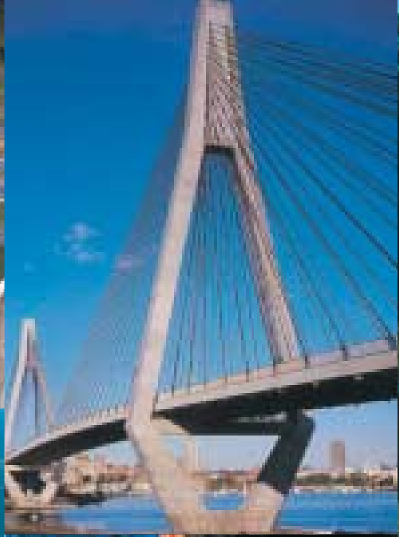

a guide to the use of iron and steel slag in roads

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a guide to the use of iron and steel slag in roads

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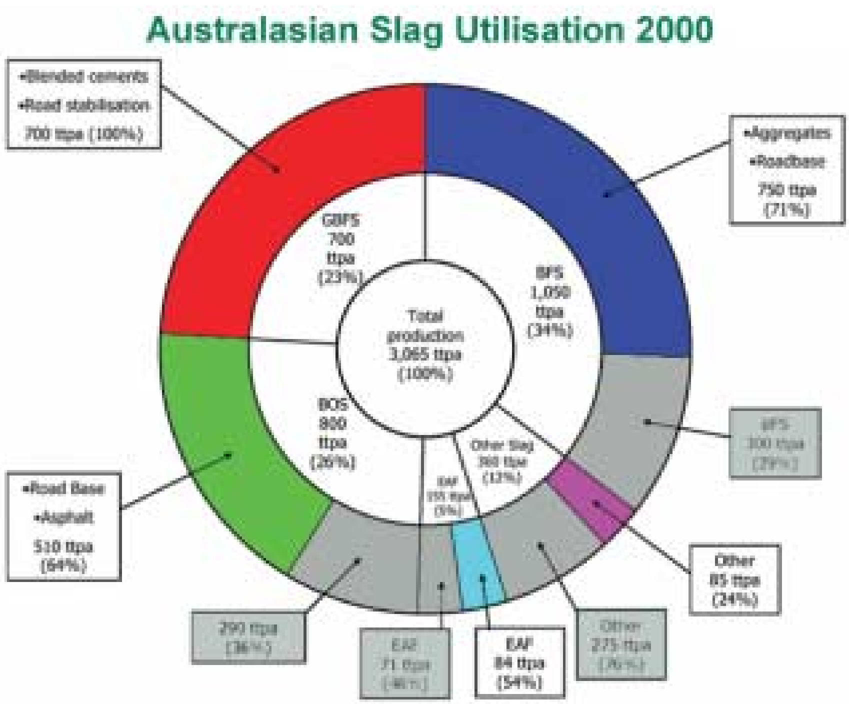
Australasian Slag Association

Slag Production and Member Locations in Australasia and South East Asia

Figure 1



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Australasian Slag Association Inc.
PO BOX 1194
Wollongong NSW 2500
AUSTRALIA

Copies of this document can be obtained by contacting the Association on +612 4225 8466 or via email **info@asa-inc.org.au**

FOREWORD

This Guide supersedes the 1993 version of "A Guide to the Use of Slag in Roads." The 1993 Guide was intended to give a broad appreciation of the many uses for iron and steel slag products in the construction and maintenance of roads, including pavement materials, wearing surfaces and concrete.

Since then two more detailed Guides have been produced relating to specific areas of slag usage:-

- A Guide to the Use of Iron Blast Furnace Slag in Cement and Concrete (1997), and
- A Guide to the Use of Steel Furnace Slag in Asphalt and Thin Bituminous Surfacings (1999)

Since 1993 there have been significant improvements in road technology in Australasia, particularly in the area of pavement materials development and road stabilisation. Slag has played a significant part in these improvements. Moreover, there is now considerably more data available on the performance of slag based road materials to the extent that slag materials and blends are now considered to be a premium roadbase material and stabilising binder by many experienced users.

This Guide is directed to designers, specifiers and users of road materials and presents up to date information, so that, where appropriate, the use of road materials incorporating slag products may be considered on an informed basis. References are provided to enable the reader to obtain more detailed information about specific products and how they relate to current specifications and work practices.

As slag is an industrial by-product, its constructive use provides an opportunity to displace the use of finite natural resources on a substantial scale, thus helping to conserve them and reduce the impact on the environment.

The Australasian Slag Association is grateful for the co-operation and valuable input received from the Roads and Traffic Authority of NSW, VicRoads, Transport South Australia, Department of Transport QLD, NSW Environment Protection Authority and Australian Stabilisation Industry Association in the production and the publication of this Guide.

Further information is available at www.asa-inc.org.au

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1. INTRODUCTION

1.1 Purpose of Guide

The need to preserve diminishing natural resources and increase reuse, recycling or reprocessing, with disposal being the last resort has become an issue of great importance in our modern society.

International, Federal, State and Local Governments support this approach, with respective regulating authorities empowered to ensure these sustainable goals are met.

Use of Iron and Steelmaking slags represent an excellent success story consistent with these goals. Generated as by-products in the manufacture of iron and steel, these reprocessed materials provide opportunities in road construction and maintenance to recycle on a large scale.

During 2000 approximately 3.1 million tonnes of iron, steel and other slags were produced in Australia and New Zealand. The major regional centres are Port Kembla and Whyalla for Blast Furnace and Steel Furnace Slag. Electric Arc Furnace steel slag is produced in smaller quantities at Melbourne, Sydney and Newcastle.

Since the formation of the Australasian Slag Association in 1990, significant changes have occurred in the effective utilisation of slag materials. The production rate in 1990 was approximately 4.5 million tonnes with an effective utilisation in the order of 30 to 35%. Effective utilisation means the use of slag materials in a productive or economically beneficial way and therefore not requiring disposal as landfill, which in today's society must always be a last resort.

Of the 3.1 million tonnes of slag produced in 2000, 75% was used effectively. The major contributors to this increase being GBFS (Granulated Blast Furnace Slag) at 100%, BFS (Blast Furnace Slag) at 71%, BOS (Basic Oxygen Slag) at 64%, EAFS (Electric Arc Furnace Slag) at 54% and other slags at 24%. FIGURE 1 (Inside front cover) shows a simple multi-level pie graph — Slag Utilisation for 2000.

Significantly increased utilisation has been aided by the benefits from using slag products being more widely understood and appreciated by material users particularly in road construction.

As by–products in the iron and steel making processes, slag products are a result of the same quality process controls and modern technology used to achieve high quality metal products. As products of a manufacturing process the consistency of chemistry and quality of slag products is assured.

Beyond the production process, slag processors have generally adopted Quality Assurance principles in line with AS/NZS ISO 9000 standards for their products to ensure the supply of quality products to the market.

The use of slag in road construction can be traced back to the very early days when the Romans used iron slag as a pavement material in parts of the famous Appian Way. Iron slag was first produced commercially in Australia at Mittagong, NSW, in 1848 and the slag known locally as Mittagong Stone, was used for road construction.

In more recent times in New South Wales, modern iron and steel slag has been used extensively for road construction for almost 50 years and has proved to be very successful, particularly for high speed, heavily trafficked roads and airport pavements.

In 1988 the Roads & Traffic Authority of NSW conducted trials using the Accelerated Loading Facility (ALF) to re-examine the use of crushed iron blast furnace slag as a roadbase. These trials, conducted at Prospect, NSW, led to the publishing of a Research Report No. ARRB 170 by the Australian Road Research Board (Kadar & Walter 1989). This report says in part "The experiments indicated that slag can be used in place of high quality crushed rock in road bases".

A further ALF trial was carried out in 1994 on deep-lift pavements in which slag was used as one of the main stabilising binder components. This trial is reported in APRG Report No. 11 and ARRB Research Report No. 265 (June 1995) entitled "Performance of deep-lift recycling under accelerated loading: the Cooma ALF Trial." (Jameson G.W., Dash D.M., Tharan.Y., and Vertessy N.J.) This trial demonstrated the practicality of deep-lift stabilisation and the benefits of using slag as a slow setting stabilising binder component.

Due to the limited number and locations of slag production centres, transport costs will be a factor. However, the use of GBFS (Granulated Blast Furnace Slag) and GGBFS (Ground Granulated Blast Furnace Slag) as stabilising binders in recent years has significantly increased the area of usage.

The types of slag covered in this guide are:

1. Blast Furnace Slag — known as BF Slag or BFS or Rock Slag (iron process).

2. Basic Oxygen Steel Slag — known as BOS Slag or BOS (steel process).

3. Electric Arc Furnace Slag — known as EAF Slag or EAF (steel process).

Brief details of the manufacturing processes (Joshi 1997) and applications for different slag products are described in FIGURE 2 and TABLE 1.

Physical properties of Blast Furnace Rock and Steel Slags are shown in TABLE 2.

1.2 What is Slag?

Slag is a by-product of the iron and steel manufacturing process as shown in FIGURE 2.

The first step in the production of steel is to manufacture iron. Iron ore, a mixture of oxides of iron, silica and alumina, together with a fuel consisting of coke, natural gas, oxygen and pulverised coal and also limestone as a fluxing agent, are fed into a blast furnace which consists of a large vertical chamber through which large volumes of hot air are blasted (FIGURE 3).

The chemical reaction results in two products: molten iron metal and molten slag. Slag, which has a relatively lower specific gravity, does not mix with the molten metal, but floats on it. Slag is separated from the molten metal as it leaves the furnace and is commonly called Blast Furnace Slag.

Generally a blast furnace operates on a continuous basis and produces approximately 250 — 300 kg of slag per tonne of iron produced.

The liquid blast furnace slag flows into pits where it is predominantly air cooled and sprayed with a small quantity of water. The cooled slag is then transported to a crushing and screening plant where it is further processed into various products including aggregates (FIGURE 4 & 5).

Alternatively, liquid slag can be rapidly quenched using large volumes of high-pressure water to produce a sandy material called Granulated Blast Furnace Slag (GBFS), (FIGURE 6).

