REPORT

CEMENT CONCRETE & AGGREGATES AUSTRALIA

# Use of Recycled Aggregates in Construction

This publication was prepared under standards, regulations and industry practices current at the date of publication and may no longer reflect current requirements or accepted practice.

This document is retained for historical reference only and should be used with caution.

Report

**Cement Concrete & Aggregates Australia**

# Use of Recycled Aggregates in Construction

May 2008

CEMENT CONCRETE
& AGGREGATES AUSTRALIA

# Contents


**EXECUTIVE SUMMARY** ..... 3

**1 INTRODUCTION** ..... 6

1.1 General ..... 6

1.2 Classification of Aggregates ..... 6

**2 MANUFACTURED AGGREGATES** ..... 7

2.1 Foamed Blast Furnace Slag (FBS) ..... 7

2.2 Fly Ash Aggregates ..... 8

2.3 Manufactured Sand ..... 8

2.4 Polystyrene Aggregate ..... 9

2.5 Expanded Clays, Shales and Slates ..... 10

**3 RECYCLED AGGREGATES** ..... 10

3.1 Recycled Concrete Aggregate (RCA) ..... 10

3.2 Recycled Concrete and Masonry (RCM) ..... 11

3.3 Reclaimed Aggregate (RA) ..... 12

3.4 Reclaimed Asphalt Pavement (RAP) ..... 12

3.5 Reclaimed Asphalt Aggregate (RAA) ..... 13

3.6 Glass Cullet ..... 13

3.7 Scrap Tyres ..... 14

3.8 Used Foundry Sand or Spent Foundry Sand ..... 14

**4 REUSED BY-PRODUCT** ..... 15

4.1 Air-cooled Blast Furnace Slag (BFS) ..... 15

4.2 Granulated Blast Furnace Slag (GBS) ..... 16

4.3 Electric Arc Furnace Slag (EAF) ..... 17

4.4 Steel Furnace Slag (BOS) ..... 17

4.5 Fly Ash (FA) ..... 19

4.6 Furnace Bottom Ash (FBA) ..... 19

4.7 Incinerator Bottom Ash (IBA) ..... 20

4.8 Coal Washery Reject (CWR) ..... 20

4.9 Organic Materials ..... 21

4.10 Crusher Fines ..... 21

**5 SUMMARY** ..... 21

**6 REFERENCES** ..... 22

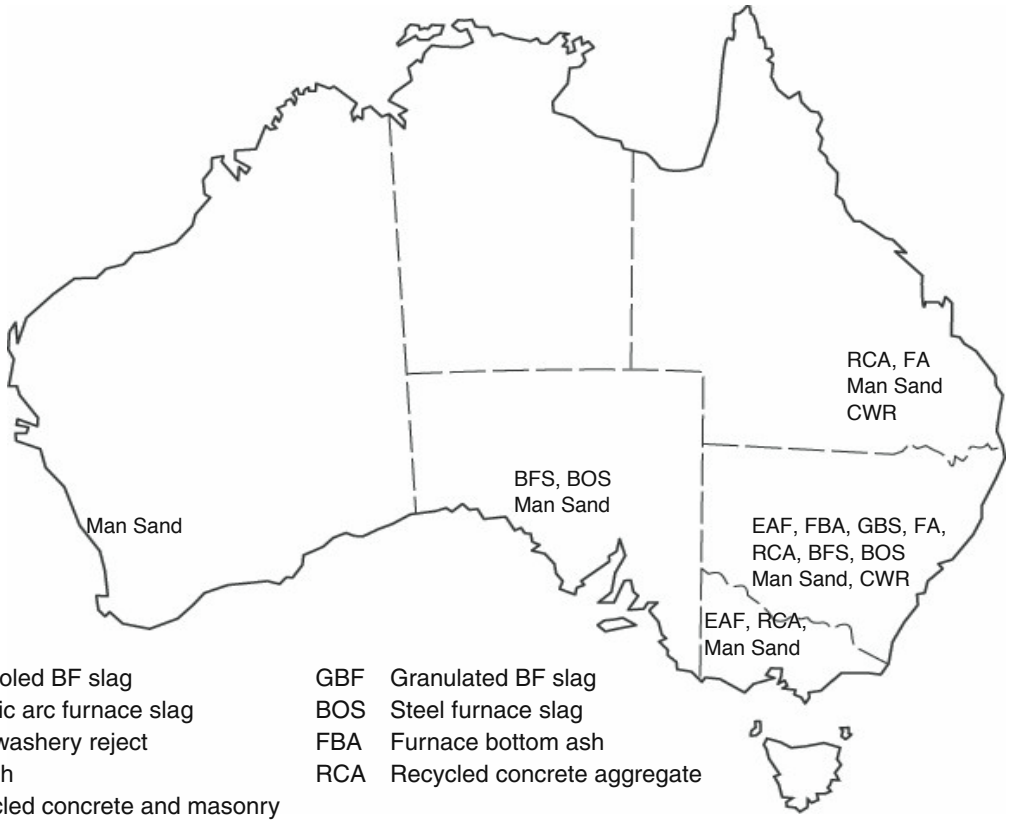
## EXECUTIVE SUMMARY

This report reviews the various types of aggregates and their potential for use in concrete and/or road construction materials. For the purpose of this review, aggregates are classified into manufactured, recycled and reused by-product aggregates. They are described in terms of sources and production process, physical and mechanical characteristics, the benefits and limitations of their use in concrete and/or road construction, and their availability. These are summarised in **Figure 1** and **Table 1**.

In many countries, including Australia, recycled concrete aggregates (RCA) have been proven to be practical for low-strength concretes and to a limited extent for some structural grade concrete. The processing and quality control cost associated with their use plus the premium paid for mix design adjustment to achieve the same strength grade as concrete with natural aggregates can vary considerably. Aggregates from selected materials and industrial by-products, on the other hand, have greater potential for use in concrete and/or as road construction materials.

A number of manufactured and recycled aggregates are readily available in certain localities. Air-cooled blast furnace slag (BFS) and manufactured sand are two good examples of concrete coarse and fine aggregates. Comprehensive performance data are available for air-cooled blast furnace slag and work is continuing to obtain performance data and appropriate specifications for manufactured sand. In other construction applications such as pavement, roadbase and sub-base, there is limited information on the performance of each material as assessment appeared to be based on field trials, especially those by road authorities.

In all cases, the availability and consistency of supply are prerequisites for the use of manufactured and recycled aggregates in the various applications.




**Legend:**

| | | | |
|---|---|---|---|
| BFS | Air-cooled BF slag | GBF | Granulated BF slag |
| EAF | Electric arc furnace slag | BOS | Steel furnace slag |
| CWR | Coal washery reject | FBA | Furnace bottom ash |
| FA | Fly ash | RCA | Recycled concrete aggregate |
| RCM | Recycled concrete and masonry | | |

**Figure 1** Sources of recycled aggregates

**TABLE 1** Summary of recycled aggregates in construction

| TYPE OF AGGREGATE | DESCRIPTION | APPLICATIONS | AVAILABILITY IN AUSTRALIA |
|---|---|---|---|
| **Manufactured Aggregates** | | | |
| Foamed Blast Furnace Slag | Water cooled blast furnace iron slag with stream trapped porous mass. | Lightweight concrete. | Not available. |
| Fly Ash | Sintered fly ash lightweight aggregate. Chemically bound fly ash aggregate. | Medium strength concrete. No data available. | Not available. |
| Manufactured Sand | Purposed-made crushed fine aggregate. | Partial sand substitute in concrete and asphaltic concrete. | Available commercially. |
| Polystyrene | Crushed waste expanded polystyrene or coated small polystyrene beads. | Lightweight concrete. | Proprietary products available. |
| Expanded Clays, Shales and Slates | Expanded clay lightweight aggregate. | Structural grades concrete. | Not available. |
| **Recycled Aggregates** | | | |
| Recycled Concrete Aggregate (RCA) | Crushed sound and clean waste concrete of at least 95% by weight of concrete with typical total contamination lower than 1% of the bulk mass.<br>Class 1A RCA is a well graded RCA with no more than 0.5% brick content. | Partial replacement (30%) for natural aggregate in concrete for sidewalks, kerbs and gutters. Also for structural concrete (with mix adjustment) and inferior permeability and shrinkage properties. | Available commercially particularly in the Sydney and Melbourne market. |
| Recycled Concrete and Masonry (RCM) | Graded aggregate produced from sorted and clean waste concrete and masonry.<br>Class 1B RCA is a class 1A RCA blended with no more than 30% crush brick. | Road base course and subbase material. | Available commercially. |
| Reclaimed Aggregate (RA) | Coarse aggregates reclaimed from returned concrete by separating the aggregates from the water-cement slurry. | Up to 32-MPa concrete with 100% reclaimed aggregates, and as partial replacement of natural aggregate in grades up to 80 MPa. | Self generated aggregate available to specific batching plants. |
| Reclaimed Asphalt Pavement (RAP) | Old asphalt concrete. | New asphaltic concrete pavement.<br>RAP/RCA blends for RCC in flexible pavement and sub-grade material. | Available for road construction. |
| Reclaimed Asphalt Aggregate (RAA) | Reclaimed coarse aggregate and recycled asphalt granules from waste asphalt concrete. | Concrete with penalties in mix adjustment. | Not available. |

