction, ageing of the aggregate is required.
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**Australian / New Zealand Standards**

AS 1141.4-2000, *Methods for sampling and testing aggregates: bulk density of aggregate.*


AS 1141.5-2000, *Methods for sampling and testing aggregates: particle density and water absorption of fine aggregate.*


Austroads’ Guide to Pavement Technology Part 4E: Recycled Materials presents the latest information on products manufactured from recycling various wastes through registered recycling and reprocessing facilities. In particular, this guide deals with the specification, manufacture and application of incorporating recycled materials into products commonly used in pavement construction.

Guide to Pavement Technology Part 4E

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