The iron is collected in a liquid state and transported to

FIGURE 2: TYPICAL SLAG PRODUCTION PROCESS

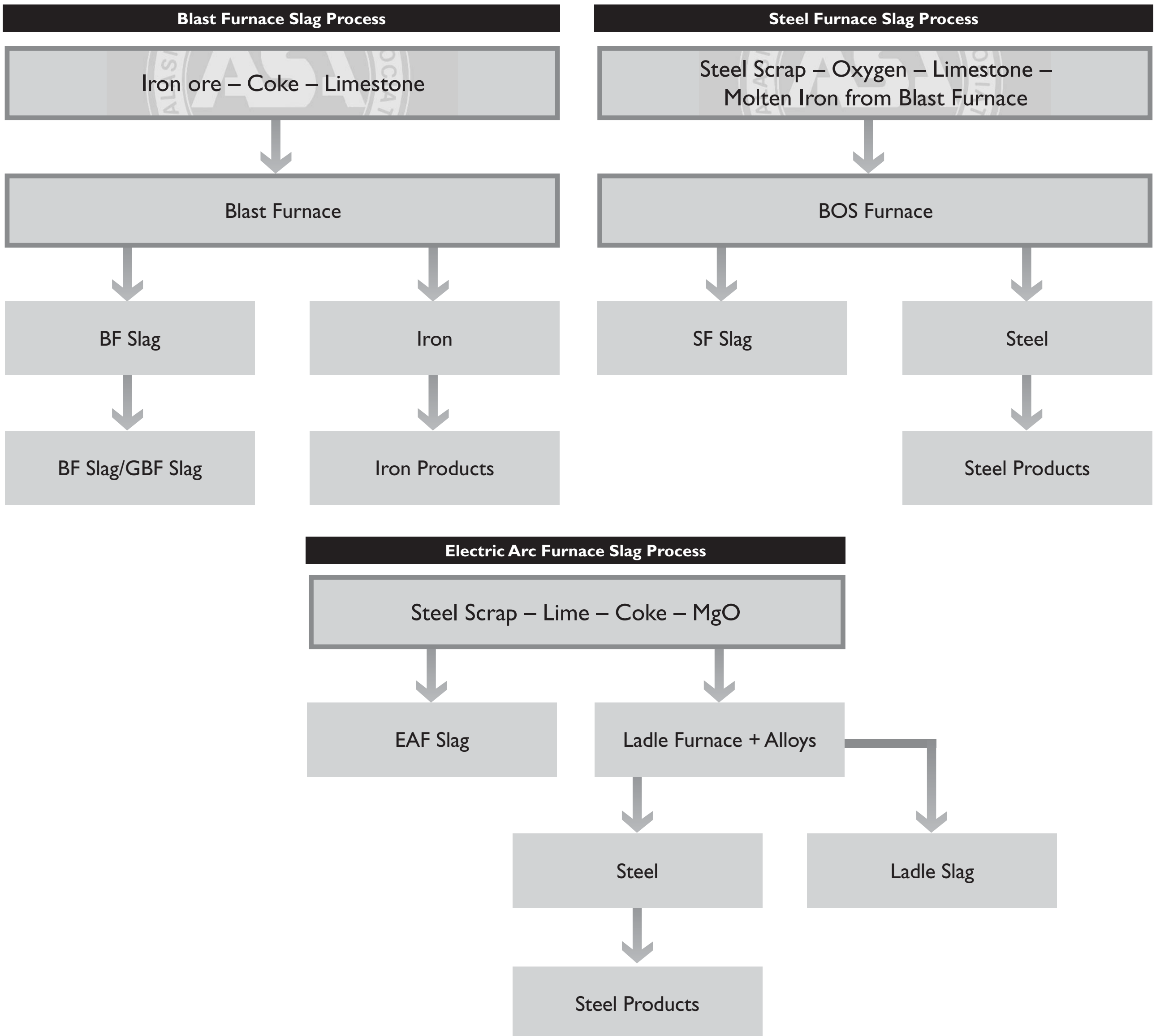

TABLE 1
SUMMARY OF MANUFACTURING PROCESSES AND APPLICATIONS FOR IRON AND STEEL SLAGS

SLAG SOURCE	COMMON NOMENCLATURE	MANUFACTURING PROCESS	APPLICATIONS
Blast Furnace Iron Slag	Rock slag or air cooled slag	Crushing and screening slag which has been slowly air cooled. Also available as uncrushed slag, i.e. spalls or skulls.	Base Subbase Concrete aggregate Filter aggregate Construction fill and selected fill Scour Protection Rockwoo l
	Granulated slag or slag sand	Rapidly quenching molten slag with high pressure, high volume water sprays.	Subbase Construction fill Construction sand Stabilising binder Cement manufacture Grit blasting Reinforced earth wall infill Glass manufacture
	Ground Granulated Slag (GGBFS)	Grinding granulated slag to cement fineness.	Cement replacement able to enhance concrete durability and other desirable properties. Stabilising binder, either alone or blended
	Pelletised slag (Not produced in Australia)	Water quenching molten slag on a sloped table and rotating drum, which throws the pellets into the air for further cooling.	Cement manufacture. Lightweight aggregate for concrete and masonry products.
	Expanded slag or lightweight slag (Not produced in Australia)	Controlled cooling of slag as a thin layer in a pit followed by crushing and screening.	Lightweight aggregate for masonry products and structural concrete. Skid resistant aggregate.
Basic Oxygen Steel Slag	BOS slag	Crushing and screening slag which has been air cooled and watered.	Sealing aggregate (skid resistant) Asphalt aggregate Base, subbase Construction fill Subsoil drains Grit blasting
Electric Arc Steel Slag	EAF slag	Crushing and screening slag which has been air cooled and watered.	Sealing aggregate (skid resistant) Asphalt aggregate Base, subbase Construction fill Subsoil drains Grit blasting

TABLE 2
PHYSICAL PROPERTIES OF TYPICAL BLAST FURNACE ROCK & STEEL SLAGS

PHYSICAL PROPERTY — AGGREGATE	BLAST FURNACE SLAG	STEEL SLAG		TEST METHOD
	ROCK SLAG	BOS SLAG	EAF SLAG	
Particle density Dry (kg/m3) SSD	2,450 — 2,550 2,550 — 2,650	3,300 — 3,400 3,350 — 3,450	3,300 3,400	(AS1141.5 & 6)
Dry strength (kN)	85 — 100	275	250	(AS1141.22)
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 2 — 4 fine	1 — 2 coarse 2 — 4 fine	(AS1141.5 & 6)
LA abrasion	37 — 43	12 to 18	16	(AS1141.23)
Polished Aggregate Friction Value (PAFV)	N A	58 to 63	58 to 63	(AS1141.41/42)
Sodium Sulfate Soundness (%)		<4	<4	(AS1141.24)
PHYSICAL PROPERTY — ROADBASE				
Maximum Dry Density (kg/m^3) (20mm GMB Standard Compaction)	2,050 — 2,150	2,300 — 2,400	2,300 — 2,400	(AS1141.5.1.1)
Optimum Moisture Content (%)	8 — 12	8 — 12	8 — 12	(AS1289.2.1.1)

Note:- [1]OMC depends on the components of the mix.

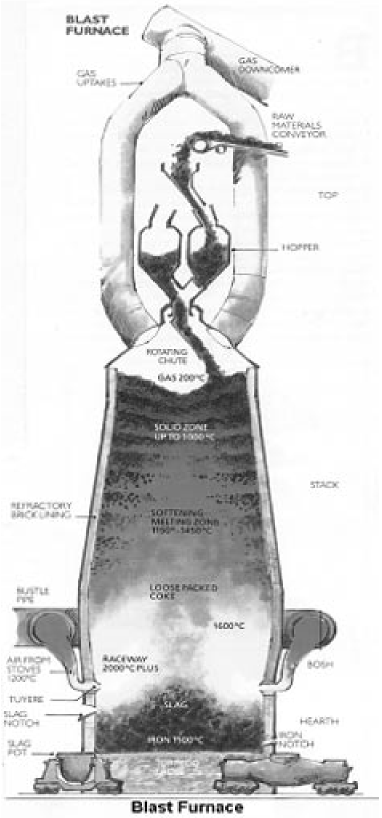

FIGURE 3: TYPICAL BLAST FURNACE.

a steel manufacturing furnace for future processing.

Iron has a high carbon content and is too brittle for many applications, hence the need to reduce its carbon content and produce steel. The most common method used in Australia is the Basic Oxygen Steel (BOS) process. Another steel production method is the Electric Arc Furnace (EAF) process.

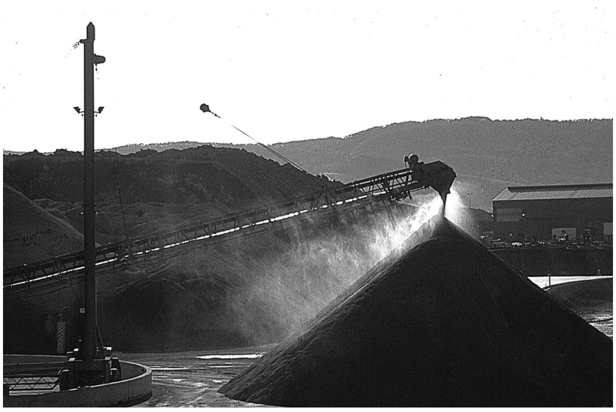

FIGURE 4: PRODUCTION OF AGGREGATES.

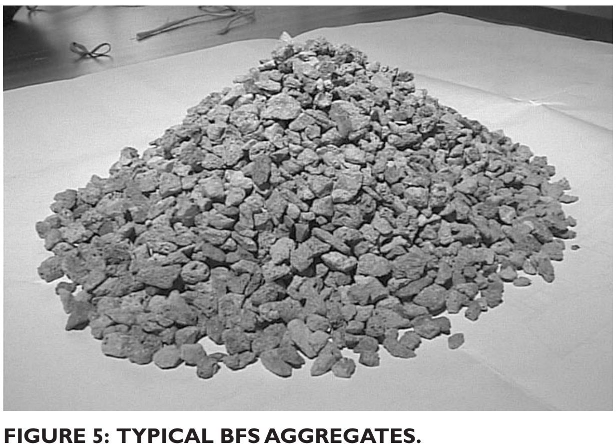

FIGURE 5: TYPICAL BFS AGGREGATES.

FIGURE 6: GRANULATED BLAST FURNACE SLAG.