**TABLE 1** *continues*

**TABLE 1** *continued*

| TYPE OF AGGREGATE | DESCRIPTION | APPLICATIONS | AVAILABILITY IN AUSTRALIA |
|---|---|---|---|
| Glass Cullet | Glass cullet pulverised into a sand-like product. | Partial replacement of fine aggregate in concrete (with small penalties in mix design). | Available in NSW. |
| Scrap Tyres | Processed scrap tyres as tyre chips and crumb rubber aggregate. | Crumb rubber in asphalt and sprayed bitumen seals. | Available. |
| Used Foundry Sand | Spent foundry sand. | Partial replacement of fine aggregate in concrete and asphaltic concrete. | Available in NSW. |
| **Reused By-product Aggregates** | | | |
| Air-cooled BF Slag | Slowly air-cooled crystalline iron slag – crushed and screened. Also available as uncrushed slag. | All structural grade concrete. | Commercially available from Port Kembla and Whyalla |
| Granulated BF Slag | Sand-like rapidly quenched iron slag with high volume of water sprays. | Concreting sand with some reservations. | Availability dependent on demand as SCM |
| Electric Arc Furnace Slag | Air-cooled steel slag – crushed and screened. | Road stabilisation and controlled low-strength fill. | Commercially available in Melbourne, Sydney and Newcastle. |
| Steel Furnace Slag | Air-cooled steel slag from the Basic Oxygen System (BOS) – crushed and screened. | Asphalt aggregate or for road bases and subbases. | Commercially available from Port Kembla and Whyalla. |
| Fly Ash | Run-of-the-station fly ash from coal fired power station. | Fine aggregate for concrete, and road stabilisation. | Commercially available in the Sydney market. |
| Furnace Bottom Ash | Particle or agglomerates of ash collected at the bottom of furnace. | Fine aggregate for concrete products and road base component. | Commercially available in the Sydney market. |
| Incinerator Bottom Ash | Incinerator residues. | Sintered domestic refuse artificial aggregate. | Proprietary products with limited availability. |
| Coal Washery Reject | Coal reject or colliery spoil. | Road subbases. | Commercially available in NSW and Queensland. |
| Organic Materials | Rice husks, woodchip and sawdust. | Lightweight aggregate in products. | Not available. |

# 1 INTRODUCTION

## 1.1 General

There is increasing demand and interest in aggregates from non-traditional sources such as from industrial by-products and recycled construction and demolition (C&D) wastes. The American Concrete Institute (ACI)[1] focuses on the removal and reuse of hardened concrete whereas the Department of the Environment and Water Resources in Australia and CSIRO[2] have developed a guide on the use of recycled concrete and masonry materials.

The Waste & Resources Action Programme (WRAP) in the UK classified aggregates from primary, recycled and secondary material resources. Recycled aggregates encompass industrial by-products and reused construction products, all of which were once considered wastes and dumped in landfill. The recently introduced European Standards for aggregates do not discriminate between different sources, and are for 'aggregates from natural, recycled and manufactured materials'. The focus is on fitness for purpose rather than origin of the resource.

The purpose of this report is to review the various sources of aggregate and examine their potential use in concrete and/or road construction materials.

## 1.2 Classification of Aggregates

For the purpose of this report, the following classifications are adopted.

***Natural aggregate***
Construction aggregates produced from natural sources such as gravel and sand, and extractive products such as crushed rock.

***Manufactured aggregate***
Aggregates manufactured from selected naturally occurring materials, by-products of industrial processes or a combination of these.

***Recycled aggregate***
Aggregates derived from the processing of materials previously used in a product and/or in construction.

***Reused by-product***
Aggregates produced from by-products of industrial processes.

The aggregates in each of these classes are:

| Class | Aggregates |
|---|---|
| Natural | Crushed rock<br>Sand and gravel<br>Crushed river gravel |
| Manufactured | Foamed Blast Furnace Slag (FBS)<br>Fly Ash Aggregate<br>Manufactured Sand<br>Polystyrene Aggregate (PSA)<br>Expanded Clays, Shales and Slates |

| | |
|---|---|
| Recycled | Recycled Concrete Aggregate (RCA)<br>Recycled Concrete and Masonry (RCM)<br>Reclaimed Aggregate (RA)<br>Reclaimed Asphalt Pavement (RAP)<br>Reclaimed Asphalt Aggregate (RAA)<br>Glass Cullet<br>Scrap Tyres<br>Used Foundry Sand |
| Reused by-product | Air-cooled BF Slag (BFS)<br>Granulated BF Slag (GBS)<br>Electric Arc Furnace Slag (EAF)<br>Steel Furnace Slag (BOS)<br>Fly Ash (FA)<br>Furnace Bottom Ash (FBA)<br>Incinerator Bottom Ash (IBA)<br>Coal Washery Reject (CWR)<br>Organic Materials<br>Crusher fines<br>Mine tailings |

This report will focus on reviewing manufactured, recycled and reused by-product as aggregates in terms of their physical and mechanical characteristics and the benefits and limitations of their use in concrete and/or road construction materials.

## 2 MANUFACTURED AGGREGATES

These are purpose-made from selected materials such as crushed rocks for manufactured sand, fly ash for fly ash aggregate, and by-products from other mineral-extraction processes such as clay for expanded clay aggregate.

### 2.1 Foamed Blast Furnace Slag (FBS)

***Description*** Foamed blast furnace slag (FBS) is a by-product of iron slag produced in a similar way to granulated blast-furnace slag but with a controlled amount of water, applied to the molten slag to trap the steam in the mass, giving a porous, pumice-like product. This product is then crushed and screened to sizes suitable as lightweight aggregate. The foaming process can change advantageously the mineralogical composition of the slag, removing the unsoundness in almost all slag as well as rendering it stable by the elimination of the β- and γ-dicalcium silicate inversion.

Foamed slag was probably first produced in Germany. The lighter types can be used as aggregates in concrete blocks and in insulating concretes, roof screeds, and the heavier ones for structural concrete. In Australia, foamed slag was produced by controlled pouring of pot blast furnace slag into specially constructed slag bays.

Foamed slag aggregate is not available in Australia.

***Applications and limitations*** Concrete made with foamed slag aggregate has a density of about 2000 kg/m$^3$ and may be possible to produce concretes of strengths greater than 30 MPa. Physical characteristics of some experimental products are shown in **Table 2**.

Foamed slag in a pelletized form has been developed in Canada[3]. Production of this type is claimed to contribute less to air pollution than does the normal process.

**TABLE 2** Typical physical properties of lightweight coarse aggregates *(after Popovics[4])*

| Aggregate | Bulk specific gravity, SSD | Unit weight (kg/m$^3$) | Water absorption (% by weight) |
|---|---|---|---|
| Foamed blast-furnace slag<br>Australian experimental products (Jones and Murrie[41]) | 1.15–2.20<br>– | 400–1200<br>885–1375 | 8–15<br>0.7–19.2 |
| Expanded clay, shale and slate | 1.1–2.1 | 560–960 | 2–15 |
| Sintered fly ash<br>(Powerlyte[5]) | ~17<br>1.20–1.47 | 590–770<br>650–790 | 14–24<br>16–25 |
| Saw dust | 0.35–0.60 | 128–320 | 10–35 |
| Polystyrene foam | 0.05 | 10–20 | ~50 |
| Scoria | | 2000 | |

*Note: Fine particles of lightweight aggregates usually have higher bulk specific gravity and unit weight than coarse particles of the same kind of material.*

### 2.2 Fly Ash Aggregates

***Description*** Several lightweight concrete aggregates can be produced from fly ash. In addition to the use of furnace bottom ash in concrete masonry, pellets of fly ash can be bound by thermal fusion or chemically, using cement or lime. Such materials have many desirable properties.