In the BOS process, a large open-top vessel is generally used into which molten iron, steel scrap and lime are placed. High pressure oxygen is blown into the vessel and a violent chemical reaction takes place. On the completion of the reaction, the steel is drained into one ladle and the slag is poured into another.

In the EAF 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 which react similarly to the BOS process. Steel and slag are also separated similarly.

This slag, known as Steel Furnace Slag (SFS) is then poured into pits where, after initial solidification, the slag is cooled with water sprays and then processed into aggregates (FIGURE 7).

The slag produced in the BOS and EAF processes amounts to approximately 120 — 150 kg per tonne of steel produced.

FIGURE 7: TYPICAL SFS AGGREGATES.

Constituents as Oxides	Symbol	BFS Slag (%)	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_20)	0.3	0.02	0.1
Chromium Oxide	(Cr_2O_3)	<0.005	0.1	1
Vanadium Oxide	(V2O5)	<0.05	1.4	0.3
Sulphur	(S)	0.6	0.07	0.1

TABLE 3: TYPICAL CHEMICAL CONSTITUENTS.

1.3 Chemistry

The typical chemistry of BFS, BOS and EAF slags after appropriate conditioning and weathering as discussed in Section 2.2.1(c), are shown in TABLE 3.

1.4 Changing environmental paradigms

As stated previously this guide is directed at designers, specifiers and users of road construction materials, in particular, materials that comply with all relevant Australian Standards specifications and environmental testing requirements for use in construction applications.

At this stage, it should be pointed out that this guide is not designed to discuss issues associated with the disparity which occurs in environmental regulatory requirements between the States and Territories.

Regardless of the above it is important to establish our industry's efforts to educate all stakeholders (producers, processors, users and regulators) on the changing role of slag materials, past, present and future use of slag.

In previous years many people within our industry considered slag as a waste product, suitable only for landfill and having no real economic value. Today, nothing could be further from the truth.

Significant joint efforts and investment into research to validate the materials potential for use, with subsequent industry development of slag-based products has been undertaken over many years by organisations such as CSIRO. Resulting achievements over 20 years has been the increased adoption of these materials by the construction industry in major projects such as the Sydney Harbour Tunnel and Mascot Airport.

In recent years, increasing awareness of environmental issues in our society has had an impact in improved utilisation of slag. Coupled with member companies identifying new opportunities for slag products, investment will continue to ensure these markets are further developed.

As stated 75% of all reprocessed slag is sold for use in construction applications today. However regardless of these achievements labels such as "waste" continue to be part of some stakeholder vocabulary.

Our best way forward is to continue to increase effective utilisation of slag materials for the benefit of all. Through the use of market competitive forces, distributors of slag materials must and do actively compete on the same playing field and deliver materials that provide performance, durability, economical and environmental benefits.

With regards to disparity in environmental regulation requirements between the States and Territories, localised issues specifically related to slag categorisation are resolved by the combined efforts of the Association & slag distributors.

Through the efforts of all stakeholders working together to maximise this resource, we will continue to change perceived risks associated with the use of slag materials, into what is a real success story.

2. PAVEMENT MATERIALS

2.1 Overview of Pavement Design

Slag may be used as a pavement material in a variety of forms. It can be used as a base or a subbase material either unbound or bound and can be mixed with other materials either for mechanical stabilising or as a cementing or stabilising binder.

Materials require the following broad characteristics for use in pavements:-

- Workability
- Strength (both as a matrix and individual particles)
- Durability
- Stability
- Economy.

In addition, pavement materials must meet the pavement design criteria to ensure adequate performance. These criteria relate to the elastic properties of materials, which govern the distribution of loads throughout the pavement structure, and also the fatigue performance of bound materials, which determines the service life.

Unbound materials develop (shear) strength through particle interlock and have no significant tensile strength. The usual distress modes are deformation through shear and densification and also disintegration through particle breakdown.

The pavement design criteria for unbound materials consist of elastic modulus, Poisson's ratio and degree of anisotropy. However, adequate performance is governed by materials specifications, which usually cover characteristics for workability, particle strength and shear strength.

Bound materials develop shear strength through chemical bonding as well as particle interlock and have significant tensile strength. The design criteria for bound materials are again elastic modulus and Poisson's ratio.

Performance is governed by fatigue relationships, as well as materials specifications, which specify characteristics for workability, particle strength and unconfined compressive strength (usually as an empirical substitute for stiffness).

Design parameters are given in Section 6 of the AUSTROADS Guide to the Structural Design of Road Pavements (1992). Materials Specifications vary between jurisdictions (e.g RTA Forms 3051 and 3052 and Specification R73 in NSW).

Both blast furnace and steel slag have <5% misshapen particles with a calliper ratio of 3:1 indicating good particle shape. This ensures good packing of the particles and facilitates compaction. The vesicular nature of slag particles' surface also promotes good particle interlock and high shear strength.

Elastic modulus for bound materials is rarely determined directly, but usually by using a relationship between Unconfined Compressive Strength (UCS) and Modulus.

Commonly used relationships include:-

$E = 1{,}000 \times UCS$ RTA
$E = 1{,}500 \times UCS$ Austroads
$E = 2\,(1814 \times UCS^{0.88}) + 3500$ Joshi (1997)

Where E = Elastic Modulus (MPa)
And UCS = Unconfined Compressive Strength in MPa.

These relationships are illustrated in FIGURE 8.

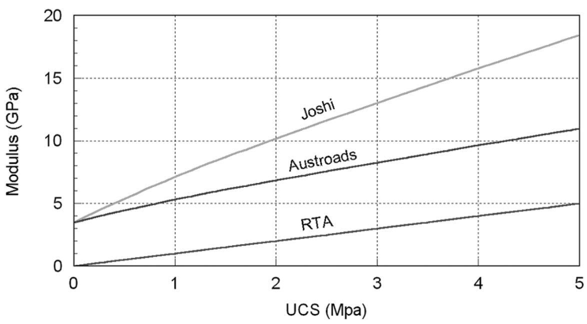

FIGURE 8: RELATIONSHIPS BETWEEN UNCONFINED COMPRESSIVE STRENGTH AND ELASTIC MODULUS.

Joshi (1997) developed his relationship from the analysis of deflection testing and core results from existing slag pavements and suggested the relationship is valid for the UCS values after 14 days of accelerated curing.

Conventional bound materials, such as cement treated crushed rock achieve about 60 to 70 % of their ultimate strength within 7 days of standard curing and close to their ultimate strength at 28 days. Slag based pavement materials increase in strength over a much longer period of time. This period of time depends largely on the components of the slag and whether an activator is present.

Standard 28 day UCS or 7 day accelerated UCS test results usually indicate the slag materials are between 0.5 and 5 MPa. However, when long term UCS results from core samples are tested, strengths greater than 4 MPa are usually evident, commonly between 7 and 10 MPa.

In achieving these strengths, another advantage, particularly with steel slag blends, is the reduction in shrinkage effects with the chemical compatibility of the blend products and the slower overall development of the compressive strength.

2.2 Pavement Materials

Both blast furnace slag and steel slag have been used in pavement construction as:

1 Engineering Fill (including select subgrade)
2. Subbase
3. Base.

For all applications, slag products may be utilised as either unbound or bound materials depending on the composition of the product used.

2.2.1 Engineering Fill (including Select Subgrade)

Blast Furnace Rock Slag

This material is used uncrushed and when compacted develops a high degree of mechanical interlock resulting in a high shear strength partly due to the rough texture (vesicular nature) of the slag. The chemical reactivity of the slag results in a self-cementing of the fill which over a period of time forms a semi-rigid mass.

The term vesicular, as applied to blast furnace slag, means that particles contain voids, which tend to be unconnected, occurring throughout each particle and appearing as blind holes on the particle surface.

Blast Furnace Granulated Slag

Granulated slag can be used as a fill material. Because of its sand like texture, it is easy to work. Its self cementing properties cause it to set up over time.

Steel Slag (BOS & EAF)

Like rock slag, steel slag is used uncrushed. It develops good mechanical interlock through compaction. As a fill material, steel slag differs from Blast Furnace rock slag because:

(a) its density is approximately 25% higher than Blast Furnace Slag.
(b) it's harder than Blast Furnace Slag.
(c) steel slag is weathered prior to use, ensuring there is no deformation of the pavement surface. The term weathered when applied to steel furnace slag means that the material has been stockpiled between one (1) and three (3) months, under normal atmospheric conditions, before use. (Water/treatment systems are in place to ensure adequate weathering takes place prior to supply). Blast furnace slag does not require weathering as it does not contain free lime. Steel slag can be advantageous as a select fill as its lime content can assist in stiffening subgrades by lime stabilisation, and combat acid sulfate soil conditions.

2.2.2 Subbase

Blast Furnace Rock Slag

Rock slag is provided either crushed and screened, to which fines may be added to conform with specification, or crushed insitu (FIGURE 9) by compaction equipment.

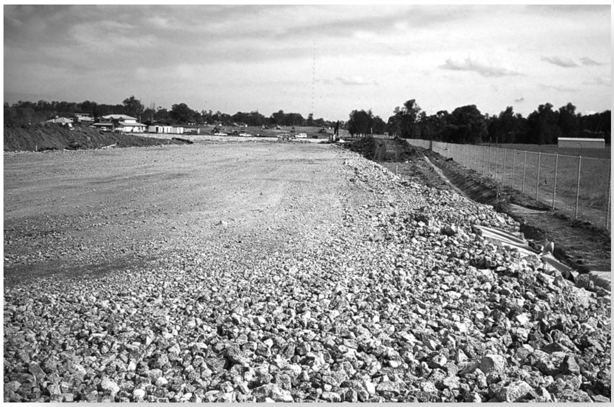

FIGURE 9: CAMDEN VALLEY WAY INSITU COMPACTION.

As the fines content increases during insitu crushing by compaction equipment, the self-cementing action of the rock slag takes place more rapidly. This self cementing phenomenon is due to the presence of 5–12% reactive glassy material produced in the slag during its solidification from the molten state.

The slag reacts slowly so that at around 12 months, sufficient strength will develop in the compacted rock slag for it to reach a stiffness equivalent to that of a heavily bound material (AUSTROADS 1992). Cores with compressive strengths exceeding 15 MPa have been extracted from in-service roads.

Granulated Blast Furnace Slag

Granulated blast furnace slag sets up more rapidly than rock slag so that from about 3 months it will resemble a coarse sand-cement mortar with an Unconfined Compressive Strength (UCS) of around 5 MPa.

Initially, the compacted surface of this material is soft but it hardens with time. Granulated blast furnace slag can have up to 99.5% reactive glassy material, which accounts for its self cementing properties.

BOS Slag

Major heavy-duty roads are being constructed successfully using:

(a) 60% of minus 25mm BOS slag blended with 40% granulated slag. The free lime present in the BOS slag is being used advantageously to activate the granulated blast furnace slag to produce a relatively rapid set.
(b) 95% of BOS slag blended with 5% fly ash gives similar results.
(c) 70% of minus 20mm BOS slag blended with 25% granulated slag and 5% fly ash. The free lime present in the BOS slag activates the fly ash and the granulated blast furnace slag to produce a rapid set.
(d) Minus 20mm BOS slag blended with proportions of power station bottom ash and fly ash has also proved to be a successful subbase. The free lime activates the fly ash and the non-plastic nature of the bottom ash ensures the material will not fail due to plastic deformation.

The above materials can be used as either subbase or base materials depending on the application.

EAF Slag

EAF slag has been successfully used as a subbase by:-

(a) Using a minus 40mm crusher run material
(b) Blending minus 20mm or minus 40mm material with appropriate insitu materials for modifying before overlaying with base materials.
(c) Blending with granulated blast furnace slag.

2.2.3 Base

Blast Furnace Rock Slag

As base, blast furnace rock slag is provided as:

(a) a graded product which is crushed and screened and to which fines may be added to conform to specification, or
(b) uncrushed rock slag which is crushed and compacted insitu, generating sufficient fines to produce a surface suitable for a sprayed seal or asphalt wearing course.

The Prospect ALF trial (Kadar and Walter 1989) showed that rock slag, although having a relatively low 10% Fines Wet Strength (70kN to 90kN)), exhibited a performance equivalent to high quality crushed rock under heavy traffic.

Trials were also carried out to assess the material's performance under Federal Airport Corporation guidelines. The trials used heavy rollers to simulate stresses imposed by heavy aircraft landing gear. The particle breakdown under this stringent test was well within the FAC specifications. The material remained non-plastic. (Ref. "Proof Rolling Effects on Slag Pavement Materials. ASMS March 1992).

Crusher run rock slag usually contains too few fines to comply with the normal particle size distribution for dense graded base (DGB). This can be achieved by the addition of basalt fines from another crushing operation. Alternatively a blend of 80% minus 20mm crusher run rock slag and 20% granulated slag has been used as heavily bound base. In addition, an activator such as hydrated lime (1–3%) or lime/fly ash (1–3%) can be used if a more rapid initial set is required.

TABLE 4 summarises test results on a mix of 80% rock slag with 20% granulated slag with 3% lime/fly ash activator (Woodbury 1991).
Cores subsequently taken from pavements with this material had strengths in excess of 10 MPa, which approximates the strength requirements of lean mix concrete.

TABLE 4: UCS TEST RESULTS.

TEST CONDITION (CURING)	AVERAGE UNCONFINED COMPRESSIVE STRENGTH (MPa)
7 day ambient	2.7
28 day ambient	3.0
7 day accelerated	4.0

BOS Slag

When slag materials were initially trialled as base course materials, blast furnace rock slag was used due to its ready availability, as well as its better yield and well known properties. However, the last 10 years has resulted in the increased utilisation of steel furnace slag to produce high quality bound materials in both the Newcastle and Wollongong regions.

Initially steel slag was introduced as a DGB 20, which has high shear strength with a modified Texas Triaxial number less than 2.0 and an average compressive modulus greater than 35 MPa.

Further to this, steel slag was blended with other materials to modify and enhance its properties. The addition of granulated slag or fly ash to produce a bound material has been trialled and proven. TABLE 5 shows test results of a blend of 60% BOS slag and 40% granulated slag (Woodbury 1991). This Steel Slag base material has been used in the Wollongong area and a similar mix has also been in use for over 10 years in the Newcastle Region.

TABLE 5: UCS TEST RESULTS.

TEST CONDITION (CURING)	AVERAGE UNCONFINED COMPRESSIVE STRENGTH (MPa)
28 day damp	5.0
7 day accelerated	3.0

TABLE 6 shows laboratory strength results for a pavement constructed with a blend of 95% BOS slag and 5% fly ash.

TABLE 6: UCS TEST RESULTS.

TEST CONDITION (CURING)	AVERAGE UNCONFINED COMPRESSIVE STRENGTH (MPa)
28 day damp	5.9
90 day damp	7.4
7 day accelerated	6.0

Cores subsequently taken from the pavement had strengths in excess of 6MPa, which exceeds the strength requirements of heavily bound base material.

Further to this, several new blends were trialled jointly by the RTA and Newcastle slag suppliers. An optimum mix of 70% steel slag, 25% granulated slag and 5% fly ash was determined. This blend, known as "MIX 3" has been used extensively in the Newcastle area since then. Average laboratory strengths are shown in TABLE 7.
Core results have shown that the material reaches strengths of approximately 10 MPa. These results have been obtained from local roads cored up to 6 years after construction.

TABLE 7: UCS TEST RESULTS.

TEST CONDITION (CURING)	AVERAGE UNCONFINED COMPRESSIVE STRENGTH (MPa)
7 day damp	1.2
14 day damp	2.3
28 day damp	3.8
35 day damp	5.0

The strength gain over time can be attributed to:-

- Free lime and contained lime from the steel slag reacting initially with the fly ash
- Any remaining free lime and contained lime from the steel slag reacting with the granulated slag
- The slag materials' self cementing action.

The material has a particle size distribution slightly finer than other base course materials. This has advantages in terms of improved workability and ease of placement and compaction. This ease of placement and strength gain over time provides rapid construction and whole-of-life costing benefits compared to more conventional materials.

BOS slag has also been blended with power station bottom ash and fly ash to obtain a non-plastic bound base material. Because the bottom ash is relatively inert compared to granulated slag, ultimate strengths are lower than those illustrated in TABLE 7. Strengths for this mix are given in TABLE 8. Core tests taken after about 12 months have shown strengths of about 6 MPa.

TABLE 8: UCS TEST RESULTS.

TEST CONDITION (CURING)	AVERAGE UNCONFINED COMPRESSIVE STRENGTH (MPa)
7 day damp	0.5
14 day damp	1.5
28 day damp	2.5
35 day damp	3.2

Roller compacted steel furnace slag blends have also been used in recent times for heavily trafficked and high maintenance areas such as transport storage terminals and chicken shed floors over poor sub-grades. The material is a triple blend of steel furnace slag, blast furnace slag and cementitious powders. The material has working times up to 12 hours and long-term strength up to 15MPa. It is placed using conventional pavement equipment and finished with multi-tyre rollers.

Rail Services Australia Capping Blend is a triple blend of steel furnace slags and power station ashes. It has been used extensively for track repair in the Hunter Valley heavy haul coal lines.

The material is used as a bridging layer/working platform over low strength subgrades with a minimum thickness of 300mm. The material has a working time in excess of 72 hours and can be stored on site prior to use.

The reaction commences after the application of adequate compaction at moisture content of optimum +1 to –3%. Long-term strengths of up to 8MPa are achieved. The material has been used from Willow Tree to Port Waratah Coal Terminal and specifically at Sandgate, Rutherford and Wickham in NSW.

EAF Slag

EAF slag has been used in two main applications as a base course.

The material has been blended at a rate of about 40% with existing base materials to rehabilitate existing pavements. The EAF slag increased the wet/dry strength value, decreased the Plasticity Index and modified the pavement materials such that it now conforms to a DGB20 specification in accordance with RTA Specification 3051.

EAF slag has also been blended with granulated slag to form a bound base material. This material is slower setting than similar BOS slag materials due to the lower free lime content, but UCS values well over 4 MPa would ultimately be expected, ensuring the material meets the heavily bound criteria.

Granulated Slag

Slag is a versatile self-cementing material that can accommodate various activators to enhance cementing action. Non-cementitious materials can also be accommodated if the cementing action needs to be suppressed.

The French Road Authority, SETRA, has developed a group of slag pavement types called 'grave laitier' or 'gravel slag' using granulated slag as a binder with hydrated lime as an activator (Howard 1988). Several of these blends have been trialled in Australia and test information is available for them (Heaton 1989, Woodbury 1991, Joshi 1997).

2.3 Construction Techniques

Due to the self-cementing properties of slag pavements certain construction techniques are applicable for placement. Because slag pavements usually become bound, some of the principles as for rigid pavement construction are required.

2.3.1 Joints

Fresh Joints

When using slag pavements fresh jointing techniques are used when the joints are placed within the allowable working time of the older material. When fresh longitudinal joints are required the outer 300–400mm of the older material is left uncompacted until the adjoining material is placed and ready for compaction.

Cold Joints

Where the older material has passed the allowable working time cold jointing techniques are required.

Transverse jointing is always at right angles to the road centre-line. Before fresh slag material is placed, a clean vertical surface shall be cut to a minimum depth of 150mm from the exposed face. If a subbase bound layer has been placed, the base layer transverse joints shall be offset at a minimum of 2m from the subbase joints.

Longitudinal jointing should be constructed in a similar fashion. If a subbase bound layer has been placed, the base layer longitudinal joints shall be offset at a minimum of 150mm from the subbase joints.

Instances have occurred where ramping of the slag layers on top of each other during construction has caused a wedge effect at the joints, and plating has occurred resulting in elevation differences at the joint. Milling the wedged joint and replacing the material with a vertically jointed slag material has fixed this problem.

Compaction and Trimming

Blended slag products are generally well graded and easy to compact. They can be compacted in a single layer up to 300mm thick.

For new construction work, multiple layers of blast furnace slag are acceptable, as the self cementing action bonds the layers together and layer thicknesses are restricted to between 170 and 200mm to achieve the high compaction standards for new construction work.

Underlying layers should not be trimmed nor finished with a smooth drum roller. This will ensure mechanical as well as chemical bonding.

For insitu rehabilitation work, thicker layers are encouraged (in excess of 300mm) to ensure that lamination in the pavement does not occur. Primary trimming should be completed above the required levels to ensure that when final trimming is done, extra material is not required in a thin layer.

If extra material is required, the existing compacted layer should be ripped up and the extra product added and re-compacted. This will avoid thin laminating layers plating and causing pavement problems when the material has gained strength.