In the mid 1990s, Pacific Power conducted a feasibility study of the production of sintered fly ash aggregates (Powerlyte) and examined the use of such aggregates in concrete production. Fly ash was pelletised and fired at controlled temperature to produce synthetic coarse and fine aggregates. These fly ash aggregates have a specific gravity range of 1.20–1.47, a bulk density range of 650–790 kg/m$^3$ and very high absorption from 16–24.8%.

There has been production of chemically-bound fly ash aggregate in Australia but there has been no commercial development of sintered fly ash aggregate.

***Applications and limitations*** Concrete containing sintered fly ash aggregates were experimentally investigated[5]. It was found that the density of the hardened concrete ranged between 1740 and 1840 kg/m$^3$ compared with 2400 kg/m$^3$ for the control concrete made from natural aggregates. Structural grade 25 concrete could be produced but with significantly higher cement contents compared to the control. The elastic modulus was found to be around 14–17 GPa compared to 28–30 GPa in the control. The drying shrinkage was found to be higher than the control.

### 2.3 Manufactured Sand

***Description*** Manufactured sand is a purpose-made crushed fine aggregate produced from a suitable source material and designed for use in concrete or road construction. Only source materials with suitable strength, durability and shape characteristics are considered. Production generally involves crushing, screening and possibly washing. Separation into discrete fractions, recombining and blending may be necessary.

Extensive research is being conducted in Australia by Cement Concrete & Aggregates Australia (CCAA) to support the specification of manufactured sands in Australian Standards

and to provide guidance on its use as fine aggregate in concrete. The RTA has also carrying out an R&D project which supports the revision of its specification for natural and manufactured sands for asphalt and concrete mixes.

CCAA research[6] recommended specification of manufactured sand in terms of density, grading, material finer than 75 um, particle shape, quantity and quality limits on deleterious fines, durability and impurities.

Manufactured sand is widely available in Australia.

***Applications and limitations*** The shape, grading and excessive amount of fines may impact the workability, bleeding rate, finishability and susceptibility to plastic cracking of concrete. Improvement in grain shape of manufactured sand can be achieved when unprocessed dust is put through an autogenous crushing action of a specific crusher. Blending of 50% fine sand with manufactured sand[7] produced more workable and generally superior concretes to those with fine and coarse natural sands. For both basaltic and crushed river gravel manufactured sands, the amount of –75 μm of up to 15% can be considered realistic and not detrimental to most plastic and hardened properties of concrete pavement mix. Adjustments of concrete mix proportions, such as in coarse aggregate to sand ratio or admixture dosages, are important to achieve the full benefits of the use of manufactured sand in concrete[8]. Various methods of removal of clay and silt from basalt crusher dust have been tried[9].

Manufactured sand can be used to replace a major proportion of natural sand with no significant loss of performance in cement-based products. Reported experience has shown that most manufactured sands in Australia are not used as the only source of fine aggregate in most concrete mix designs. Manufactured sand may be tailored for use in concrete, tile, asphalt, or masonry production.

Queensland Main Roads specification MRS11.70 allows sand replacement up to 60% with manufactured sand for insitu concrete.

### 2.4 Polystyrene Aggregate

***Description*** Crushed waste expanded polystyrene is used in combination with normal weight aggregates to produce lightweight concrete. An Australian proprietary product using coated small polystyrene beads (a maximum size of 3 mm or 1.5 mm) or recycled granulate (shredded and graded to a maximum size of 5 mm) was introduced into the market in 1990. The product is used and supplied in standard premix concrete trucks with concrete density ranging from 300–1800 kg/m$^3$ and a compressive strength range of 1–15 MPa[10]. The coated aggregate has a density of 32 kg/m$^3$ and a material thermal coefficient (k) of 0.04 w/mK. SEM has shown that the coating allows crystals of cement hydrates to grow into the surface of the polystyrene aggregate.

The density of the concrete has been reported[11] to vary between 1600 and 2000 kg/m$^3$. The cement contents of polystyrene aggregate concrete were 410 and 540 kg/m$^3$. Experimental results showed that the polystyrene aggregate concrete has a higher modulus of elasticity for a given strength than expanded shale, clay or slate lightweight aggregate concrete. Creep of polystyrene aggregate concrete increases with decrease in the density of concrete. However, the density of concrete influences the strength of concrete more significantly than its creep potential. The 150-day creep coefficient for polystyrene concrete in the density range of 1600 to 2000 kg/m$^3$, subjected to a stress/strength ratio of 0.30 and loaded at 28 days, was between 1.43 and 2.07 for the concrete with the cement content of 410 kg/m$^3$.

With the cement content of 540 kg/m$^3$, the creep coefficient ranged between 1.55 and 1.89. Polystyrene aggregate concrete that showed increased shrinkage also exhibited higher creep.

***Applications and limitations*** A comprehensive range of engineering properties of concrete made with such aggregate and many examples of their applications in Australia have been reported[12].

### 2.5 Expanded Clays, Shales and Slates

***Description*** Certain clays, shales, and slates expand several fold when heated to a semiplastic stage (as a result of the formation of gas within the mass of the material at the fusion temperature) and develop a cellular internal structure. Heavier expanded clay, shale and slate aggregates can be used for structural lightweight concretes including prestressed concrete elements. Typical properties are given in **Table 2**.

Expanded clay lightweight aggregate was successfully produced and used in Sydney (eg that used in Australia Square development) in the 1960s. However, such aggregate is no longer available commercially in Australia.

## 3 RECYCLED AGGREGATES

Recycled aggregates are aggregates derived from the processing of materials previously used in a product and/or in construction. Examples include recycled concrete from construction and demolition waste material (C&D), reclaimed aggregate from asphalt pavement and scrap tyres.

### 3.1 Recycled Concrete Aggregate (RCA)

***Description*** Coarse recycled concrete aggregate (RCA) is produced by crushing sound, clean demolition waste of at least 95% by weight of concrete, and having a total contaminant level typically lower than 1% of the bulk mass. Other materials that may be present in RCA are gravel, crushed stone, hydraulic-cement concrete or a combination thereof deemed suitable for premix concrete production.

In Australia, RCA has been the most common construction and demolition waste used in concrete production both as coarse and fine aggregate. About five million tonnes of recycled concrete and masonry are available in Australian markets principally in Melbourne and Sydney, of which 500,000 tonnes is RCA.

***Applications and limitations*** Earlier research work[13, 14] has shown the potential of RCA in a range of specific engineering applications. CSIRO[2] reported that Class 1A RCA, which is a well graded, good quality RCA with no greater than 0.5% brick content, had the potential for use in a wide range of applications, subject to appropriate test or performance requirements. Applications include partial replacement (up to 30% of coarse RCA) for virgin material in concrete production for non-structural work such as kerbs and gutters. Current field experience with the use of recycled concrete aggregates for structural applications is scarce. It was suggested that Class 1A RCA could be incorporated into 30- to 40-MPa concrete exposed to benign environments but with some penalties in mix adjustment, permeability and shrinkage properties[15]. There were no visual detrimental effects in the concrete and it was expected that the cost of the increase in cement content could be offset by the lower cost of recycled concrete aggregates.

RCA has a lower specific gravity (2.44–2.46) and higher water absorption (4.5–5.4) than most natural aggregates. Fine RCA, in particular, has an even lower SG of around 2.32 and a very high water absorption of 6.2%. RCA concrete has unit weight in the range of 2240–2320 kg/m$^3$. It has higher water demand and gave lower compressive strength than control concrete made from natural aggregate at equal water to cement ratio RCA concrete has similar flexural strength but lower elastic modulus than control. RCA also resulted in higher drying shrinkage and creep but comparable expansion to control. The adherence of mortar to the surface of RCA was the main cause of higher water absorption, lower SG and poor mechanical properties. Excessive expansion or swelling can be caused by contamination by plaster and gypsum. Adjustments of the mix design would be necessary to offset the effect of RCA on workability, absorption, strength and shrinkage.

In terms of durability properties, RCA concrete has higher rapid chloride ion permeability but similar carbonation rate (CSIRO accelerated carbonation in 4% $CO_2$ at 50% RH) to control concrete. Stark[16] reported the possible expansion due to alkali silica reaction (ASR) in new concrete containing RCA from ASR-affected concrete. A 20% cement replacement with fly ash was found to control ASR expansion in the new concrete to safe levels.