Finished Surfaces

It is common to slurry the surface of a pavement when finishing. In blended slag pavements this will aid in the curing of the pavement to contain moisture for hydration. If this practice is used the slurry must be removed before adding extra layers or prime seals to the pavement. For insitu stabilisation the slurrying of the surface is not recommended.

Moisture Content

Slag blended materials are less sensitive to moisture than conventional materials. The insitu compaction process is best achieved by the addition of large amounts of water to near saturation, providing this does not lead to softening of the layers below the slag.

This allows fines to be washed into voids and also facilitates the crushing process. The low sensitivity to moisture also allows compaction to proceed in wet weather but does require a firm stable support if insitu crushing is required. Many slag pavements have been placed in wet weather, or placed above optimum moisture content in the field. These pavements will pass compaction tests very easily but will take longer to gain strength.

Sawn Joints

For slag pavements requiring sawn joints, the jointing should be carried out according to the designer's instructions, and in most cases should be carried out 7-10 days after compaction.

2.4 Typical examples of the use of slag in pavement materials

- The F6 tollway from Waterfall to Bulli constructed 1975. (FIGURE 10)
- The F5 South Western Freeway from Campbelltown to Alymerton 1.25 million tonnes.
- Almost all roads constructed by Wollongong City Council since 1970. (FIGURE 11)
- Almost all the heavy road network constructed in the Newcastle City and Lake Macquarie Region since 1955.
- MR513 Sydney-Wollongong, Bellambi Creek Deviation, 45,000 tonnes (Woodbury, 1991).
- MR626 Wollongong Northern Distributor, Towradgi Road to Bellambi Lane (1991).
- Sydney-Newcastle Expressway, Dora Creek to Minmi.
- 3rd Runway construction — Sydney Airport 1994 (FIGURE 12)
- Heavy duty roads within BHP steelworks at Port Kembla and Newcastle
- Gwynneville Interchange — F6 — Wollongong
- Picton and Appin Roads — Wollongong
- Pacific Highway Heatherbrae — Slag roadbase trial 1994
- New England Highway — Hexham to Tarro rehabilitation — includes blast furnace road base and steel slag/natural aggregate asphalt trial
- New England Highway — Lochinvar — Mix 3 roadbase — RTA
- Pacific Highway Lake Munmorah — RTA
- The Entrance Road, Long Jetty — Wyong Council
- Henry Parry Drive, Gosford — Gosford Council
- Lake Road Glendale — Lake Macquarie Shire Council
- New England Highway Scone — RTA
- Pacific Highway — Raymond Terrace Bypass — Mix 3
- Nelson Bay Road — Sandhills Duplication — Port Stephens Shire Council — Mix 3
- Sutton to ACT — Federal Highway 2000 (FIGURE 13 & 14)
- Oaks Flats Interchange — Princes Highway 2001 (FIGURE 15)

FIGURE 10

FIGURE 11

FIGURE 12

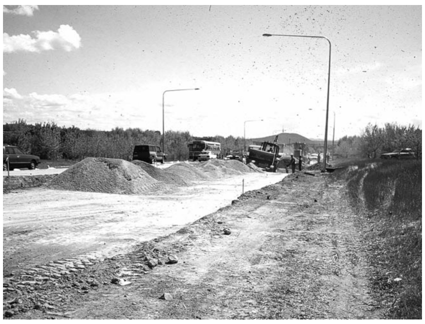

FIGURE 13

FIGURE 14

FIGURE 15: Photo courtesy of Hank Van Stuivenburg - Illawarra Mercury.

3. STABILISATION

3.1 Introduction

Various slag binders are available for the chemical stabilisation of soils, gravel and crushed rock. The potential benefits range from the general improvement of the host material's properties by modification (where the product is considered to still perform in an unbound condition), through to the production of lightly and heavily bound pavements and materials (AUSTROADS 1998).

One of the major benefits of using slag products in a stabilised pavement is the slow rate of the cementation process. The pavement material can be reworked up to two days or more after initial mixing depending on the binder, without reducing the final strength. This enables:

- The use of longer haul times and distances.
- Temporary stockpiling before use.
- A contingency for unforeseen problems.
- Extended trimming and compaction times.
- Improved rideability as a result of longer working times allowing better finishing.

3.2 Insitu stabilisation

Insitu stabilisation has been used for many years in road pavement construction and for pavement rehabilitation. However in the past it had its limitations for more heavily trafficked roads where deep pavements are required, often because the construction equipment available was inadequate to achieve the mixing and compaction requirements needed to meet the structural pavement design requirements of depths in excess of 300mm.

There were also problems with the stabilising binders. Portland cement was commonly used, which generally did not allow enough working time to achieve adequate compaction or achieve a suitable ride quality on the finished surface. For these reasons, insitu stabilisation was not frequently used on the more heavily trafficked roads.

As a result of a co-operative effort between government, the construction industry and material suppliers in the early nineties, the problems with insitu stabilisation have been largely overcome.

To satisfy structural pavement design requirements for heavily trafficked roads, where the stabilised layers are the primary load bearing layer, stabilised layers of at least 300mm thickness with a modulus value of at least 5,000 MPa are usually required. Lesser thicknesses and/or stiffnesses may suffice when there are other load bearing layers in the pavement structure. It is also highly desirable that the stabilised layers be constructed in a single lift to minimise the chance of any problems that may result from subsequent layer debonding, as has occurred in the past.

Equipment and binder developments have enhanced insitu stabilisation processes, namely:-

FIGURE 16: DEEP LIFT PAVEMENT EQUIPMENT.

- Powerful, self-propelled recycling machines, particularly the CMI RS500, became available in Australia. These machines are easily able to recycle pavements to depths well in excess of 300mm. (FIGURE 16)
- In conjunction with this, more sophisticated Australian developed equipment became available for more accurate spreading of stabilisation binders as well as heavier rollers which were able to handle the compaction of the thicker layers required.
- Binder suppliers began making slower setting binders containing combinations of granulated ground blast furnace slag, lime and fly ash which could be individually designed to meet the requirements of the material being stabilised and specific job conditions. These binders have significantly longer setting times than Portland Cement which allows adequate compaction and shaping of the stabilised layer to occur. In addition, they generally have improved shrinkage properties compared with Portland Cement, which allow the formation of a shrinkage cracking pattern of much finer cracks which do not adversely effect subsequent pavement performance.

FIGURE 17: BINDER DELIVERY TO SITE.

These factors provided the basis for significant cost savings for pavement rehabilitation of the rural and metropolitan road networks, including lightly trafficked roads managed by Local Governments.

3.2.1 Proving the New Technology

A number of co-ordinated field trials were conducted to introduce the new stabilisation technology. This then led to the publishing of a guide to good practice for deep-lift stabilisation (RTA 1994). VicRoads have also published similar guidelines (VicRoads 1997).

In addition, to gain an understanding of the long term performance of deep-lift stabilised pavements, an Accelerated Loading Facility (ALF) trial was conducted near Cooma in 1994 (Jameson et al 1995).

The Cooma ALF trial demonstrated that the deep-lift recycling process produced pavements which met the structural design requirements of the Austroads Guide to the Structural Design of Road Pavements (1992). In fact the Cooma ALF trial was instrumental in the development of revised performance criteria for cemented materials, which were introduced in 1997.

3.2.2 Utilisation of Deep-lift Stabilisation

Since the early 1990s deep-lift stabilisation has been widely used as a cost effective treatment for rehabilitation of the road network. Many hundreds of kilometres of pavement have been successfully rehabilitated in this manner.

For stabilised layers in excess of 300mm it is necessary to have sound subgrade in order to be able to achieve adequate compaction of the thick layer (the anvil effect). The performance of deep-lift stabilised layers is sensitive to the level of compaction, which has a strong correlation with strength.

Inadequate compaction can lead to a substantial reduction in strength, which will cause premature cracking, and an increase in deflection. Subsequent moisture ingress and trafficking can lead to pumping and erosion with significant loss in structural capacity.

An automated Benkelman Beam or Deflectograph survey is recommended prior to the commencement of work to identify any soft substrata. Areas of soft substrata must be removed and replaced or stabilised prior to the rehabilitation of the existing pavement.

Despite this, if inadequate support is provided by the sub-strata during compaction, as evidenced by movement of the stabilised material under construction equipment and the appearance of flexure cracking during the final stages of compaction, this must be corrected. This involves removal of the stabilised layer and either replacement of the supporting layers with better quality material or stabilising the supporting layers to improve their bearing capacity. The stabilised layer can then be replaced, re-stabilised and compacted.

The availability of ground granulated blast furnace slag has increased its use as a component in blended cementitious stabilising binders. These binders primarily consist of lime, fly ash and slag (often called "triple blends) and can be blended in different combination of components depending on:-

- The type of material being stabilised
- The strength of the stabilised material required
- The availability and cost of the stabilising component materials

These blended binders require individual evaluation for each material to be stabilised, to ensure an optimum result in terms of material properties and cost is achieved.

A detailed discussion of cementitious stabilisation is provided in Austroads "Guide to Stabilisation in Roadworks." (1998).

Details of some slag stabilisation binders and their features are as follows:

3.3 Granulated Blast Furnace Slag (GBFS) and Ground Granulated Blast Furnace Slag (GGBFS) as Stabilising Binders

The performance of both GBFS and GGBFS in stabilisation depends on the degree of fineness of the material which in turn is a matter of economics. The cost of producing a finer grade of granulated slag (ground granulated slag or slag cement), coupled with the reduced amount of slag stabilising binder needed to provide equivalent strength, must be balanced against haulage costs.

The effect of grinding slag to different degrees of fineness was illustrated in a laboratory study carried out by Wong (1992). 4% of a 85:15 ground granulated slag:hydrated lime mix was added to a fine crushed rock and UCS testing was carried out after delaying compaction for various times up to 48 hours. This was carried out for three different grinds of slag; Fineness index 450 m^2/kg, 335 m^2/kg and 256 m^2/kg. The results (FIGURE 18) showed that the finest grind consistently gave the highest strength.