The impact of high water absorption of recycled fine aggregate on increased shrinkage and gas permeability of concrete has been highlighted[17]. This was due to the migration of water absorbed by the aggregate to the paste around particles of aggregates, thus influencing the volume of water and pores in the paste. Recycled fine aggregate has high water absorption due to it containing a large quantity of hydrated cement paste from the demolished concrete.

Increasing the level of cleanliness of RCA, in terms of the amount of mortar adhering to aggregate particles, has been found[18] to improve the workability, mass per unit volume and compressive strength of the concrete and to reduce the air content.

The CSIRO guide[2] gives contamination limits for various classes of RCA. The binder content for Grade 1 RC concrete with 30% partial replacement with coarse Class 1A RCA is comparable to that required for concrete containing 100% natural aggregate. For Grade 2 RC mixes containing up to 100% coarse Class 1A RCA, extra binder loading may be required to achieve the specified compressive strength.

The Dutch standard VBT 1995 allows up to 20% replacement of natural aggregate with RCA or recycled mixed aggregates (RMA) without a need for additional testing for all concrete up to a characteristic strength of 65 MPa and all relevant environmental classes (equivalent to specific maximum levels of W/C). Since 1997 the Dutch standard on aggregates for concrete has been updated to accommodate for the application of specific recycled aggregates, provided their specific mass is over 2000 kg/m$^3$.

RTA3051 specification for unbound and modified base and subbase materials allows the use of crushed concrete for surfaced road pavements.

### 3.2 Recycled Concrete and Masonry (RCM)

***Description*** Coarse recycled concrete and masonry (RCM) is graded aggregates produced from sorted and clean waste concrete and masonry typically for road subbase applications. The material may contain small quantities of brick, gravel, crushed rock or other forms of stony material as blended material. Fine recycled aggregate may also be referred to as crushed concrete fines.

***Applications and limitations*** The impact of 100% replacement of river gravel with RCA or RCM (mixture of broken masonry and concrete debris) and up to 50% replacement of natural sand with washed recycled crusher sand has been examined in the production of Grade 35 flowable concrete[19]. There were difficulties in controlling the water due to high water absorption of the recycled aggregates. High range superplasticiser was required to maintain a correct workability for sufficient time. The compressive strength was influenced by the actual w/c in a much more pronounced way than the type and amount of recycled material. The mixtures with RMA showed a slightly lower strength than the concrete with RCA (with about the same w/c). Higher amounts of recycled sands made it increasingly difficult to obtain a mixture with the desired w/c and workability. RCM gave more swelling in seawater, creep and a higher chloride intrusion than the RCA. The concrete with natural aggregate gave the lowest values. There was no evidence of risk of ASR with the types of recycled aggregates used.

In Australia, Class 1B RCA is a Class 1A RCA blended with no more than 30% crushed brick. This type of blend is considered suitable for granular base course and subbase material.

### 3.3 Reclaimed Aggregate (RA)

***Description*** Aggregate can be reclaimed from concrete returned to a batching plant by separating the aggregates from the water-cement slurry using one of a number of alternative technologies, most of which are based on washing the material with water. Aggregates are screened for later use and the water may be reclaimed, depending on the technology adopted.

As an alternative method for reclaiming aggregates from the returned concrete in fresh state, a process of allowing it to harden for a short period, after which it is crushed for use as aggregate in new mixes, has been examined[20].

Reclaimed aggregate is relatively clean and has a combined grading of both coarse and fine aggregate. Like any graded aggregate it must be handled in such a way as to avoid segregation. The physical and mechanical properties of reclaimed aggregate reflect those of the original aggregates used except for their combined grading.

***Applications and limitations*** Reclaimed aggregate is used to replace part or all aggregates in concrete with mix adjustments made to compensate for the fine particles (eg –2 mm) removed with the wash water. In Australia, structural grades up to 32 MPa have been used with 100% reclaimed aggregate[21]. Partial replacement with reclaimed aggregate has also been introduced into higher grades concrete of up to 80 MPa.

The initial finding for concrete with reclaimed aggregates from hardened returned concrete indicated that properties such as strength might be enhanced by the use of the aggregate within a certain time frame. Other properties such as workability may be decreased due to the nature of the crushed material.

### 3.4 Reclaimed Asphalt Pavement (RAP)

***Description and constituents*** Reclaimed asphalt pavement (RAP) is a reuse of old asphalt concretes as the aggregate base for new asphaltic concrete.

***Applications and limitations*** RTA QA Spec R116 Asphalt permits the use of up to 15% reclaimed asphalt pavement (RAP) in new asphalt mixes. A technical direction allowing up to 20% recycled asphalt within certain asphalts was released in August 2005. Further increases in recycled content will be considered when performance implications of the current amendment are demonstrated.

The possible use of RAP and RCA as a substitute for roller compacted concrete (RCC) in flexible pavement has been evaluated through laboratory and field trials[22]. This type of material has been used in several RTA projects including the M7 Motorway. A new brick/RAP blended material for use as a select sub-grade material has proven to have superior properties to conventional material such as sandstone[23].

### 3.5 Reclaimed Asphalt Aggregate (RAA)

A new reprocessing method has been developed in Japan[24] to produce reclaimed coarse aggregate and recycled asphalt granules from waste asphalt concrete and concrete dust. There is no reported use of this process in Australia.

Concrete with reclaimed asphalt aggregate achieved about 55%, 65% and 105% of the compressive, tensile and bending strengths respectively of concrete with new aggregate.

### 3.6 Glass Cullet

***Description*** Glass cullet may be pulverised into a sand-like product, for which there are limited applications as non-structural concrete aggregate, fill material and for drainage. A 2003 scoping study by the Australian Environment Business Network[25] found that approximately 15,000 tonnes of glass fines currently going to landfill annually in New South Wales could be used in asphalt.

In Australia, it has been found that crushed cullet sand (–2.46 mm) has a specific gravity between 2.4 and 2.5 and water absorption less than 1%[26]. It may contain up to 2% of impurity and 5% loss on ignition.

***Applications and limitations*** Crushed cullet sand performed well in concrete both in laboratory and field tests if appropriately blended with natural sand. ASR arising from cullet use as fine aggregate replacement was found to be significantly reduced with the use of binders containing at least 30% fly ash. There was a corresponding 5% reduction in concrete compressive strength at 5% cullet substitution for natural sand in concrete compared to a 27% reduction at 30% substitution level. Marginally lower drying shrinkage values were obtained for glass cullet concrete compared to equivalent conventional concrete mixes. A 20% cullet replacement limit was recommended[26] for non-structural concrete such as footpaths and cycleways.

In 2005, the RTA and the DEC[27] initiated a project to assess the technical and economic performance of recycled crushed glass fines as partial cement and sand replacements within concrete used for road pavement construction and related civil works. The RTA intends to revise its specifications and purchasing policy if the laboratory and field trials demonstrate that such changes are technically and economically feasible.

In Germany, expanded glass granulates have been made from recycled glass which are round and with diameters from 0.04 to 16 mm[28]. This type of product is promoted as lightweight aggregate suitable for drymix mortar applications, such as plasters, mortars, adhesives and screeds.

In the US, the amount of glass used as aggregate has rapidly increased over the last few years and it is estimated that potentially it could amount to several million tonnes. There are examples of its use for beach recharge in the US (eg Fort Bragg, California). However, waste glass in the UK commands a prohibitively high market value, as demand outstrips supply, and it may not at present be available in sufficient quantities to satisfy bulk applications. It also requires some treatment before use.

### 3.7 Scrap Tyres

***Description*** The possible use of scrap tyres in the form of tyre chips and crumb rubber aggregate. There is a US Patent on a crumb rubber-reinforced concrete, and research, conducted on concrete with tyre chips and crumb rubber aggregate. Another development is in the use of finely ground scrap or crumb rubber in asphalt. There are three manufacturing methods:

- Wet process where the crumb rubber is added to the hot mix asphalt during the manufacturing process using special mixing equipment
- Dry process, where the crumb rubber is added to the aggregate prior to the addition of the asphalt concrete
- Terminal blend process, where the rubber is added to the asphalt concrete at the bitumen refinery.

The current use of scrap rubber in Australia is in specialised sprayed bitumen seals for road works.