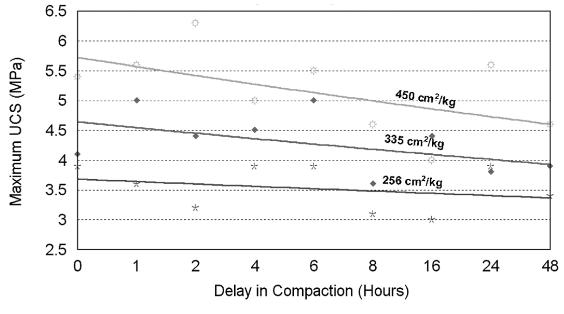

FIGURE 18: MAXIMUM UCS VS DELAY IN COMPACTION FOR A RANGE OF SLAG FINENESS.

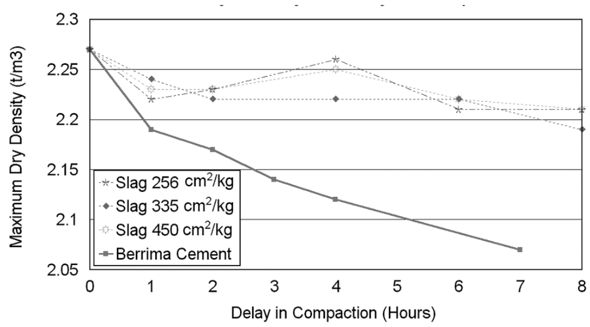

FIGURE 19: MAXIMUM DRY DENSITY VS DELAY IN COMPACTION.

Wong also demonstrated that, unlike GP cement where the maximum dry density decreases rapidly with any delay in compaction, the slag:lime blends showed little decline in the maximum dry density even with up to 8 hours delay in compaction (FIGURE 19).

Both GBFS and GGBFS require an activator to achieve their strength potential. Activators include hydrated lime, fly ash, gypsum and portland cement used separately or in combination. When using GGBFS, the activator (generally hydrated lime), is blended with the binder which is then stored and handled in the same way as normal cement prior to stabilisation. The binder does not commence reaction until water is available for hydration to take place.

Triple blends (GGBFS, lime and fly ash) have gained acceptance as they can be individually blended to suit a particular job and also fly ash and slag are usually more economical than GP cement.

In designing these binders, the primary aim is to have sufficient lime available to promote the pozzolanic reaction with the slag, fly ash and the clay component of the material being stabilised. This usually means a minimum of 12 to 15% hydrated lime in the blend but this may need to be raised to 50% for materials with high clay contents. Where insufficient lime is available in the blend, the performance of the stabilised material will be compromised.

Blends using slag, fly ash and lime have working times up to 4 times that of GP cement with working times of up to 48 hours being available with some soils. (Walter 1999).

VicRoads also have research findings for stabilisation using cementious blends incorporating GGBFS (VicRoads 2000).

3.4 Special Slag Cements

Various slag cements, classified as General Purpose Blended Cements (GPBC), are available for use as stabilisation binders. Some of these perform similarly to normal cements and others will produce the additional advantage of slow setting time when more working time is required. Laboratory testing should be carried out to assess the suitability of these cements for particular applications if setting time is critical.

These special slag cements contain GGBFS (>5%) with a proportion of any or all of the following components

- Portland Cement
- Fly ash
- Lime.

3.5 Testing

Laboratory testing is normally carried out to determine the quantity and type of binder required to meet design requirements for particular materials. The 7 Day Accelerated Unconfined Compressive Strength (UCS) is commonly used for this purpose. It should be noted that the result will only reflect a portion of the long term insitu strength. Cores taken from the field after 9 to 12 months have been shown to be often two or three times greater than the 7 day accelerated UCS value obtained.

Guidelines for laboratory testing procedures may be found in Austroads (2001)

Coring of stabilised pavements is recommended after 12 months to provide feedback on:-

- Depth of stabilisation
- UCS of top and bottom halves of stabilised layers
- Delamination within layers

3.6 Handling

The incorporation and mixing of the binder can be achieved using conventional insitu mixers or pugmills. The handling, compaction and trimming operations are carried out using normal methods and equipment, although for deep-lift stabilisation care should be taken that appropriate compaction equipment is used to achieve adequate density throughout the full depth of the stabilised layer.

Although the strength gain is relatively slow, immediate or early trafficking is generally allowed. The shear strength and stability of the compacted material is normally sufficient to carry the early traffic loading and this does not adversely affect the long term cementitious strength gain and may assist by discouraging the formation of an adverse cracking pattern.

3.7 Curing

Damp curing should be maintained, as for normal stabilisation, until the layer is covered or sealed. Care should be taken to avoid erosion and leaching of the surface by excessive watering.

3.8 Future Developments

Austroads, in co-operation with Australian Stabilisation Industry Association are pursuing research to improve the laboratory testing regime for characterisation of stabilised materials. A revised guide to deep-lift stabilisation is also being prepared by Austroads.

4. SLAG MATERIALS IN ASPHALT AND SPRAYED SEALING

4.1 Introduction

Both steel furnace and blast furnace slag have been successfully used in spray sealing and asphalt applications.

Steel furnace slag is most commonly used as its better strength, abrasion and impact resistance than blast furnace slag make it particularly suitable for use in areas subjected to heavy vehicle loads and high shear stress.

Information on sprayed sealing design on materials selection may be gained from the RTA Sprayed Sealing Guide (1991). A summary of slag properties for sprayed sealing and asphalt is shown in TABLE 9.

TABLE 9: COMPARITIVE PROPERTIES OF SLAG MATERIALS.

Property	BOS & EAF Slags	Blast Furnace Slag
Strength	Very good	Fair
Abrasion resistance	Very good	Fair
Impact resistance	Very good	Average
Shape	Very good	Very good
Stripping resistance	Very Good	Very good
Skid resistance	Very good	Good

TABLE 10 gives a broad indication of the uses of blast furnace, BOS and EAF slags in asphalt and sprayed sealing work.

TABLE 10: SLAG APPLICATIONS.

Application	BOS & EAF Slags	Blast Furnace Slag
Asphalt	All applications including; heavy duty roads and high stress areas like roundabouts	Lightly trafficked roads, intermediate asphalt layers, carparks.
Sprayed sealing	All applications including; heavy duty roads and high stress areas like roundabouts	Lightly trafficked roads, carparks, Strain Alleviating Membrane Interlayers (SAMI) applications.

Detailed guidance on the properties and usage of BOS and EAF slags in asphalt and sprayed seals may be obtained from the ASA's publication "A Guide to the Use of Steel Furnace Slag in Asphalt and Thin Bituminous Surfacings" 1999. Detailed guidance on the selection of road surfacings may be obtained from the Austroads publication "Guide to the Selection of Road Surfacings" 2000.

4.2 Skid Resistance

Steel furnace slags have a higher friction value than most other commonly use aggregates. Blast furnace slag, although having a high friction value, has a lower particle strength than steel furnace slag.

4.3 Density

Steel furnace slag is typically 20% denser than traditional material whereas, depending on the size fraction, blast furnace slags are slightly lighter than most traditional materials.

4.4 Particle Size Distribution

For sprayed seal and asphalt application, crushed and screened slag can be supplied to specified requirements.

4.5 Shape and Fractured Faces

Both steel furnace and blast furnace slag when crushed, consistently produce cubic shaped particles with a high percentage of fractured faces. These properties help produce a dense mat in sprayed seal applications and ensure good mechanical interlock in asphalt.

4.6 Stripping

Steel and iron slag aggregates are basic and therefore have a high affinity for bitumen in the clean dry state and may be used without precoating. However for sprayed sealing it is a normal requirement for aggregate to be pre-coated.

4.7 Asphalt Mix Design

When designed in accordance with Roads and Traffic Authority Specification Procedure No. R116, steel furnace slags produce mixes which display low creep characteristics and high resilient moduli and are suitable for use on roads subjected to high traffic loads and shear stresses. Blast furnace slag may be used in asphalt as indicated in TABLE 7. Blast furnace slag has a long history overseas of successful use in wearing courses

4.8 Case Studies

The following case studies are presented in Section 7 of the "Guide to the Use of Steel Slag in Asphalt and Thin Bituminous Surfacings".

- Roads and Traffic Authority — Illawarra District
  - Picton Road
  - Intersection of F6 and the Northern Distributor
  - Bulli Pass
  - Tomerong Bypass
- Sydney Region
  - Pennant Hills Road
  - Roberts Road, Padstow
- Newcastle Region
  - BHP Steelworks
  - Kooragang Island
  - New England Highway

Monitoring of these roads is continuing.

5. BLAST FURNACE SLAG CONCRETE AGGREGATES

5.1 Introduction

Blast furnace slag aggregates are available in a full range of sizes and blends as required for concrete manufacture.

It is important that slag aggregate should not be directly substituted for other aggregate in an existing concrete mix. Rather a mix should be specifically designed based on BF slag's slightly lighter weight and higher absorption.

Detailed information on the properties and usage of blast furnace slag in cement and concrete is provided in the ASA's publication "A Guide to the Use of Iron Blast Furnace Slag in Cement and Concrete" 1997.

5.2 Characteristics

5.2.1 Particle Shape

Blast furnace slag crushes to produce a desirable cubical shape.

5.2.2 Density

Owing to the vesicular nature of slag, bulk densities may vary slightly depending on particle size. Users should therefore take this into account when concrete mixes are being designed.

5.2.3 Surface Texture

Because blast furnace slag aggregate is a vesicular material, it will absorb additional water. Therefore it is important that the material is pre-wetted and this condition maintained prior to batching.

5.2.4 Physical

The physical durability (as expressed by the wet/dry strength variation) is good, though the wet strength tends to be low. The reason for this is the vesicular nature of the material, rather than the particle integrity. This is compensated for by the particle/aggregate interlock within a concrete mix, except where required to provide aggregate interlock across joints in plain undowelled concrete pavements.

RTA has allowed up to 30% blast furnace slag as coarse aggregate in base course concrete paving mixtures.

Testing has shown that slag aggregate concrete produces flexural strengths comparable to other aggregates.

5.2.5 Abrasion

The "rounding" (breaking of corners) observed under Los Angeles testing is not evident in the batching and mixing process.

5.2.6 Chemical Durability

Slag aggregate exhibits a high degree of sodium sulfate resistance.

5.3 Mix Design

As stated previously, because of the different characteristics of blast furnace slag, aggregate mix designs using other aggregates should not be applied directly to slag.

It is possible that binder content can be reduced on account of the improved mechanical interlock of the aggregate and the cementitious action of the aggregate surface.