***Applications and limitations*** Concretes with tyre chips and crumb rubber aggregate were found to exhibit lower compressive strength and splitting tensile strength. However, they have ductile characteristic and ability to absorb a large amount of plastic energy under compressive and tensile loads[29,30].

In Australia, apart from the use of scrap rubber in specialised sprayed bitumen seals, the RTA and DEC[27] have been working to develop a Code of Practice for the manufacture and handling of asphalt containing finely ground scrap or crumb rubber since 2003. RTA field trials and studies have demonstrated that scrap rubber asphalt not only extends road life and enables the use of thinner pavements, but can also significantly reduce road traffic tyre noise. It is particularly suitable for use in overlaying fatigued/cracked pavements, and can also be used as a durable crack-resistant asphalt surface in new construction. Although it is more expensive, the longer life and higher coverage makes scrap rubber asphalt an economically attractive alternative pavement[27]. With more than six million tyres consigned to NSW landfills every year, the recovery and recycling of scrap tyres is of national importance and a key priority for the NSW DEC. The current application in specialised sprayed bitumen seals in road works diverts a relatively small amount of the scrap rubber waste stream from landfills. Approximately nine million of the US's 250 million scrapped tyres are converted into crumbed rubber each year. Ground tyre rubber is used as a fine aggregate addition (dry process) in asphalt friction courses.

### 3.8 Used Foundry Sand or Spent Foundry Sand

***Description*** Spent foundry sands are generated by the metal casting industry. Foundries purchase new, virgin sand to make casting moulds, and the sand is reused numerous times within the foundry. However, heat and mechanical abrasion eventually render the sand unsuitable for use in casting moulds, and a portion of the sand is continuously removed and replaced with virgin sand. The spent foundry sand is either recycled in a non-foundry application or landfill. Estimates are that less than 15% of the 6–10 million tons of spent foundry sands generated annually in the US are recycled.

The US Environmental Protection Agency (EPA) believes a greater percentage of spent foundry sand can be safely and economically recycled. The EPA has found that spent foundry sands produced by iron, steel, and aluminium foundries are rarely hazardous.

In New South Wales, at least 8000 tonnes of foundry sand that are currently going to landfill annually are blendable with asphalt[27].

***Applications and limitations*** The US Environmental Protection Agency[31] supports the use of spent foundry sands from these foundry types in the following applications:

- As partial replacement for fine aggregate in asphalt mixtures
- As partial replacement for fine aggregate in portland cement concrete
- As source material for the manufacture of portland cement
- As sand used in masonry mortar mixes.

In addition, use of foundry sand from iron, steel and aluminum foundries in flowable fill, road embankments, road base, manufactured soil, agricultural amendments, and similar uses may be appropriate depending on the site and the sand composition[32]. For these applications, characterisation of the sand and a site-specific assessment are recommended before use.

Regardless of the application, foundries and foundry sand recyclers should consult state regulators to ensure that planned uses are consistent with state beneficial use and waste management programmes and that the chemical and physical properties of the sand meet applicable state environmental limits, engineering performance criteria, and other state requirements. The South Australian EPA 329/03[33] provides guidelines for the classification and disposal of used foundry sand (UFS).

Used foundry sand should be managed in a way that will prevent contamination and provide a quality product to the end user so that it is more likely that foundries will be successful in finding reuse and recycling markets for the spent sand. As an example, a test report on the sand from a foundry in Sydney which classified it as inert reduced disposal costs from $92 per tonne to $34 per tonne.

## 4 REUSED BY-PRODUCT

Reused by-product aggregates are aggregates produced from by-products of industrial processes. Examples include various aggregates from iron and steel manufacturers.

In 2005, 2.35 million tonnes (Mt) (78%) of the 3.1 Mt of iron and steel slag produced in Australia was effectively utilised in productive or some beneficial manner and therefore not requiring disposal as landfill[34] In the same period, a total of 12.5 Mt of coal combustion product was produced, of which 1.97 Mt (16%) was sold, 1.46 Mt (12%) for use as supplementary cementitious material (SCM).

### 4.1 Air-cooled Blast Furnace Slag (BFS)

***Description*** Air-cooled blast furnace slag (BFS) is a by-product of iron manufacturing, in which silica and alumina constituents combine with lime to form a molten slag collected on the top of the iron in a blast furnace. The slag issues from the furnace as a molten stream at 1400–1600°C. If this is allowed to cool slowly, it solidifies to a grey, crystalline, stone-like material, known as air-cooled slag. This product is then crushed and screened to sizes suitable as coarse aggregate.

Typical chemical constituents and physical properties of BFS are given in **Tables 3 and 4** respectively. The vesicular nature of air-cooled slag means that care is needed to use the aggregate in a saturated condition if rapid slump loss and lack of pumpability are to be avoided. There also tends to be a distinct difference in specific gravity (SG) between different

size fractions. Excellent bond strength can be developed owing to both the vesicularity and the chemical composition of the aggregate, while particle shape tends to be better than natural aggregates[35]. Coarse air-cooled blast furnace slag aggregate has a specific gravity of 2.54 with 3.3% water absorption.

Air-cooled blast furnace slag is available from Port Kembla and Whyalla. Since 2000, over one million tonnes of blast furnace slag has been available annually of which over 700,000 tonnes is used by the concrete industry.

***Applications and limitations*** Concrete of various strength grades has been produced using BFS aggregate. Grades 20, 25 and 32 concrete containing air-cooled slag aggregate was found to give higher or similar results for compressive, indirect tensile and flexural strengths at ages of 3, 7, 28 and 91 days to control mixes made from crushed river gravel (CRG) and the same amounts of cement and fly ash[36]. Drying shrinkage of the Grades 20 and 32 concrete was lower for the slag aggregate for all periods of drying up to 56 days. For Grades 20 and 40 concrete, the elastic modulus and Poisson's ratio of the slag aggregate concretes were similar to and marginally higher than control concrete respectively. The specific creep of the Grade 20 was lower than control, while Grade 40 concrete had similar specific creep to control.

In Grade 50 concretes, and in comparison to control mixes proportioned with basalt or CRG as coarse aggregate, concrete with slag coarse aggregate demands similar cement content and has lower 56-day drying shrinkage but higher specific creep factors[37]. In-service performance of the use of Port Kembla blast furnace slag as concrete aggregate in concrete wharf structures have been reported[38, 39, 40].

The commercial use of BFS aggregate appears to be limited. This is possibly due to cost associated with the transportation of the product from the specific source.

### 4.2 Granulated Blast Furnace Slag (GBS)

***Description*** Granulated blast furnace slag or *slag sand* is the product of rapid quenching of molten blast furnace slag with an excess amount of water to produce a sand-like product. In Australia, granulated slag is used primarily in the production of ground granulated blast furnace cement. Excess amount of such granulates can be used as a fine aggregate (coarse sand). The chemical composition of *slag sand* is similar to that of air-cooled blast furnace slag given in **Table 2**. Because of the rapid quenching process, its structure is more amorphous.

The availability of slag sand in Australia is largely dependent on the competing demand on its use as a supplementary cementitious material. It is understood that no slag sand has been supplied commercially in recent years.

***Applications and limitations*** Several hundred cubic metres of concrete made with granulated slag sand have been used at Port Kembla[41]. It was difficult to regulate the slump of the concrete due to the shards and slivers of the slag sand. Rod milling of the sand has proved to be appropriate to produce concrete sand and tests showed the applicability of the material. However, water demand for slag sand concrete was still high and further test work would be required to develop appropriate mixes to minimize this. The deficiency of slag sand was put down to the weakness in the grains[35].

### 4.3 Electric Arc Furnace Slag (EAF)

***Description*** Electric arc furnace (EAF) slag is a by-product of steel formed in an electric arc furnace. In the process, steel scrap and fluxes are added to a refractory lined cup-shaped vessel. This vessel has a lid through which carbon electrodes are passed. An arc is induced between the scrap and electrodes and the resultant heat generated melts scrap and fluxes. Steel and slag are also separated similarly to the steel furnace slag process. EAF slag is available in Australia.

EAF slag contains different forms of iron oxides; mostly include magnesium and manganese compounds. The major hydrate compounds in EAF slag are quick lime (CaO), magnesium compounds and calcium silicates with amounts present depending on the source of the slag. Typical chemical constituents and physical properties are given in **Tables 3 and 4** respectively.

EAF slag is available in small quantities in Melbourne, Sydney and Newcastle.

***Applications and limitations*** EAF slag has been found to contain low sulphur and hence the potential to be used as concrete aggregate. The strength development of mortar made from EAF slag has been found to be better than equivalent mortar made with 'inert' sand. EAF slag has also been found to be stable in the presence of moisture. EAF slags are potentially suitable in road stabilisation and controlled low-strength fill to reduce the cost of binder.

In Australia, EAF slag is used primarily as asphalt aggregate or for road base and subbase.

### 4.4 Steel Furnace Slag (BOS)

***Description*** Steel furnace slag is a by-product of steel formed in the Basic Oxygen System (BOS). BOS slag is tapped from the vessel after the exothermic refinement of molten iron and recycled steel in the presence of fluxes and oxygen. It consists of calcium silicates and ferrites combined with fused oxides of iron, aluminium, calcium, magnesium and manganese. After air-cooling, the material has a predominantly crystalline structure and is crushed and screened for use as coarse aggregate. Typical chemical constituents and physical properties of BOS slag are given in **Tables 3 and 4** respectively.

BOS slag is available from Port Kembla and Whyalla. Since 2000, over 800,000 tonnes of BOS slag has been available annually, of which over 510,000 tonnes was used for road base and asphalt.

***Applications and limitations*** In Australia, BOS slag is used as asphalt aggregate or for road base and subbase. In asphalt, replacing natural aggregate with steel slag aggregate brings some advantages such as improvement in skid resistance and enhanced durability. Steel slag aggregate should not be used as aggregate in concrete due to a potential durability problem caused by lime expansion, and an aesthetic problem associated with the rust stains on the concrete surfaces[42]. The aggregate is an abrasive material and will result in substantial wearing of equipment such as well as agitators. The high density of steel slag, with an apparent density of the order of 3.3 t/m$^3$, was found to increase transport cost.

**TABLE 3** Typical chemical constituents of EAF and BOS slags *(after Heidrich[43])*

| **Constituents as oxides** | **BFS** (%) | **BOS Slag** (%) | **EAF Slag** (%) |
|---|---|---|---|
| Calcium oxide (CaO) | 41 | 40 | 35 |
| % Free lime | 0 | 0–2 | 0–1 |
| Silicon oxide ($SiO_2$) | 35 | 12 | 14 |
| Iron oxide ($Fe_2O_3$) | 0.7 | 20 | 29 |
| Magnesium oxide (MgO) | 6.5 | 9 | 7.7 |
| Manganese oxide (MnO) | 0.45 | 5 | 5.7 |
| Aluminium oxide ($Al_2O_3$) | 14 | 3 | 5.5 |
| Titanium oxide ($TiO_2$) | 1 | 1 | 0.5 |
| Potassium oxide ($K_2O$) | 0.3 | 0.02 | 0.1 |
| Chromium oxide($Cr_2O_3$) | <0.005 | 0.1 | 1 |
| Vanadium oxide ($V_2O_5$) | <0.05 | 1.4 | 0.3 |
| Sulphur S | 0.6 | 0.07 | 0.1 |

**TABLE 4** Physical properties of slags

| | | **Iron slag** | **Steel slag** | | |
|---|---|---|---|---|---|
| **Physical property** | | BFS | BOS | EAF | **Test method** |
| CONCRETE APPLICATIONS | | | | | |
| Particle density ($kg/m^3$) | Dry | 2400–2500 | 3300–3400 | 3300 | AS 1141.5 and AS 1141.6 |
| | SSD | 2500–2600 | 3350–3450 | 3400 | |
| Dry strength (kN) | | 85–100 | 275 | 250 | AS 1141.22 |
| Wet strength (kN) | | 65–90 | 230–300 | 240–300 | |
| Wet/dry strength variation (%) | | 10–20 | 5–20 | 5–15 | |
| Water absorption (%) | | 4–7 | 1–2 coarse<br>2–4 fine | 1–2 coarse<br>2–4 fine | AS 1141.5 and AS 1141.6 |
| LA abrasion | | 37–43 | 12–18 (B) | 16 (B) | AS 1141.23 |
| Polished Aggregate Friction Value (PAFV) | | NA | 52–58 | 58–63 | AS 1141.41 and AS 1141.42 |
| Sodium sulfate soundness (%) | | – | <4 | <4 | AS 1141.24 |
| ROAD-BASE APPLICATIONS | | | | | |
| Max. dry density ($kg/m^3$) 20 mm GMB Standard compaction | | 2050–2150 | 2300–2400 | 2300–2400 | AS 1141.5.1.1 |
| Optimum moisture content (%) | | 8–12* | 8–12* | 8–12* | AS 1289.2.1.1 |

* *Optimum moisture content depends on the components of the mix*

### 4.5 Fly Ash (FA)

***Description*** When coal is burnt in a modern pulverised fuel furnace, two types of ash are produced. The fine ash, which is recovered from the flue gas, is fly ash (FA). This material accounts for up to 90% of the total ash produced. The remainder consists of similar particles that have fused together into aggregate-size-lumps. They fall to the bottom of the furnace and are known as furnace bottom ash (FBA).

Fly ashes produced in Australian power stations are light to mid-grey in colour and have the appearance of cement powder. Particle sizes range from less than 1 μm to 200 μm and are irregular to spherical in shape. In Australia, the majority of fly ash produced is categorised as ASTM Class F – being mainly silica and alumina (80–85%). Class F fly ash is highly pozzolanic and reacts with various cementitious materials. Typical chemical compositions are given in **Table 5**.

Fly ashes are widely available in Queensland and New South Wales principally as supplementary cementitious material (SCM). More recently, fly ash from a Western Australian power station has been found to be suitable for use as an SCM[44]. Run-of-the-station fly ashes are those used for sand replacement and is available in the Sydney market.

***Applications and limitations*** Historically, the addition of fly ash to concrete had been considered to be part of fine aggregate replacement. Modern mix design treats fly ash exclusively as part of the binder system with the use of higher amount of fly ash in high volume fly ash (HVFA) concrete. Refer to CSIRO guidelines for the use of HVFA concretes[45].

**TABLE 5** Typical chemical constituents of Australian fly ash

| Constituents as oxides | Source | | | ASTM C618 Class F fly ash |
|---|---|---|---|---|
| | 1 | 2 | 3 | |
| Silicon oxide ($SiO_2$) | 61.8 | 59.2 | 55.5 | |
| Aluminium oxide ($Al_2O_3$) | 24.3 | 23.4 | 26.4 | |
| Iron oxide ($Fe_2O_3$) | 3.7 | 4.1 | 3.8 | |
| $SiO_2$+ $Al_2O_3$+ $Fe_2O_3$ | 89.8 | 86.7 | 85.7 | Min. 70 |
| Calcium oxide (CaO) | 1.6 | 2.8 | 2.0 | |
| Magnesium oxide (MgO) | 0.9 | 1.1 | 1.0 | Max. 5.0 |
| Potassium oxide ($K_2O$) | 1.4 | 2.2 | 2.2 | |
| Sulfate ($SO_3$) | 0.1 | 0.2 | 0.1 | Max. 5.0 |
| Loss on ignition (LOI) | 2.1 | 1.7 | 4.4 | Max. 6.0 |

### 4.6 Furnace Bottom Ash (FBA)

***Description*** Bottom ash is formed when ash adheres as hot particles to the furnace walls, agglomerates and then falls to the base of the furnace where it is collected for disposal. Bottom ash and boiler slag make up approximately 10% of the total ash produced and range in grain size from fine sand to coarse lumps. Bottom ash has chemical compositions similar to fly ash.

Furnace bottom ash is available in the Sydney market.

***Applications and limitations*** Coarse furnace bottom ash (FBA) is used as a fine aggregate for lightweight blocks, a road-base component, for agricultural drainage mediums and as engineered bulk fill.

Potential applications include controlled low-strength material or flowable fill, low-strength permeable or drainage layer, and a range of roller-compacted products, partial replacement of coarse sand in structural concrete, and for kerb and gutter[15].

### 4.7 Incinerator Bottom Ash (IBA)

***Description*** More than 90% (by mass) of incinerator residues consist of bottom ash, a slag-like material. As far as domestic refuse is concerned, the incinerator ash, after removal of ferrous and non-ferrous metals, can be ground to a fine powder, blended with clay, pelletized and fired in a kiln to produce sintered domestic refuse artificial aggregate[46].