To aid workability and pumpability of slag aggregate mixes, it is usual to incorporate a larger proportion of fine sand than with less vesicular aggregate mixes.

5.4 Properties of Fresh Concrete

5.4.1 Slump

Measured slump is often taken as an indication of workability. Slag concrete has better workability than other concretes with the same slump.

In performing a standard slump test on concrete containing blast furnace slag aggregate, it will be noted there is a lower than expected slump for the required workability.

5.4.2 Workability/Pumpability/Finishing

As with all concrete these properties are highly dependent on mix design. Concrete using slag aggregates will usually require a higher fine sand content. The consistent particle shape of slag aggregates, combined with pre-wetting, result in excellent pumping characteristics.

5.4.3 Curing

Again with all concrete, good curing practices are important. Slag aggregate concrete benefits from the self curing provided by the moisture contained in the aggregate.

5.5 Properties of Hardened Concrete

5.5.1 Density

The density of hardened concrete containing blast furnace slag is approximately 3% lower than concrete containing basalt aggregate. Internal vesicles do not necessarily fill with paste as they may be initially filled with water or air.

5.5.2 Drying Shrinkage

Concrete containing blast furnace slag aggregates exhibits approximately 15% lower drying shrinkage than natural aggregate concrete. (Ref. Building Research Centre BRC, testing to RTA Test Method T312, June '92). This is due to the water stored in the vesicles being slowly released, thus aiding the curing process.

5.6 The Use of Slag Aggregate in Concrete

At present (2002) over 450,000 tonnes of slag aggregate and slag sand is used by the concrete industry annually. Some examples of Slag cement and aggregate applications include,

- Sydney Harbour Tunnel — The cement for the immersed tube segments comprised 40% ACSE (Shrinkage limited) cement with 60% GBFS interground with optimised gypsum content. Approx. 36,000 tonnes of cement was used for these units.
- Anzac (Glebe Island) Bridge, Sydney — The two pile caps supporting the towers for this cable stayed bridge utilised high slag cement as used in the Sydney Harbour Tunnel. Each of the caps contained approx 2,800m^3 of concrete which was continuously poured.
- No. 6 Blast Furnace — Port Kembla. The foundation block for this 100 metre tall furnace, comprising 2300m^3 of concrete used a tertiary cement comprising four parts high slag (60-65%) cement with one part of fly ash to limit the heat of hydration. BF slag aggregate was also used in the concrete. A further 13,000m^3 of slag cement/slag aggregate was used for associated works.
- Esso — West Tuna-Bream B Oil Platforms — These concrete gravity structures (CGS) were constructed at the Port Kembla casting basin before towing to their locations in Bass Strait. The caissons or the fully submerged sections of the platforms utilised two different mixes, viz. The base concrete comprised high slag (60%) cement with 20mm aggregate. The caisson walls used a quaternary blend of 87% high slag (60%) cement with 11% fly ash and 2% silica fume and 10mm aggregate. The upper sections of the CGS's including the roof and shafts which incorporate the splash zone, were cast with a blend of 50% OPC with 35% slag, 10% fly ash and 5% silica fume and 14mm aggregate.
- Sandringham Marina — Port Phillip Bay, Melbourne — A tertiary cement was used comprising 55% ordinary Portland cement with 35% slag and 8 to 10% silica fume.
- Maribyrnong River Bridge — This bridge has a total length of 520m (54m spans) and was constructed using an incremental launch system. The construction method allowed segments to be placed at one end and subsequently launched (jacked) into position on a weekly cycle. Slag cement 70% OPC, 30% slag. 20,000m^3 of concrete.
- Calder Freeway Upgrade (Bridges) 60% OPC, 40% slag.
- New Crown Casino Piles — Aggressive ground water conditions adjacent to the Yarra River required piles to have a high durability. 30,000m^3 of concrete using high slag and fly ash was used.
- New Melbourne Exhibition Centre — This 84m × 360m post tensioned floor used 30-50% slag cement to give 30,000m^3 of pillarless uninterrupted space. (Largest open area exhibition space in the Southern Hemisphere).
- Post tensioned floor system for Major Warehouse / Distribution Centre for the Murray Goulburn Company. Slag cement 70% OPC, 30% slag. 17,000m^3 of floor space.
- Ballarat Road Bridge. Melbourne — 35% slag, 65% OPC. 5,000m^3 of concrete. 35% slag, 65% OPC. 16,000m^3 of concrete.
- Womens Prison — Deer Park, Victoria 35% slag, 65% OPC. 4,000m^3 of concrete.
- Textile Factory, Melbourne 35% slag, 65% OPC. 15,000m^3 of concrete paving.
- Offshore Oil Storage Platform — Wandoo, Western Australia. 65% slag cement. Structure weight 81,000 tonnes.

6. SLAG BENDED CEMENT IN CONCRETE

6.1 Introduction

Blast furnace slag has a chemical composition similar to Portland cement although in different proportions. Ground granulated blast furnace slag satisfies the requirements of Australian Standard AS3582.2 Supplementary Cementitious Materials for Use With Portland Cement, Part 2. Slag blended cement meets the requirements of Australian Standards AS3972 Portland and Blended Cement.

Hinczak, 1991 reported that:

> "The benefits of slag cements have been enjoyed overseas for many years. In Australia, investigations indicate the identical benefits are possible with local materials and technology.
>
> Granulated slag does not only allow production of concrete with ordinary Portland (GP) cement performance but concrete possessing properties such as thermal stability, sulfate, marine and chloride resistance. There is no doubt that the chemical resistance possible with slag cements is not readily achievable with Portland cements.
>
> The use of ground granulated blast furnace slag in concrete allows the design of cements which provide the required concrete properties to suit the application required by the engineer.
>
> To fully utilise slag cements, engineers and specifiers must acquire an understanding of the properties, potentials and limitations of these materials"

6.2 Specific Properties of Slag Blended Cement in Concrete

6.2.1 Replacement Levels

By varying the ratio of ordinary Portland cement (GP cement) to ground granulated blast furnace slag, it is possible to optimise specific properties of the concrete.

Generally the replacement level is 20% to 50%, however it will depend on the application. Where high resistance to chemical attack (e.g. chlorides and sulfates) is required, 65% replacement is common practice. In some marine applications, such as the offshore North West Shelf natural gas complex in Western Australia, grouts containing 90% ground granulated blast furnace slag have been successfully used.

6.2.2 Workability

Concretes made with slag blended cement have excellent flow characteristics particularly where vibration is employed. For a given slump, concrete made with slag cement is easier to place and compact and it is therefore possible to use concrete with a lower slump to exploit this advantage. This allows the use of less water, in the order of 3 to 5%, and will thereby reduce the water/binder ratio to improve the strength and durability of the concrete. The problems caused by excessive water such as aggregate segregation, bleeding and high concrete porosity are also lessened. With respect to finishing, concrete containing slag blended cement may appear more cohesive. This aids the production of a good surface finish.

The lubrication value of slag cement also yields excellent concrete pumping characteristics with reduced pipe line wear, lower power requirements, and the ability to reach high levels or achieve long pumping distances.

6.2.3 Setting Time

The setting time for blended cements may be longer than for Portland cements, particularly in cooler temperatures, due to the slower initial rate of reaction between the ground granulated blast furnace slag and water, compared to that of Portland cement. In general with replacement of up to 40% GGBF slag, initial set is unlikely to be extended by more than one hour. In the summer periods the initial set may only be marginally affected. Longer periods may occur at higher replacement levels and although significant retardation has been observed at low temperatures and high replacement levels, the addition of suitable accelerators can greatly reduce or eliminate this effect.

In addition to the proportion of slag in the cement used, the degree to which the setting time is affected is dependent on the initial curing temperature of the concrete and the water to binder ratio. However, it should be noted that in hot dry conditions, the slower setting time is a marked advantage as it allows more time to work the concrete and minimise the generation of cold joints.

6.2.4 Bleeding

The bleeding capacity and bleeding rate of concrete is affected by the ratio of the surface area of solids to the unit volume of water. Provided that proper mix design is used and the water content is lowered, slag cements will produce a concrete which will bleed less. This avoids the problem of excessive bleeding which results in a high water/binder ratio at the surface making the surface concrete weak and susceptible to scaling, pitting and dusting.

However, an aspect which needs to be considered, is that in hot windy weather, some bleeding considerably reduces the likelihood of surface cracking. Of course normal precautions should always be taken to protect any concrete from plastic cracking in hot adverse weather conditions.

6.2.5 Curing

Due to the slower hydration of ground granulated blast furnace slag and the tendency for early drying shrinkage, curing is important in all circumstances in order to achieve the desired eventual lower drying shrinkage. Curing of concrete should start immediately after finishing and should be continued so the design requirements for strength, stripping and serviceability will be met.

The minimum period for effective moist curing of concrete containing slag is as recommended in TABLE 11.

TABLE 11: SLAG CURING.

AVERAGE ATMOSPHERIC TEMPERATURE DURING CURING	REPLACEMENT RATIO (% OF GROUND GRANULATED BLAST FURNACE SLAG TO GP CEMENT)		
	30 — 40	40 — 55	55 — 70
10 — 17°c	7 days	8 days	9 days
> 17°c	5 days	6 days	7 days

6.2.6 Strength Development

Slag blended cement develops strength more steadily than GP cement. The initial rate of gain of strength is slower, but strength development continues for a longer time.

Typically 3 and 7 day strengths are lower. Comparable strength can usually be achieved around 28 days but over time slag blended cement concrete develops higher strengths.

The rate of strength development and the age at which parity with GP is achieved, are dependent on the ratio of ground granulated blast furnace slag to GP and on other mix design criteria .

6.2.7 Heat of Hydration

Slag blended cement concrete does not develop heat as rapidly as GP concrete and this property can be used to considerable advantage in reducing the risk of thermal cracking in thick-sectioned structures, or applications where high cement contents are necessary.

The heat of hydration of concrete containing ground slag is affected by the reactivity of the slag with the cement used, as well as by the slag replacement ratio.

6.2.8 Resistance to Sulfate Attack

Slag blended cement is highly resistant to sulfate attack and in most conditions slag blended cement can be used as an alternative to sulfate-resisting Portland cement.

For very high sulfate resistance, typically 35% GP cement 65% ground granulated blast furnace slag blends are employed.

6.2.9 Permeability

Provided the concrete is designed and cured correctly, slag cement that has a greater volume of hydrate, tends to reduce the pore size and segment the capillary structure. This reduces the permeability and improves the durability of the concrete.

R.F.M. Bakker of the Netherlands on his visit to Australia in 1991 to participate in a series of Supplementary Cementitious Seminars furnished the information as detailed in TABLE 12.

6.2.10 Resistance to Chloride Ion Penetration

Properly proportioned slag blended cement offers improved protection for reinforcement in chloride environments. This is particularly useful for structures in marine applications.

6.3 Typical Examples of the use of Slag Blended Cement in Concrete:

- Sydney Harbour Tunnel submerged tube units. Cement contained 60% ground granulated blast furnace slag (FIGURE 20).
- Pile Cap Foundation Blocks for the Anzac Bridge, (Glebe Island Bridge), Sydney. Cement contained 60% ground granulated blast furnace slag (FIGURE 21).
- GGBFS and fly ash used as a blended cement in Yandina Bypass on the Bruce Highway in Queensland.
- High slag blend 65/35 used in lift wells for Colonial Stadium Melbourne to reduce heat of hydration and thermal cracking (FIGURE 22).
- Sydney Airport Link Tunnel used high slag blend cement for high acid soil environments (FIGURE 23).
- Floating oil platforms used high slag blended for chloride resistance (FIGURE 24).

TABLE 12: CHLORIDE DIFFUSION.

COEFFICIENT OF CHLORIDE DIFFUSION 10-8cm2/sec (Tests conducted on 28 day old mortar)		
W/C Ratio	**GP Cement**	**60% GGBFS**
0.55	3.6	0.12
0.60	6.2	0.23
0.65	8.5	0.41

FIGURE 20: SYDNEY HARBOUR TUNNEL

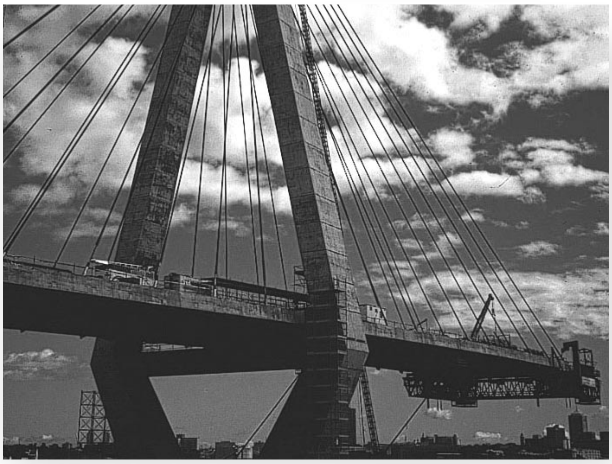

FIGURE 21: ANZAC BRIDGE

FIGURE 22: COLONIAL STADIUM MELBOURNE

FIGURE 23: SYDNEY AIRPORT LINK TUNNEL

FIGURE 24: FLOATING OIL PLATFORMS

7. HANDLING CHARACTERISTICS

7.1 Overview

Slag materials are handled similarly to natural quarried and cement products. No special equipment or methods are required. Slag can be ordered to meet various grading requirements. It is not as sensitive when used as a bound material to the fine grading ratios required in some specifications.

7.2 Pavement materials

Blast furnace rock slag used in pavement applications requires minimal engineering controls. This material is readily compacted and is not sensitive to moisture. The insitu compaction process is best achieved by the addition of large amounts of water to near saturation, providing this does not lead to softening of the layers below the slag. This allows fines to be washed into voids and also facilitates the crushing process. The low sensitivity to moisture also allows compaction to proceed in wet weather but does require a firm stable support if insitu crushing is required.

The permeability of rock slag insitu is a function of the grading of the slag and the presence of voids. A properly compacted DGB20 pavement should be impermeable. However, a moderately compacted uncrushed slag base will most likely be permeable because of the lack of fines to fill the voids.

Due to the self cementing nature of slags, re-use of the product through crushing and compacting is quite practical, provided contamination with lesser quality materials has not taken place during reclamation.

Blended slag base and subbase materials as a result of the components and grading used in the mixes are very workable and can be compacted with a minimum of effort to specified density requirements without the use of heavy compaction equipment.

7.3 Asphalt materials

Slag materials used in asphalt aggregate applications require minimal additional engineering controls. Site stockpiles should be placed in accordance with good engineering practices.

Steel slag aggregates are normally weathered between one (1) and three (3) months prior to use to ensure free lime expansion has taken place.

7.4 Concrete materials

Blast furnace rock slag (BFS) aggregate used in concrete applications requires no additional engineering controls. These materials are produced and supplied in accordance with AS2758.1 — 1998.

Given the vesicular nature of concrete aggregates, pre-conditioning with water prior to concrete manufacture is essential to improve workability.

For Granulated Blast Furnace Slag (GBFS) particular care needs to be taken because of the minute sharp glass shards it may contain. This is also important where granulated slags are stockpiled. The stockpiles should be kept wet to prevent spreading by wind action and if practical secure from public interference.

Ground granulated blast furnace slag (GGBFS) is a very fine powder and is handled the same way as for cement. Products must be kept moisture free.

7.5 Blast Furnace and Steel Furnace Slag as Construction Fill

Iron & steel making slags have for many decades provided an economic and high quality source of material for engineering construction applications in the region.

The aim of this section is to advise of procedures to correctly use and to minimise adverse environmental impacts.

The activity of placing engineering construction fill on development projects has the potential to impact adversely on the environment unless appropriate site controls are introduced to control dust and the formation of leachate where significant water is available.

Developers who proceed without implementing the necessary controls when using any engineering fill material, could be in breach of environmental legislation — see your state EPA requirements.

The key is to prevent water entering the completed site or to prevent possible "leachate" draining to nearby water streams. There are recognised site practices that can reduce the risks of site problems occurring and these should be implemented.

Accredited suppliers of slag have the technical knowledge to recommend the most appropriate use of slag to minimise environmental impacts. It is therefore the User's responsibility to advise the accredited supplier of the site location and the proposed construction activity. The supplier will then assess the site, make recommendations on the material to be used and provide appropriate placement guidelines.

7.6 Alkalinity

As slag materials are generally alkaline in nature, care should be taken during any handling phase.

7.7 Testing

Testing of slag base and subbase materials is similar to other non-plastic materials. The non-plastic nature makes it difficult to mould and results in an optimum moisture content approaching saturation.

Due to the vesicular nature of blast furnace slag, moisture contents should not be determined in a microwave oven as high temperature settings may cause the particles to explode.

7.8 Safety

Slag materials are handled similarly to natural quarried and cement products. Suitable personal protection equipment (PPE) should be worn when working with slag materials.

Material Safety Data Sheets on all slag materials are available from slag suppliers.

7.9 Environmental Considerations

Occasionally when using blast furnace rock slag, there may be a green-yellow leachate generated where water has been allowed to pass through the material. Experience has shown this oxidises rapidly and will neutralise within a few days.

This coloured leachate is more likely to occur when fresh slag (un-weathered) is used or where moisture passes through finer fractions (<6mm). It is not always present and appears in some site specific situations when particular ground waters are encountered and/or where drainage conditions are poor.

Generally 90% of all slag products are used in bound applications and water free environments. Comprehensive monitoring of State Rail Authority embankments involving a quarter of a million tonnes of rock slag, have shown no adverse effects on the environment (Muston 1991).

A sulfur smell may also be evident at some sites, but again this will dissipate within a short time.The incidence of leachate with sulfur odours will be minimised when weathered slag is used which is the current practice.

Research carried out by The University of Newcastle Research Associates (TUNRA) have also shown that steel making caster slags pose no significant environmental threat. (TUNRA 1995 & 1996).

In summary, where good engineering site controls are employed as for other similar quarried and concrete products, the use of slag presents no significant long term environmental threat.

8. CONCLUSION

Since the first Guide to the Use of Slag in Roads was published in 1993, environmental awareness and recycling are receiving increased attention. In road construction and maintenance operations, slag is playing an important role.

The slag products described in this publication are all suited to the purposes detailed, and as such they are competent construction materials suitable for use in their own right and are not, as often believed, a waste material.

The use of slag in cement represents a substantial reduction in the generation of greenhouse gases. A reduction of one tonne of CO^2 discharged into the atmosphere for every tonne of slag substituted for GP cement in the production of blended cement. The use of rock slags conserves the energy already expended in their production and also conserves our finite natural resources.

As with any pavement or concrete material, when considering the use of slag in road construction, it is important to assess the whole of life cost of the structure as well as the initial cost.

This Guide, together with the other Guides published by the ASA and the references included therein, are intended to provide the data to enable Engineers to evaluate the cost effectiveness of slag as an engineering material.

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Name	**Company/Organisation**
Adam Kelly*	Steelstone Services
Alex Leshchinsky*	Australian Steel Mill Services
Andrew Papacostas	Geopave (Vic Roads)
Brian Heaton*	University of Newcastle
Bruce Fenton	Roads & Traffic Authority NSW
Chris Francis	Roads & Traffic Authority NSW
Carsten Osmers	EPA Victoria
Craig Heidrich*	Australasian Slag Association Inc
David Dash	Roads & Traffic Authority NSW
David Hazell	Transport South Australia
Dereck Wingham	Sunstate Cement
Doug Prosser	Hon. Member
Geoff Youdale*	Consultant
George Vorobieff	Australian Stabilisation Industry Association
Ian Reeves	Department of Main Roads — Queensland
Ihor Hinczak*	Australian Steel Mill Services
John Ingold	EPA NSW
Martin Venour*	Hon. Member
Michael Ceccato	Australian Steel Mill Services
Norm Clifford	Steelstone Services
Peter Hanley*	Steelstone Services
Peter Taylor	Australian Steel Mill Services
Steve Brown	Geopave (Vic Roads)
Trevor Jones	Environmental Protection Authority NSW
Tom Wauer*	Independent Cement and Lime
Vijay Joshi	Australian Steel Mill Services
Wayne James*	Australian Steel Mill Services

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ASA OFFICE:

Suite 2, Level 1, 336 Keira Street

Wollongong NSW Australia 2500

Telephone: 02 4225 8466 | **Facsimile:** 02 4228 1777

Email: info@asa-inc.org.au | **Web:** www.asa-inc.org.au

POSTAL ADDRESS:

PO Box 1194, Wollongong NSW 2500