No technical reports have been found on the use of sintered domestic refuse artificial aggregate in Australia.

***Applications and limitations*** The possible use of cement-treated municipal solid waste incinerator bottom ash (IBA) in concrete has been investigated[47]. The specific gravity of IBA was found to be around 2.2 and water absorption of around 2.4%. IBA is weaker than natural aggregate with Los Angeles abrasion value of 40%. Artificial aggregate, produced from the blending of IBA with clay, pelletized and fired in a kiln, has been used to produce concrete with compressive strengths as high as 50 MPa at 28 days. Long-term durability characteristics of this material have yet to be determined. The splitting tensile strength, relative density, water absorption, and porosity of the aggregate were shown to be dependent on the composition of the incinerator residue, as well as the firing time and temperature in the kiln. Tests on the performance of the aggregate, in both the plastic and hardened concrete give satisfactory results. There has been no reduction in the strength or elasticity of concretes stored in water for a period of up to 1½ years.

IBA is used in road construction. The use of raw IBA in concrete was found[47] to cause swelling and cracking in concrete due to the reaction between metallic aluminium and cement. This reaction could be avoided by immersing bottom ash in sodium hydroxide for 15 days. It was claimed that such treated IBA could partially replace natural aggregate without affecting the durability.

### 4.8 Coal Washery Reject (CWR)

***Description*** Coal reject material or colliery spoil is a by-product of the coal preparation process and is mostly produced in conjunction with the beneficiation of coking coal. Raw coal is washed to remove the high ash materials contained within it when it is mined. The material producing ash includes: plies of non-carbonaceous or low carbonaceous material within the coal seam; roof and floor material inadvertently mined with the coal; and dyke rocks that have intruded into the coal seam.

The generated quantity of CWR in Australia divides evenly between New South Wales and Queensland – the two principal coal producing states. About 20% of the total CWR is produced as tailings and 80% as coarse coal reject[48].

***Applications and limitations*** CWR has been used successfully within unsealed road pavements and for haul roads at many collieries. CWR has been used sparingly by the NSW RTA in the Lithgow and Wollongong areas as a subbase material. Subbase CWR is typically stabilised with cement in Lithgow and lime in Wollongong.

### 4.9 Organic Materials

***Description*** Certain organic materials are suitable for lightweight aggregates such as rice husks, woodchips and sawdust. Woodchips and sawdust consist largely of cellulose, but they also contain soluble sugars, acids, resins, waxes, and other organic substances in varying quantities. Some of these have inhibiting effects on the setting and hardening of cement. Many patents have been registered on methods of pre-treating sawdust in order to avoid these deficiencies.

No applications of organic materials have been reported in Australia.

***Applications and limitations*** In the US, sawdust has been used as an aggregate for more than 50 years for floor, wall and roof units. Sawdust concrete is used to a limited extent because it possesses very low strengths[3]. Typically, 1:2 and 1:6 mixes (cement:sawdust by volume) yield a 7-day compressive strength of 7.5 MPa and 0.75 MPa, respectively. Sawdust concrete has a good insulation value, resiliency, low thermal conductivity, and can be sawn and nailed. Sawdust concrete can absorb large amounts of water and expand. Sawdust must be pre-soaked to remove soluble matter before use in concrete.

### 4.10 Crusher Fines

***Description*** Crusher fines is a sand-size material produced as a result of the crushing and screening operations within a quarry plant. It is most commonly produced from hard rock quarry operations but may also be generated from the crushing of gravel deposit materials which liberate suitable fines. Unlike manufactured sands, which are designed and manufactured to provide material with consistent engineering properties, crusher fines are not generally designed to have any specific property other than maximum size, eg –5 mm.

***Applications and limitations*** Where source rock and quarry processing are consistent with suitable properties, crusher dusts have been used as coarse sand replacements in some concrete; more commonly they are used as the finer filler fractions in asphalt. In some quarry operations excess crusher dust may cause stock imbalances, leading to other and alternative uses such as road base or shotcrete additives. Due to the inconsistent properties of crusher dusts, their applications will always be limited and their quality needs to be constantly monitored. While crusher dusts may have similar size, and in some cases similar application, they should never be considered a replacement for well-designed manufactured sands.

## 5 SUMMARY

The review presented in this report clearly indicates an increasing trend and incentive for the greater use of manufactured and recycled aggregates in construction. There are, however, limitations to the use such materials. This report focuses on known benefits and limitations of a range of manufactured and recycled aggregates. Successful strategy must be based on both *cost* and *performance*.

In terms of performance, many countries are focusing on recycled concrete aggregates (RCA) which is proven to be practical for non-structural concretes and to a limited extent for some structural-grade concrete. However, the processing and quality control cost associated with their use plus the premium paid for mix design adjustment to achieve the same strength grade as concrete with natural aggregates can vary considerably.

In Australia, there are a number of manufactured and recycled aggregates readily available in certain localities which have the potential to be used in construction. Air-cooled blast furnace

slag (BFS) and manufactured sand are two good examples of concrete aggregates. Work is continuing to obtain performance data and appropriate specifications for manufactured sand.

In other construction applications such as pavement, roadbase and subbase, there is limited information on the performance of each material as assessment appeared to be based on field trials, especially those by road authorities.

In all cases, the availability and consistency of supply are prerequisite for the use of manufactured and recycled aggregates in the various applications.

## 6 REFERENCES


1 *Removal and Reuse of Hardened Concrete* (ACI 555R–01), American Concrete Institute

2 *CSIRO Guide to the use of recycled concrete and masonry materials* (HB 155) Standards Australia, 2002.

3 Ramachandran VS *Waste and By-Products as Concrete Aggregates* National Research Council Canada, CBD–215, 1981.

4 Popovics S *Concrete Materials: Properties, Specifications and Testing* Second Edition, Noyes Publication USA.

5 Wong P and Sirivivatnanon V 'The Manufacture of Synthetic Fly Ash Aggregates for Use in Concrete' *Proceedings of the National Symposium on the Use of Recycled Materials in Engineering Construction*, Sydney, May 1996, pp. 136–140.

6 Research Report Cement Concrete & Aggregates Australia, on *Manufactured Sand – National test methods and specification values*, January 2007.

7 Dumitru, I., 'The effect of improvement in shape of quarry dust on the plastic and hardened concrete properties of concrete', Inst of Quarrying, 41st Annual Conf., 1997.

8 Dumitru, I., Smorchevsky, G. and Formosa, M. 'Further investigation into the effects of shape, texture and gradings of manufactured sands on the plastic and hardened concrete properties of concrete', Inst of Quarrying, 42nd Annual Conf., Launceston, 1998.

9 Sullivan, B.W.P., 'Basalt crusher dust as a sand replacement in concrete', Proc. 18th Biennial Conf, Adelaide, 1997, pp 567–574.

10 Orsos, T., 'BST: The Lightweight concrete aggregate', Concrete Institute of Australia seminar on Special Use Concretes, Melbourne, 1992.

11 Sabaa, B. and Ravindrarajah, R. Sri, 'Engineering Properties of Lightweight Concrete Containing Crushed Expanded Polystyrene Waste', Faculty of Engineering, University of Technology, Sydney, Australia.

12 Edwards, C.J., 'Lightweight concrete made with coated polystyrene aggregate', Proc of 16th Biennial Conf, Melbourne, 1993, pp 513–523.

13 Sagoe-Crentsil, K.K., Brown, T., Mak, S.L. and Taylor, A., 'Engineering Properties and Performance of Concrete made with Recycled Construction Aggregates, Proceedings of the National Symposium on the Use of Recycled Materials in Engineering Construction, Sydney, May 1996, pp 132–135.

14 Ravindrarajah, R. Sri, 'Effects of Using Recycled Concrete as Aggregates on the Engineering Properties of Concrete, Proceedings of the National Symposium on the Use of Recycled Materials in Engineering Construction, Sydney, May 1996.

15 Dumitru, I., Smorchevsky, G. and Caprar, V., 'Trends in the Utilisation of Recycled Materials and By-Products in the Concrete Industry in Australia', Proc. of the Concrete Institute of Australia 19th Biennial Conf., Sydney, 1999, pp 289–301.

16 Stark, D., 'The Use of Recycled-Concrete Aggregate from Concrete Exhibiting Alkali-ilica Reactivity', Research and Development Bulletin RD114, 1996.

17 Fumoto, T. and Yamada, M., 'Durability of Concrete with Recycled Fine Aggregate', American Concrete Institute, SP234, Durability of concrete, Seventh Int Conf, Montreal, Canada, 2006, 457–472.

18 Montgomery, D.G. and Sturgiss, D., 'Properties of Concrete Incorporating Recycled Concrete Aggregates', Proceedings of the National Symposium on the Use of Recycled Materials in Engineering Construction, Sydney, May 1996,

19 Fraair, A.L., Pietersen, H.S. and de Vries, J., 'Performance of Concrete with Recycled Aggregates', Proc. of the Int Conf on Sustainable Concrete Construction, Dundee, Scotland, 2002, pp 187–198.

20 Rashwan, M.S. and Abourizk, S., 'The properties of recycled concrete', Concrete International, Vol. 19, No. 7, 1997, 56–60.

21 Private communication with Graeme Dahlstrom and Bill Bowie of Boral Ltd.

22 Dumitru, I, Bakasetas, J., Formosa, M. and Walter, P., 'A New Recycled Roadbase Developed from Reclaimed Asphalt Pavement (RAP) Material and Recycled Crushed Concrete', Proc 19th ARRB Conf, Sydney, 1998, p 94–104.

23 Department of Environment and Conservation (NSW). NSW Waste Reduction & Purchasing Policy Biennial Progress Report 2005 – For NSW Roads and Traffic Authority 2005.

24 Hisari, Y., Sano, M., Yagishita, F. and Yamada, M., 'Studies on the reprocessing of waste asphalt concrete for recycling', Proc. of the Concrete Institute of Australia 19th Biennial Conf., Sydney, 1999, pp 62–92.

25 Australian Environment Business Network. Scoping study: Blending of various waste resources into asphalt. May 2003.

26 Sagoe-Crentsil, K, Brown, T., Taylor, A., 'Guide Specification: Recycled glass as sand replacement in premix concrete', CSIRO Building, Construction and Engineering, June 2001.

27 Department of Environment and Conservation NSW. NSW Government Waste Reduction and Purchasing Policy (WRAPP) Progress Report 2006.

28 'Innovative building material of recycled glass', ZKG International, Volume 60, No. 6, 2007, pp 49.

29 Eldin, N.N. and Senouci, A.B., 'Rubber–Tire Particles as Concrete Aggregate,' Journal of Materials in Civil Engineering, V.5, No. 4, November 1993.

30 Lee, H. S., Lee, H., Moon, J. S. and Jung, H. W., 'Development of tire-added latex concrete', ACI Materials Journal, V. 95, No. 4, July–Aug.,1998, pp. 356–364.

31 The Federal Highway Administration. "http://isddc.dot.gov/OLPFiles/FHWA/011435.pdf" Foundry Sand Facts for Civil Engineers, Federal Highway Administration booklet Report Number FHWA–IF–04–004, 80 pp.

32 "http://www.ars.usda.gov" The United States Department of Agriculture (USDA) has been conducting research on various agricultural uses of foundry sand. USDA and EPA are partners in increasing the recycling and use of industrial by-products, and USDA will be publishing guidelines for the use of industrial by-products in agricultural applications.

33 EPA 329/03 Guidelines Used foundry sand (UFS) – classification and disposal. Government of South Australia. Re-issued September 2003.

34 Heidrich, C., I. Hinczak, and Ryan, B. 'GGBFS lowering Australia's greenhouse gas emissions profile'. Global Slag Conference, Bangkok, Thailand, 2006.

35 Day, K.W., 'Concrete Mix Design, Quality Control and Specification', 3rd Edition, Taylor & Francis, London and New York, 2006.

36 Ashby, J., 'Air Cooled Blast Furnace Slag as a Concrete Aggregate for Engineering Construction', Proceedings of the National Symposium on the Use of Recycled Materials in Engineering Construction, Sydney, May 1996, pp 110–115.

37 Mak SL, Forster G, Chirgwin and Ho DWS 'Engineering Properties of Heat-Cured Slag Cement Concretes for Bridge Structures' Proceedings of 18th Biennial Conf, Adelaide, 1997, pp 45–52.

38 Visek, J.C., Information collected for preparation of a Technical Paper on the Utilisation of Steelplant slag products – Boral Concrete, 22 October, 1979.

39 Munn, R.L.; 'Blast Furnace Slag as an Aggregate in Concrete', Utilisation of Steel plant Slag Symposium. Aust. I.M.M., February, 1979, Port Kembla.

40 Haber, E., 'Physical Characteristics of Concretes containing Port Kembla Iron Blast Furnace Slag Aggregates', Concrete in Australia, Vol. 20, No. 2, June 1994.

41 Jones, E.E. and Murrie, S.J., 'Utilization of steel plant slag products in Australia', Excerpt from a paper presented at the 1st Process Technology Conference, March 25, 1980, Washington D.C.

42 Leshchinsky, A., 'Slag sand in ready-mixed concrete', Concrete, Vol. 38, No. 3, March 2004, pp. 38–39.

43 Heidrich, C., 'Slag – Not a Dirty Word', Geopolymers 2002, Melbourne, 2002.

44 Munn, R.L., 'Development of techniques to improve the reliability of blended cement concretes made with Collie flyash', Proc 23rd Biennial Conf, of Concrete Institute of Australia, Adelaide, October 2007, 149–158.

45 Sirivivatnanon, V., Cao, H.T., Khatri, R.P. and Bucea, L., 'Guidelines for the use of HVFA concretes', CSIRO Technical Report TR95/2, 1995.

46 Wainwright, J., 'Artificial aggregate from domestic refuse', Concrete, May 1981, pp 25–29.

47 Pera, J., Coutaz, L., Ambroise, J. and Chababbet, M., 'Use of Incinerator Bottom Ash in Concrete', Cement and Concrete Research, Vol. 27, No. 1, pp. 1–5, 1997.

48 Leventhal, A., 'Coal Washery Reject as an Engineered Material', Proceedings of the National Symposium on the Use of Recycled Materials in Engineering Construction, Sydney, May 1996, pp 54–59.

## CCAA OFFICES

**SYDNEY OFFICE:**
Level 6, 504 Pacific Highway
St Leonards NSW Australia 2065
**POSTAL ADDRESS:**
Locked Bag 2010
St Leonards NSW 1590
**TELEPHONE:** (61 2) 9437 9711
**FACSIMILE:** (61 2) 9437 9470

**BRISBANE OFFICE:**
Level 14, IBM Building
348 Edward Street
Brisbane QLD 4000
**TELEPHONE:** (61 7) 3831 3288
**FACSIMILE:** (61 7) 3839 6005

**MELBOURNE OFFICE:**
2nd Floor, 1 Hobson Street
South Yarra VIC 3141
**TELEPHONE:** (61 3) 9825 0200
**FACSIMILE:** (61 3) 9825 0222

**PERTH OFFICE:**
45 Ventnor Avenue
West Perth WA 6005
**TELEPHONE:** (61 8) 9389 4452
**FACSIMILE:** (61 8) 9389 4451

**ADELAIDE OFFICE:**
PO Box 229
Fullarton SA 5063
**TELEPHONE:** (61 8) 8274 3758

PREMIXED CONCRETE AND
EXTRACTIVE INDUSTRIES OFFICE
PO Box 243
Henley Beach SA 5022
**TELEPHONE:** (61 8) 8243 2505
**FACSIMILE:** (61 8) 8125 5822

**TASMANIAN OFFICE:**
PO Box 246
Sheffield TAS 7306
**TELEPHONE:** (61 3) 6491 1509
**FACSIMILE:** (61 3) 6491 2529

**WEBSITE:** www.ccaa.com.au

**EMAIL:** info@ccaa.com.au

**Disclaimer:** Cement Concrete & Aggregates Australia is a not for profit organisation sponsored by the cement, concrete and aggregate industries in Australia to provide information on the many uses of cement, concrete and aggregates. This publication is produced by CCAA for that purpose. Since the information provided is intended for general guidance only and in no way replaces the services of professional consultants on particular projects, no legal liability can be accepted by CCAA for its use.

CCAA respects your privacy. Your details have been collected to provide you with information on our activities, publications and services. From time to time your details may be made available to third party organisations who comply with the Privacy Act such as affiliated associations, sponsors of events and other reputable organisations whose services we think you may find of interest. If you do not wish to receive information from CCAA or wish to be taken off the database please write to the Privacy Officer, CCAA, Locked Bag 2010, St Leonards, NSW, 1590